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Advanced Oak Seedling Development as Influenced by Shelterwood Treatments, Competition Control, Deer Fencing, and Prescribed Fire

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Advanced northern red oak (*Quercus rubra*) seedlings in an 85-year-old forest located in north-central Pennsylvania were observed for 10 years after manipulation of available sunlight by shelterwood treatments, reduction of interfering plants by broadcast herbicides and/or a single prescribed fire, and reduction of deer damage by fencing. Twenty-four treatment combinations including untreated controls were studied on 72 permanent plots. The key to sustainable oak regeneration is to enhance both survival and growth of the advanced oak seedlings several years before a planned overstory harvest. In this study, survival and growth of 4,235 tagged oak seedlings were greatest in plots that received an overstory shelterwood harvest or midstory removal to increase sunlight, plus mist-blown herbicides to reduce interfering plants and fencing to reduce deer browsing. The overstory shelterwood harvest and midstory removal treatments reduced basal area by 30 and 12%, respectively. The prescribed fire treatment reduced survival because of the small size of the seedlings at the time of the burn. Published dominance probabilities were applied to the density and size of seedlings present after 10 years to compare the predicted number of codominant oaks resulting from the various treatments. Predicted success was greatest in fenced plots that received herbicide reduction of interfering plants and either the overstory shelterwood harvest or midstory removal treatments.

Keywords: *Quercus*, shelterwood, prescribed fire, herbicide, deer fence, oak seedlings

Regenerating northern red oak (*Quercus rubra*) on high-quality growing sites is a continuing problem in the central Appalachian region. New stands that develop after overstory harvests often contain fewer oaks than the preceding stands. The basic problem is that overstory harvests are applied when an insufficient number of competitive advanced oak seedlings are present to compete with other hardwood species after the harvest (Brose et al. 2008, Dey 2014).

In undisturbed mature oak stands, advanced oak seedlings usually exhibit both poor survival and slow growth. In one study, the survival of a cohort of northern red oak seedlings that germinated after a good acorn crop steadily declined from 60% after 1 year to only 10% after 10 years (Beck 1970). Similarly, the average total height of survivors was less than 1 ft after 1 year and generally did not increase over the next 10 years. As mixed-oak stands in the central Appalachians approach maturity, adequate advanced oak reproduction usually does not develop due to several factors: acorns are consumed or damaged by deer, insects, rodents, and birds; advanced oak seedlings and sprouts are browsed by deer; and cohorts of new seedlings are suppressed and killed by excessive shade from dense interfering vegetation in the midstory and understory strata (Dillaway et al. 2007, Rebbeck et al. 2011). As a result, few oak seedlings are able to ascend into the canopy of the new stand after the parent oaks are removed. Instead, competing species occupy a greater proportion of the new stand, and the proportion of oaks in the overstory often falls short of manage-

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ment objectives (Fei and Steiner 2007). These conditions call for preparatory treatments that reduce acorn predation, reduce deer browsing of established seedlings, and reduce interfering plants so that more advanced oak seedlings survive and grow to sufficient sizes before the parent trees are removed (Marquis et al. 1976, Marquis 1981, Tilghman 1989, Lorimer 1992).

Numerous research studies have indicated that successful oak regeneration depends on the presence of competitive sources of oak reproduction when overstory harvests or other stand-replacing disturbances occur (Dey 2014). One reason why large, competitive advanced reproduction does not develop in mature mixed-oak forests is that a dense overstory and interfering plants in the understory limit the availability of sunlight (Brose et al. 2008, Rebbeck et al. 2011). Examples of interfering plants include ferns, grasses, suppressed shade-tolerant trees, and various evergreen or deciduous shrubs. Throughout the eastern oak region, repeated partial harvest practices, heavy deer browsing, fire suppression, and diseases have contributed to the development of interfering plants (Schuler 2004, Nowacki and Abrams 2008, Rooney 2009). Such interference often develops and persists over many decades. Without a natural or prescribed intervention to reduce the interference, successive acorn crops rarely become competitive advanced seedlings to sustain the oak component in the next stand (Loftis 1985).

Successful oak regeneration is related to the size and number of advanced seedlings present when harvests occur (Sander et al. 1984, Loftis 1990a, Johnson et al. 2009). For example, on northern red oak site index 80 (base age 50 years), the probability that an advanced oak seedling with a 0.1-in. basal diameter will become dominant or codominant 20 years after a harvest is essentially zero. Although numerous small seedlings may be present before a harvest, very few will compete successfully after the harvest due to their small initial size. This probability increases to 1% for a 0.2-in. basal diameter and 8% for a 0.7-in. basal diameter. Dominance probability is inversely related to site index; thus, oak regeneration is more difficult on better quality growing sites. As the seedling size and probability of success increase, fewer seedlings are needed to achieve sustained regeneration after a harvest. A preharvest inventory of advanced oak seedlings is recommended to determine whether the new stand will contain a sufficient oak component. Dominance probabilities applied to the size and number of seedlings present should indicate a minimum of two to three codominant oaks in the new stand at canopy closure for each percentage point of desired oak stocking at stand maturity. For example, at least 120 codominant oaks are needed at canopy closure to achieve 50% oak stocking at maturity (Ward and Stephens 1994, Brose et al. 2008). If the projected number of codominant oaks is insufficient, then silvicultural treatments may be needed to increase the growth and survival of advanced seedlings before the overstory is removed (Loftis 1990b).

Forest managers can increase the probability of successful oak regeneration by prescribing preparatory treatments that enhance the size and competitiveness of advanced oak seedlings several years before a planned overstory harvest (Carvell and Tryon 1961, Sander and Clark 1971, Gottschalk 1983, Hannah 1987, Beck 1988, Loftis 1990b, Marquis et al. 1992). Shelterwood treatments reduce stand density and increase the amount of sunlight and other site resources available to advanced oak seedlings. The added sunlight increases both survival and growth of advanced oak seedlings, thus increasing the abundance and competitiveness of advanced oaks in the next stand. In the southern Appalachians, overstory shelterwood harvests that removed more than 50% of the stand basal area stimulated the growth of advanced oak seedlings but also stimulated the development of competing species such as sweet birch (*Betula lenta*) and yellow-poplar (*Liriodendron tulipifera*), particularly where canopy gaps were created (Loftis 1983). A similar shelterwood harvest followed 4–7 years later by prescribed fire is an effective method for reducing competing species and promoting vigorous oak sprouting in preparation for the final overstory harvest (Brose et al. 2014). Applying prescribed fire in stands where advanced oak reproduction is sparse or too small to be fire resistant can severely reduce or eliminate any advanced oak reproduction that is present until the next acorn crop (Loftis 1990b, Brose et al. 2006, Alexander et al. 2008, Green et al. 2010, Brose 2014, Dey 2014).

An important factor to consider in prescribing a shelterwood treatment is the appropriate amount of sunlight needed to enhance the survival and growth of advanced oak seedlings without overstimulating their competitors. At very low levels of microsite light, advanced oak seedlings will not grow or survive once resources within the acorn are exhausted (Rebbeck et al. 2011). Northern red oak exhibits intermediate shade tolerance (Trimble 1975) and has the ability to sprout after a top disturbance if an adequate root system has had time to develop (Brose et al. 2014). At very high levels of microsite light, the response of competing species may surpass that of the oaks (Loftis 1983). If prescribed fire or other remedial treatments are not available to control competing vegetation several years after a heavy shelterwood harvest (Brose et al. 1999), a gentler approach to stimulating oak seedling growth and survival may be necessary. Alternative shelterwood treatments that removed only midstory trees from below the overstory canopy (with no canopy gaps) increased the de-

Management and Policy Implications

Research has shown that commercial harvests in oak-dominated forests can remove valuable forest products, stimulate the development of diverse wildlife habitat, protect water resources, and provide adequate sunlight and other favorable environmental conditions to restore and sustain oak-dominated forests in the future. The key to sustaining oak forests is to assess the competitive status of advanced oak reproduction present before a planned overstory harvest. In many cases, preparatory treatments are needed several years before an overstory harvest to promote a competitive cohort of advanced oak seedlings that can later replace parent trees after they are harvested. Preparatory treatments include various combinations of mechanical and/or chemical control of interfering plants, reduction of deer herbivory, timely application of prescribed fire, and manipulation of sunlight available to young oak seedlings. Forest managers and policymakers can use the information in this report for planning and prescribing preparatory treatments that enhance the survival and development of advanced oak seedlings in the decade before a planned overstory harvest. If properly applied, these preparatory treatments can increase the probability of successful regeneration and restoration of oak species in mixed-hardwood forests.

velopment of advanced oak seedlings without stimulating competing species (Loftis 1988). Recent studies of similar treatments described as "midstory removal" have shown that gently increasing microsite light under a closed canopy can have positive effects on oak seedling growth and survival (Miller et al. 2004, Lhotka and Loewenstein 2009, Motsinger et al. 2010, Parrott et al. 2011, Rathfon 2011). Although similar treatments have not been widely tested in the central Appalachians, advanced oak reproduction was found to be more abundant in mature stands where the overstory canopy was closed and the midstory density was relatively sparse (Schuler and Miller 1995, Miller 1997).

This study examined how manipulation of available sunlight by shelterwood treatments, reduction of interfering plants by broadcast herbicides and/or a single prescribed fire, and reduction of deer damage by fencing (alone and in various combinations) affected the development of 4,235 advanced northern red oak seedlings under a mature oak forest in north-central Pennsylvania from 2002 to 2012. The objective was to identify strategies that would prepare for sustained regeneration of oak species in the subsequent forest after an overstory removal harvest.

Methods

Study Site

The study site is located in the unglaciated Allegheny Plateau physiographic province in Clearfield County of northcentral Pennsylvania within the Moshannon State Forest, managed by the Pennsylvania Department of Conservation and Natural Resources (PA DCNR), Bureau of Forestry. Forests within the general vicinity are characterized by relatively flat topography, average elevation of 2,150 ft, average annual precipitation of 46 in., and average annual temperature of 44° F. In 2001, the second-growth forest on the study site was about 85 years of age, with initial basal area of 142–151 ft^2/ac, relative density of 99%, and site index 74 for northern red oak. The dominant overstory tree was northern red oak, with white oak (*Quercus alba*), chestnut oak (*Quercus montana*), red maple (*Acer rubrum*), black cherry (*Prunus serotina*), white ash (*Fraxinus americana*), white pine (*Pinus strobus*), and eastern hemlock (*Tsuga canadensis*) as common associates in the overstory. Few advanced oak seedlings were present in 2000 when installation of the permanent plots began. Initially, oak regeneration stocking was zero as defined by Brose et al. (2008). Stocking of tall woody interference and low woody interference was 65 and 60%, respectively, and stocking of rhizomatous fern interference was 62%. The woody interference was composed mainly of striped maple (*Acer pensylvanicum*), red maple, and American beech (*Fagus grandifolia*). The fern interference was mostly hay-scented fern (*Dennstaedtia punctilobula*). As defined by Brose et al. (2008), initial deer impact on the study site was level 4, characterized by the absence of preferred herbaceous and woody browse species, a lack of vertical structure in woody reproduction, and heavy infestation of interfering ferns and woody species typical of severe and sustained deer browsing. Soils on the study site are described as Cookport channery loam (Hallowich 1988). A relatively abundant acorn crop fell in the autumn of 2001, and by late spring of 2002 there was an abundant and ubiquitous cohort of new oak seedlings present on the study site.

Treatments

Three 50-acre rectangular research areas in relatively close proximity were installed on the study site with 24 rectangular 2.1-acre treatment plots in each area. The treatment plots were arranged in three rows, with eight plots in each row. The treatments included two levels of deer impact control via fencing, two levels of prescribed fire, two levels of interfering plant control using herbicides, and three levels of residual overstory density for a total of 24 treatment combinations. The 24 treatment combinations were assigned to the individual treatment plots by a restricted randomization whereby the 50-acre research areas were split for commercial installation of fences and then were split again for random assignment of the prescribed fire and herbicide treatments. For example, the fencing treatment was randomly assigned to half of each 50-acre area. In each research area, approximately 25 acres was surrounded by a single fence, thus minimizing installation and maintenance costs. Then the prescribed fire treatments were randomly assigned to each half of the 50-acre research area, such that half of the fenced section received the prescribed fire treatment and half of the unfenced section received the prescribed fire treatment. Similarly, the herbicide treatments were randomly assigned to half of the plots, thus producing a split-split-split plot assignment of fence-prescribed fire-herbicide treatments. Finally, the three levels of residual overstory density were randomly assigned to the three rows of eight plots in each 50-acre research area and resulted in a split-split-split-strip restricted randomization of treatments assigned to the 24 treatment plots in each area (Supplemental Figure S1).[S] Such arrangements also led to increased efficiency of operations for the commercial contractors. The logging operations, fence installation, prescribed fire, and herbicide applications were conducted by commercial operators under contract with the PA DCNR, Bureau of Forestry. Detailed descriptions of each treatment are provided below.

The three levels of residual overstory density included the following: a control overstory treatment where both the midstory and overstory were left intact; a midstory removal of trees in the suppressed and intermediate crown classes where the canopy was left intact and 12% of the initial basal area was removed; and an overstory shelterwood harvest treatment where canopy gaps were created and 30% of the initial basal area was removed. The overstory treatments were applied during the dormant season 2001–2002. Plots assigned to the control overstory treatment had no tree felling or logging activity in the midstory or overstory. The midstory removal treatment involved felling trees from 4 to 10 in. dbh by commercial logging contractors. The overstory shelterwood harvest treatment involved removing the same tree size classes as the midstory removal treatment plus a partial removal of codominant trees in the overstory canopy. During logging in the midstory removal and overstory shelterwood harvest plots, some felled trees in the 8- to 10-in. dbh range were removed from the plots at the discretion of the contractor, whereas smaller trees were left on the plots. Tree-length logs were skidded from plots in both the midstory removal and overstory shelterwood harvest treatments to log landings located outside the 50-acre research areas. Care

[S] Supplementary data are available with this article at http://dx.doi.org/10.5849/jof.16-002.

Table 1. Summary of initial inventory (2001) by assigned overstory treatment and residual inventory (2003) after all understory treatments were installed.

Inventory	No. of plots	Stems			Basal area (ft^2/ac)	Residual stand		Volume	
		Saplings	Poles	Sawtimber		Basal area	Relative density	ft^3/ac	bf/ac
		. . . . (no./ac)				. . . . (%)			
All plots combined									
Initial	72	105	50	69	148	100	99	3,074	12,896
Overstory shelterwood									
Initial	24	87	46	68	142		95	2,980	12,443
Residual	24	4	8	48	100	70	53	2,329	10,208
Midstory removal									
Initial	24	120	54	69	151		102	3,133	13,214
Residual	24	8	16	67	133	88	72	2,914	13,609
Control									
Initial	24	108	50	71	150		101	3,108	13,028
Residual	24	15	49	71	148	99	95	3,155	13,366

* International 1/4-in. rule.

was taken to avoid locating skid trails within the interior of the treatments plots where detailed measurements were taken during the 10-year study.

Although the control overstory treatment was intended to exhibit ambient sunlight conditions, the midstory removal treatment was intended to gently increase sunlight on the forest floor without creating canopy gaps (Loftis 1990b). The overstory shelterwood harvest was similar to a traditional shelterwood harvest where canopy gaps are created to provide a relatively greater increase in sunlight on the forest floor (Brose et al. 2008). In summary, the control overstory, midstory removal, and the overstory shelterwood harvest treatments were applied to one-third of the treatment plots, respectively, and provided a continuum of sunlight conditions.

The deer impact control treatments included the following: exclusion by an 8-ft-tall woven wire fence and no fence. After logging activities were complete in the spring of 2002, an 8-ft-tall woven wire deer fence was installed by commercial contractors around 12 treatment plots in each 50-acre research area; thus, half of the plots had no deer impact and half of the plots had ambient deer impact. The integrity of the fence was maintained throughout the study by the PA DCNR, Bureau of Forestry.

The herbicide treatment involved broadcast mist blowing by machine in June and July of 2001 to control herbaceous competition (mostly ferns) and low woody competition (mostly striped maple, red maple, and American beech $<$2 in. dbh). The broadcast herbicide consisted of a tank mixture of 4 quarts per acre of Accord (glyphosate) and 2 ounces per acre of Oust (sulfometuron methyl) in water applied at the rate 25 gallons of mixture per acre. Soon after logging operations in both the midstory removal and overstory shelterwood harvest treatments, trees from 1 to 4 in. dbh were injected with herbicide in plots assigned to the herbicide treatment, whereas they were felled in plots assigned to the no-herbicide treatment. The stem injection herbicide consisted of 50% Garlon 3A (triclopyr amine) in water applied at the rate of 0.05 ounce (1.5 ml) per in. dbh on treated stems. Herbicide treatments were applied to 12 plots in each 50-acre research area; thus, half of the plots received herbicide treatments and half did not.

The prescribed fire treatment involved the following: strip head fires applied in the spring of 2004, two growing seasons after the overstory, herbicide, and fencing treatments were applied and no fire. The delay in applying prescribed fire was intended to allow advanced oak seedlings to develop a larger root mass and greater fire resistance and enhance their ability to produce vigorous sprouts after the fire (Brose et al. 1999). Similar in design to the fencing and herbicide treatments, the prescribed fire treatment was applied to 12 plots in each 50-acre research area; thus, half of the plots were burned and half were not.

The 24 treatment combinations could be viewed as a continuum of increasing disturbance or intervention in ambient conditions on the study site. Some plots received no manipulation of overstory density, no fire or herbicide control of interfering understory vegetation, and no protection from deer. At the other extreme, some plots received a dramatic increase in sunlight through canopy gaps, control of interfering vegetation by herbicide and fire, and protection from deer by fencing. Once the study was fully installed, all 24 combinations of treatments and their associated degrees of intervention were represented.

Measurements

Within each treatment plot, a rectangular 0.75-acre measurement plot was installed such that it was surrounded by a similarly treated buffer zone (Supplemental Figure S1). An average of 64 advanced northern red oak seedlings were tagged for long-term monitoring in spring 2002 and their locations were fixed by azimuth and distance from 10 permanent reference points within each measurement plot. Basal diameter and height of tagged seedlings were recorded at various intervals from 2002 to 2012. Mean percent fern cover on each treatment plot was determined from 2000 to 2008 using the same 10 reference points based on an ocular estimate of fern foliage occupying the surrounding 26-ft radius circular area around each reference point.

Percent photosynthetically active radiation (PAR) in each plot was measured with Accupar linear ceptometers at 10 reference points within each 0.75-acre plot on overcast days in late July or early August from 2001 to 2008. This method uses one ceptometer placed in a nearby open site to measure above canopy sunlight and a second time-synchronized ceptometer in each treatment plot to measure the percentage of ambient sunlight reaching the subject seedlings. In two previous studies, measurements of PAR taken on overcast days were found to be superior estimates of season-long avail-

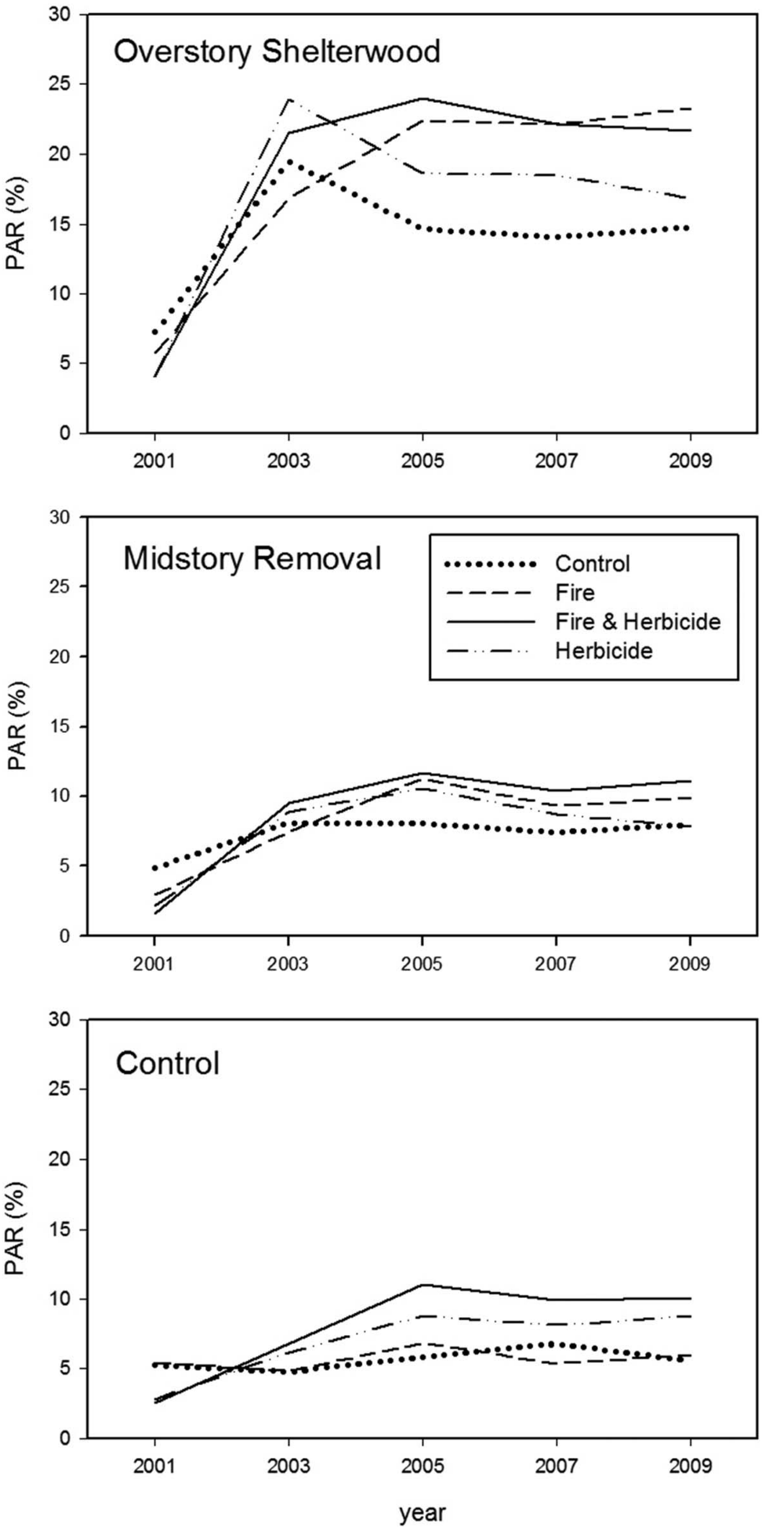

Figure 1. Mean microsite light levels as measured by percent PAR by overstory and understory treatment combinations from 2001 to 2009.

able sunlight (Parent and Messier 1996, Gendron et al. 1998). Similar measurements on sunny days were less accurate because sun flecks inadvertently intercepted in below-canopy readings yielded overestimates of PAR.

Statistical Analyses

Four analyses were conducted in which the response variables were PAR, fern cover, seedling basal diameter, and seedling height, all using similar statistical procedures. For PAR and fern cover, repeated measures were collected at fixed points within the 0.75-acre treatment plots and included years 2001, 2002, 2004, 2006, and 2008 for PAR and years 2000, 2002, 2004, and 2008 for fern cover. For seedling basal diameter and height, repeated measures were collected on tagged seedlings within the 0.75-acre treatment plots and included years 2003, 2007, and 2012. The treatment plots were surrounded by similarly treated buffer zones, thus assuring that treatments did not affect response variables in adjacent plots and precluding autocorrelation. For each of the response variables, the initial measurements were evaluated as possible covariates in their respective analyses but were not statistically significant.

In each analysis, the dependent variables were compared within a repeated-measures split-split-split-strip plot design to examine the effect of the fence (factor 1), the prescribed fire (factor 2), the herbicide treatment (factor 3), the overstory treatment (factor 4), and the measurement years (factor 5). The three 50-acre research areas comprising the 24 treatment plots served as blocks. Because of the unequal spacing between repeated-measures years, the spatial power covariance structure was used to model the correlation between years. This design generated five error terms in the model. Each of the split plots and the strip plot and their associated interactions were analyzed by their associated block × factor effect. The repeated measures was the last error term and was associated with the residual error. Each response variable was analyzed using a lognormal distribution and the identity link function that generated the best residual plots using the generalized linear mixed-model routine via PROC GLIMMIX in SAS (SAS Institute, Inc. 2008). To keep pseudoreplication out of the study, an average of the response variable was taken for the five effects so only one observation was used in the analyses instead of individual measurements. The Kenward-Rogers denominator degrees of freedom method was used in each analysis and the Tukey-Kramer least-squares mean separation test was used for all multiple comparisons (see Supplemental Code S2). Treatment effects were considered to be statistically significant when $P < 0.05$. For each analysis, the residuals were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using the Levene test.

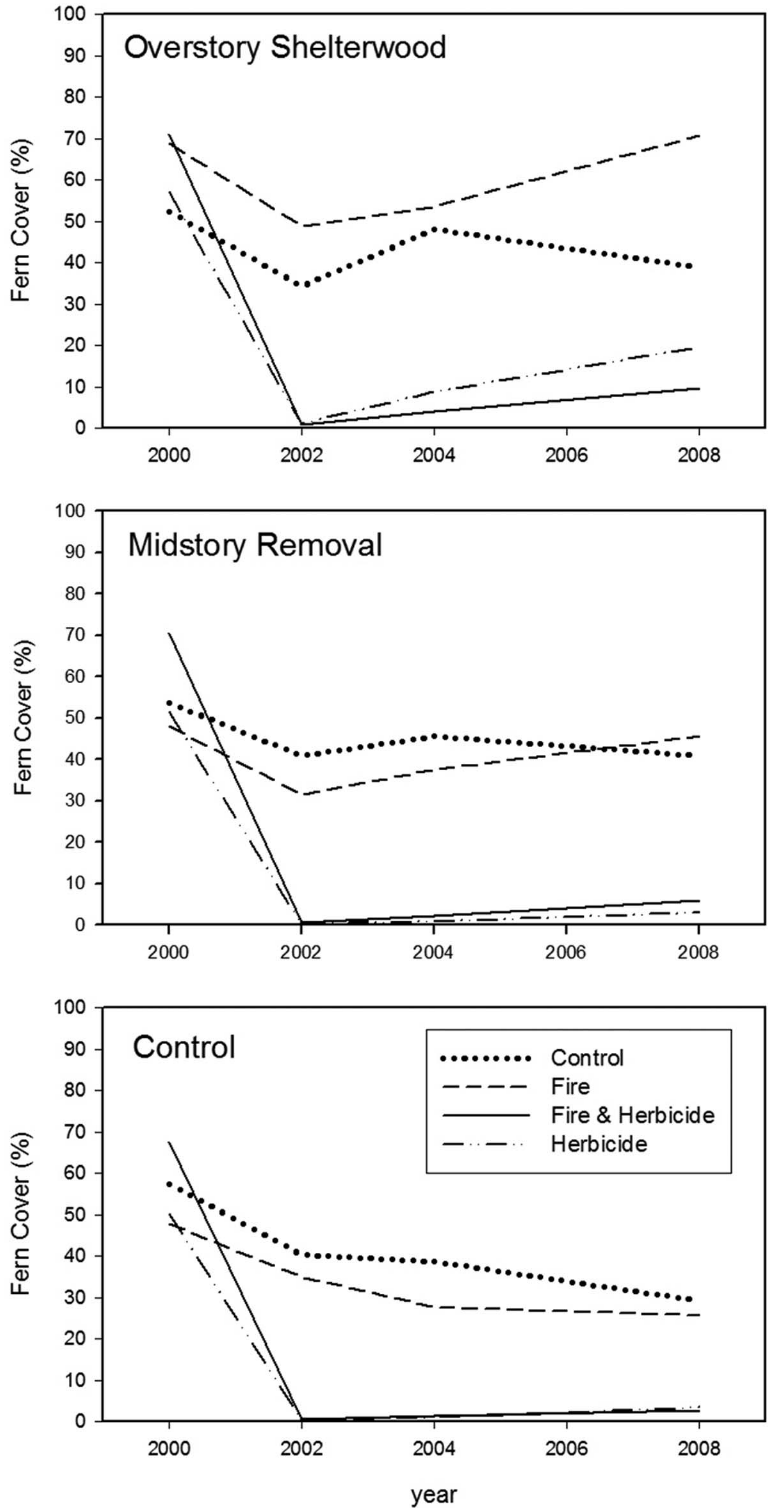

Figure 2. Mean percent fern cover by overstory and understory treatment combinations from 2000 to 2008.

Results

The three overstory treatments resulted in three distinct levels of residual basal area and residual relative density (Table 1). The control overstory treatment had no impact on the midstory or overstory, leaving the number of poletimber and sawtimber trees per acre essentially intact. In plots that received the control overstory treatment plus the herbicide and prescribed fire treatments, the number of saplings per acre was greatly reduced. The midstory removal treatment reduced the number of poletimber trees per acre by 70%, thus reducing basal area by 12%. The overstory shelterwood harvest treatment reduced the number of poletimber and sawtimber trees per acre by 83 and 29%, respectively, thus reducing basal area by 30%. The residual stand relative density, as measured by Marquis et al. (1992), was reduced to 72 and 53% for the midstory removal and overstory shelterwood treatments, respectively.

Microsite Light

Percent PAR was not significantly affected by the fencing treatment ($P = 0.72$), so the mean results were combined for fenced and unfenced plots (Figure 1). The blocking factor of the three 50-acre research areas was not significant ($P = 0.54$) in the analysis of percent PAR. The midstory removal and overstory shelterwood harvest significantly increased percent PAR compared to pretreatment conditions ($P = 0.02$). The overstory shelterwood harvest alone, without the additional impact of the herbicide and prescribed fire treatments, increased PAR from 7 to 19%. The overstory shelterwood harvest treatment plus the herbicide treatment further increased PAR to about 23%. Once all treatments were applied and mortality of low woody vegetation was manifest, percent PAR remained elevated in the overstory shelterwood harvest treatment through 2009 when the last light readings were recorded. Similarly, the midstory removal treatment significantly increased percent PAR compared with pretreatment conditions ($P < 0.01$), and the increase was sustained through 2009. The combined herbicide and prescribed fire treatments increased percent PAR in the midstory removal and control overstory treatments by small amounts, usually less than 5% ($P < 0.01$). In all three overstory treatments, the prescribed burn treatment was applied in the spring of 2004, so the effect of that treatment on percent PAR was not fully evident until the 2006 growing season.

Fern Cover

Fern cover was not significantly affected by the fencing treatment ($P = 0.52$), so the mean results were combined for fenced and unfenced plots. The blocking factor of the three 50-acre research areas was significant ($P < 0.01$) in the analysis of percent PAR, but significant interactions with the other treatments was not evident. The herbicide treatment significantly reduced fern cover ($P < 0.01$) under all three over-

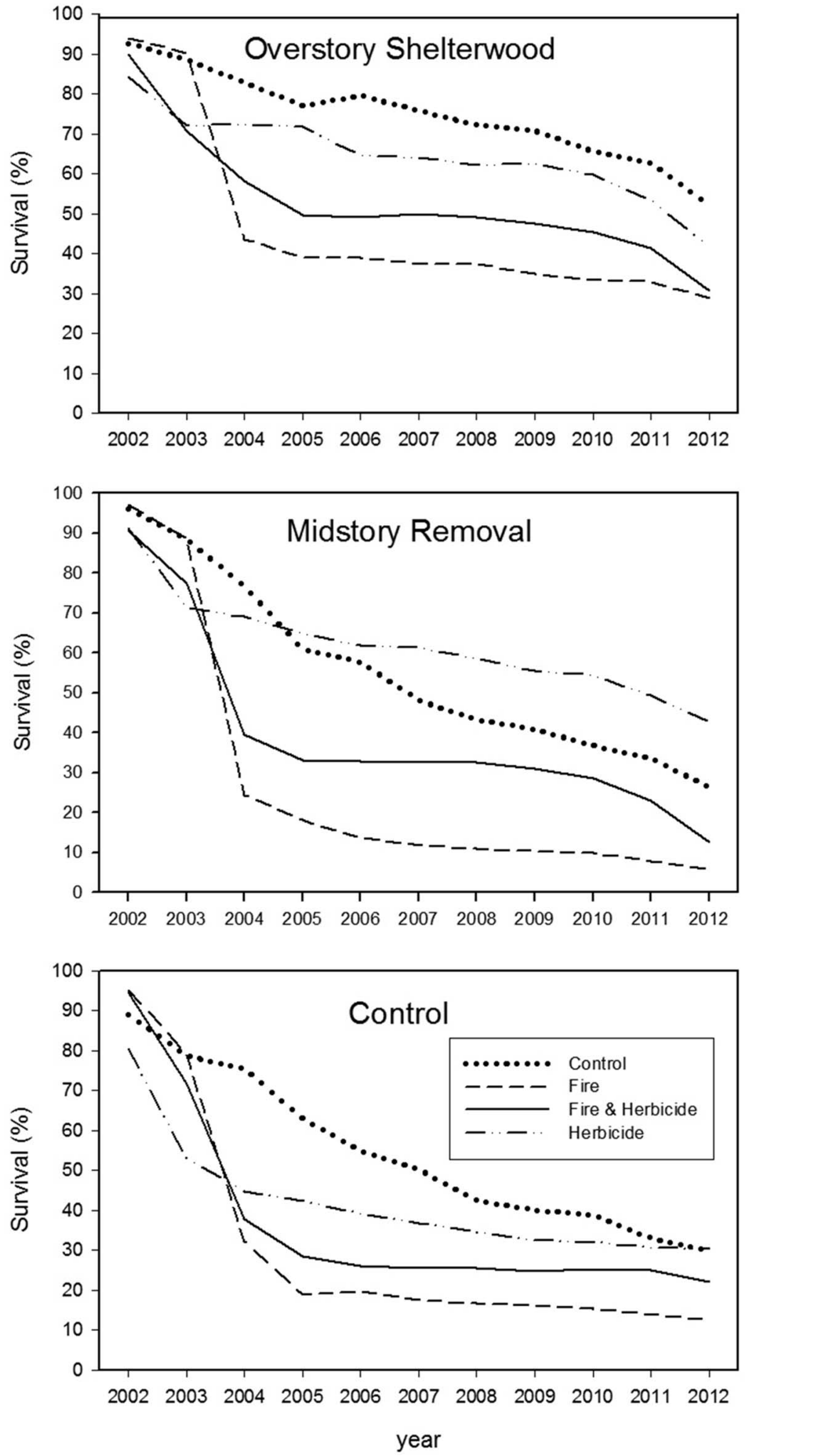

Figure 3. Mean survival of tagged northern red oak seedlings by overstory and understory treatment combinations in plots protected by deer exclusion fences from 2002 to 2012.

story treatments from the 2002 growing season measurements for the duration of the study (Figure 2). In the midstory removal and overstory shelterwood harvest treatments, where percent PAR was significantly elevated compared with the control overstory treatment, the prescribed fire treatment coupled with no herbicide treatment led to a significant increase in fern cover ($P < 0.01$). The increase in fern cover was greatest in the overstory shelterwood harvest plots that received the prescribed burn treatment and no herbicide treatment, where fern cover had returned to pretreatment levels by 2008.

Seedling Survival

The herbicide treatment was applied in the summer of 2001, and the vast majority of tagged seedlings monitored in this study originated from the acorn crop in the autumn of 2001. As a result, the herbicide treatment had a negligible effect on seedling survival in the early years. Seedling survival exceeded 45% in the overstory shelterwood harvest and midstory removal treatments where the herbicide and fencing treatments were applied (Figure 3). In contrast, the prescribed burn treatment was applied in the spring of 2004, just two growing seasons after most of the tagged seedlings germinated from the autumn 2001 acorn crop. The prescribed fire treatment had an immediate and lasting negative effect on seedling survival from 2004 to 2012 (Figures 3 and 4). Similar results were observed when a prescribed fire was applied to relatively small oak seedlings (Loftis 1990b, Green et al. 2010). In the control overstory treatment, fencing alone slightly improved survival compared with that for unfenced plots. In the midstory removal treatment, fencing alone had a negligible effect on survival. In the overstory shelterwood harvest treatment, fencing alone nearly doubled the 10-year seedling survival from 30% in unfenced plots to 59% in fenced plots (Figures 3 and 4).

Seedling Basal Diameter and Total Height Growth

The blocking factor of the three 50-acre research areas was significant ($P < 0.01$) in both analyses of seedling basal diameter and total height growth, but significant interactions with the other treatments was not evident. The overstory treatment ($P < 0.01$), herbicide treatment ($P < 0.01$), and fencing treatment ($P < 0.01$) had a significant effect on both measures of seedling growth. The prescribed fire treatment did not affect basal diameter growth ($P = 0.30$) or total height growth ($P = 0.28$). In general, maximum basal diameter growth was observed in plots that received the overstory shelterwood harvest and fencing treatments (Table 2). Seedlings on plots that received the midstory removal treatment plus fencing and the herbicide treatment had similar basal diameter growth ($P < 0.05$). In the unfenced plots, only the overstory shelterwood harvest alone or with the herbicide treatment added had comparable basal diameter growth. Similar results were observed for seedling height growth, where plots that received the overstory shelterwood harvest, fencing, and

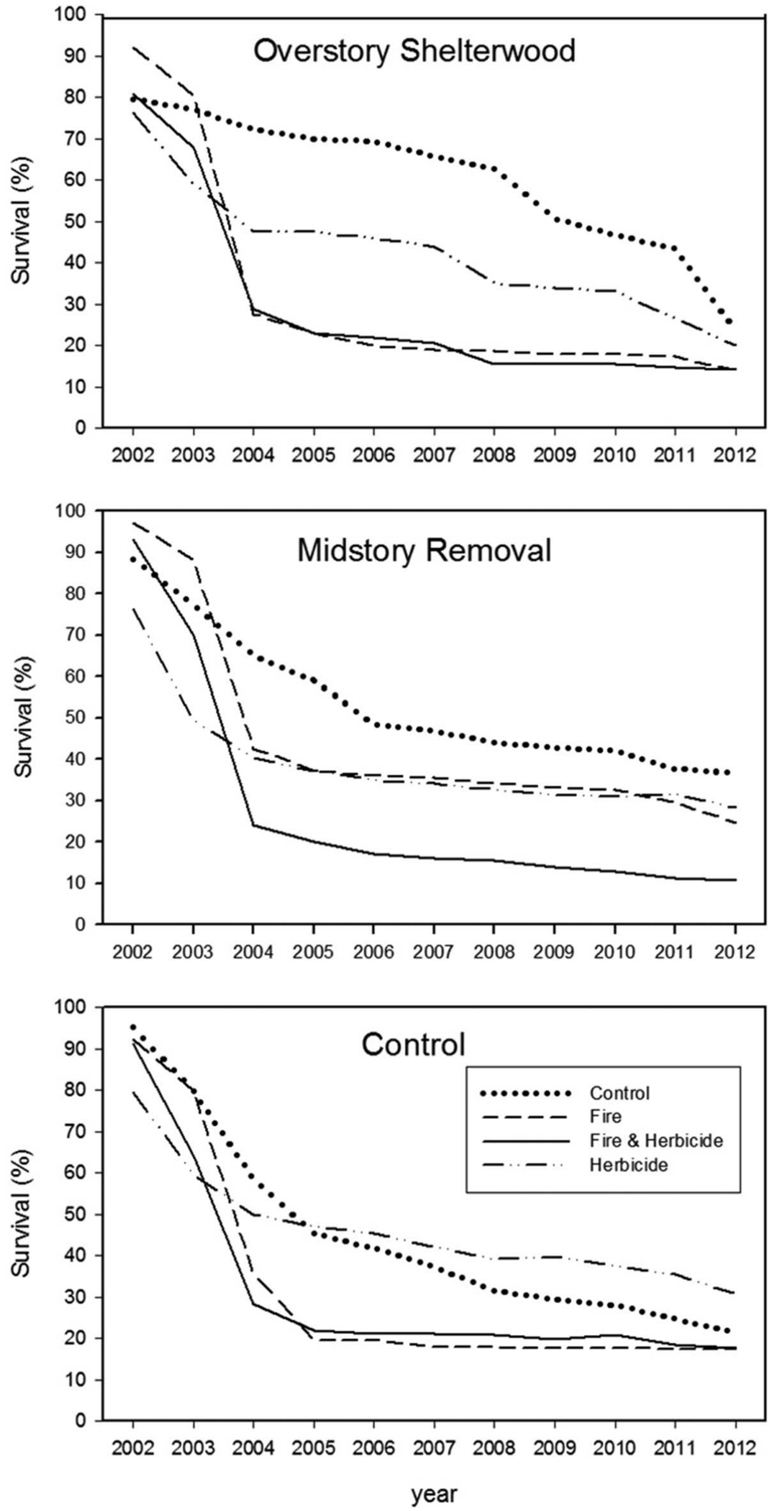

Figure 4. Mean survival of tagged northern red oak seedlings by overstory and understory treatment combinations in plots not protected by fences from 2002 to 2012.

the herbicide treatments had mean seedling heights >2.7 ft by 2012 (Table 3).

Discussion

The purpose of preparatory treatments in the oak regeneration process is to increase survival and growth of advanced oak seedlings before a planned overstory removal harvest. It is the interaction of the number of advanced seedlings available and their relative size at the time of a final overstory harvest that determines how they will contribute to overstory species composition in the next stand. To compare and contrast the treatment combinations applied in this study, dominance probabilities for northern red oak seedlings on site index 70 (Loftis 1990a) were applied to the mean densities of oak seedlings present and their associated basal diameters observed in the various treatment plots in the final year of the study (Table 4). The mean seedling densities per acre in Table 4 were determined from six 6-ft-radius plots in each measurement plot in 2012 using inventory methods described by Brose et al. (2008). Seedlings were counted in three height classes and assigned a basal diameter based on data taken on tagged seedlings in the same height classes (Tables 2 and 3). Dominance probability is a nonlinear relationship between seedling size (basal diameter) and its predicted ability to reach a codominant canopy position 20 years after an overstory removal harvest. The larger the seedling, the more likely it is to successfully compete with surrounding vegetation and reach an upper canopy position after the parent trees are removed. The number of oak seedlings available and their relative sizes are equally important in predicting how many will reach codominant status in the next stand.

Based on earlier research on the development of oak-dominated forests, about 120 codominant oaks are needed in a 20-year-old stand to achieve 50% oak stocking at stand maturity (Schnur 1937, Ward and Stephens 1994, Brose et al. 2008). In this study, several treatment combinations achieved the predicted number of codominant oaks in the next stand to meet this threshold (Table 4). Most of the plots in the overstory shelterwood harvest and midstory removal treatments protected by deer fencing were adequately prepared for a final overstory removal harvest. Without fencing, only the overstory shelterwood harvest treatments that did not include the prescribed burn treatment met this threshold. If less oak stocking is acceptable in the next stand, only 72 predicted codominant oaks per acre are needed to achieve 30% oak stocking at stand maturity.

Earlier assessments of the treatments based on dominance probability predictions in 2003 and 2007 did not yet indicate adequate advanced reproduction to proceed with an overstory harvest. The tagged seedlings were more numerous than in 2012, but they had not developed an adequate size (basal diameter) to yield codominant trees in the next stand. In most cases, an adequate period of preparatory treatments for success-

Table 2. Mean basal diameter of tagged northern red oak seedlings 1, 5, and 10 years after overstory and understory treatments were applied in fenced and unfenced plots.

	Overstory treatment and year								
	Overstory shelterwood			Midstory removal			Control		
Understory treatment	2003	2007	2012	2003	2007	2012	2003	2007	2012
	(in.)								
Deer fence									
Control	0.084	0.175	0.244 cd	0.082	0.159	0.178 bc	0.083	0.123	0.125 ab
Fire	0.093	0.160	0.205 cd	0.075	0.092	0.157 ab	0.086	0.110	0.182 bc
Fire and herbicide	0.089	0.225	0.324 d	0.083	0.099	0.144 ab	0.089	0.151	0.180 bc
Herbicide	0.100	0.233	0.341 d	0.092	0.206	0.255 cd	0.080	0.135	0.168 b
No deer fence									
Control	0.087	0.162	0.198 cd	0.085	0.120	0.122 ab	0.076	0.136	0.113 a
Fire	0.082	0.146	0.165 b	0.089	0.126	0.143 ab	0.102	0.118	0.155 ab
Fire and herbicide	0.090	0.126	0.163 b	0.077	0.094	0.106 a	0.096	0.130	0.159 ab
Herbicide	0.090	0.183	0.216 cd	0.084	0.135	0.177 bc	0.078	0.167	0.145 ab

Mean basal diameters in 2012 followed by the same letter are not significantly different ($\alpha = 0.05$).

Table 3. Mean total height of tagged northern red oak seedlings 1, 5, and 10 years after overstory and understory treatments were applied in fenced and unfenced plots.

	Overstory treatment density and year								
	Overstory shelterwood			Midstory removal			Control		
Understory treatment	2003	2007	2012	2003	2007	2012	2003	2007	2012
	(ft)								
Deer fence									
Control	0.352	0.791	1.737 d	0.332	0.584	1.187 c	0.380	0.534	0.777 ab
Fire	0.356	0.624	1.358 c	0.360	0.443	0.717 ab	0.391	0.454	0.967 bc
Fire and herbicide	0.424	1.259	2.715 d	0.326	0.441	0.832 b	0.360	0.525	0.859 b
Herbicide	0.368	1.403	2.797 d	0.354	0.859	2.067 d	0.339	0.537	0.926 b
No deer fence									
Control	0.308	0.782	0.784 ab	0.320	0.472	0.612 a	0.336	0.440	0.654 a
Fire	0.331	0.547	0.889 b	0.354	0.474	0.818 ab	0.360	0.484	0.685 ab
Fire and herbicide	0.339	0.482	0.921 b	0.250	0.380	0.517 a	0.375	0.410	0.686 ab
Herbicide	0.302	0.661	1.170 bc	0.248	0.474	0.722 ab	0.293	0.471	0.672 ab

Mean heights in 2012 followed by the same letter are not significantly different ($\alpha = 0.05$).

ful oak regeneration in the next stand will involve at least 10 years (Sander and Clark 1971, Loftis 1990b, Brose et al. 2008, Johnson et al. 2009, Dey 2014).

Although infrequent and irregular acorn crops can result in numerous small seedlings for a few years, the new cohort usually exhibits small basal diameters and relatively low dominance probabilities until they have time to grow. For new seedlings, the dominance probability is often near zero. In Table 4, most of the seedlings present in 2012 were small and had very low dominance probabilities, having germinated from sparse acorn crops in the latter years of the study. However, most of the predicted codominant trees in Table 4 were from seedlings in the 2002 cohort that had grown to larger, more competitive size classes as a result of the treatments applied (Figure 5). The treatments sustained and enhanced the development of many of the original tagged seedlings, thus raising the probability of successful regeneration after a planned overstory harvest.

The prescribed fire in this study was applied too early in the sequence of treatments. In the spring of 2004 when the strip head fire was applied, mean basal diameter of tagged seedlings was <0.1 in. (Table 2), thus leading to much lower survival of advanced seedlings for the remainder of the study (Figures 3 and 4). A more effective shelterwood-prescribed fire sequence would have involved waiting 5–7 years after the overstory shelterwood harvest (Brose et al. 2008). By 2007 and beyond, the basal diameters of many tagged seedlings were >0.25 in.; thus, survival and sprouting of top-killed oak seedlings after the prescribed fire treatments would have been increased (Brose et al. 2014).

There were other treatment sequences to consider in preparing the advanced oak reproduction for an eventual overstory removal harvest. For example, simply applying the midstory removal treatment and controlling low competitors with the herbicide treatment led to 87 predicted codominant oaks in the next stand (Table 4). An alternative approach is to apply the midstory removal and herbicide treatments and then wait several years to apply the overstory shelterwood harvest, thus adding microsite light and competition control in stages. This approach would be akin to a traditional three-step shelterwood approach (Johnson et al. 2009). The decision to apply a prescribed fire in this sequence would be contingent on the development of the advanced oak seedlings and the aggressiveness of competing vegetation along the way. Periodic assessments of the advanced oak reproduction and associated competition would be useful in timing the application of additional treatments (Brose et al. 2008).

Finally, the dominance probability pre-

Table 4. Predicted number of codominant oaks 20 years after overstory removal based on numbers and basal diameters of advanced oak seedlings present in each treatment combination.

	Overstory residual density					
	Advanced oak seedlings in 2012			Predicted codominant trees in 2032		
Understory treatment	Overstory shelterwood	Midstory removal	Control	Overstory shelterwood	Midstory removal	Control
	. . . .(no. seedlings/ac)			. . . .(no. trees/ac).		
Deer fence						
Control	19,882	21,829	23,776	253	223	138
Fire	15,016	32,686	9,036	134	279	57
Fire and herbicide	14,737	34,242	9,454	223	252	60
Herbicide	20,578	21,143	26,835	374	298	206
No deer fence						
Control	31,424	11,122	6,951	223	64	32
Fire	9,872	11,041	3,059	52	73	26
Fire and herbicide	24,888	19,882	6,536	137	108	40
Herbicide	30,032	25,723	7,092	253	148	40

Predictions based on dominance probabilities for northern red oak seedlings on site index 70 (Loftis 1990a).

Figure 5. From 2002 to 2012, mean height of advanced northern red oak seedlings was 2.7 ft, although the height of some seedlings was >7 ft in plots that were protected by a deer fence, had reduced interference by herbicide mist blowing, and then received an overstory shelterwood harvest treatment. (Photo courtesy of Kurt W. Gottschalk.)

dictions in Table 4 merely provided a derived comparison among the treatments. The actual effectiveness of the treatments observed in this study in promoting successful oak regeneration in the next stand will be monitored over the next 10–20 years. In the dormant season of 2012–2013, a near complete overstory removal harvest was applied to all 72 treatment plots. There were variations in the 2012 status of advanced oak reproduction resulting from the treatments applied in this study. Future results will indicate the relationship between preharvest conditions resulting from the various preparatory treatments and the eventual species composition in the next stand.

Pesticide Use Disclaimer

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers. This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate state and/or federal agencies before they can be recommended.

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