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The devil is in the small dense saplings: A midstory herbicide treatment has limited effects on short-term regeneration outcomes in oak shelterwood stands

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ABSTRACT

On intermediate quality sites, where oak advance regeneration often accumulates, we tested whether a low-intensity herbicide treatment of shade-tolerant saplings and poles (injection of stems >5 cm DBH with glyphosate), conducted just prior to a shelterwood harvest, could increase the proportion of oak (and hickory) in the regeneration layer after the harvest. Control and herbicide units were established at four study sites in southern Ohio. Advance reproduction was measured before and 4–6 years after a shelterwood harvest that reduced basal area by 50%. Before the harvest, shade-tolerant species, mainly red maple, blackgum, and sourwood, dominated the sapling layer but established oak-hickory seedlings were present at moderate densities. After the harvest, the proportion of oak-hickory did not change significantly on either control or herbicide units and non-oaks were dominant in the majority of plots. However, larger oak-hickory regeneration (>70 cm height) developed on nearly 50% of the sampling units (2-m radius subplots) and oak-hickory regeneration was dominant on a greater proportion of subplots in the herbicide units (26%) than in the control units (13%). Herbicide effects were limited due to the large number of smaller non-oak stems (<5 cm DBH) that were not treated and also the ineffectiveness of glyphosate to prevent red maple stump sprouting. The heavy shelterwood first removal cut stimulated the growth of both oak seedlings and competing stems, and the herbicide treatment resulted in very limited improvements in the competitive position of the oaks. However, because the oaks did survive and grow, additional treatments may still change the outcome on these sites.

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1. Introduction

Poor oak regeneration is a widespread problem in the central hardwoods region, with important ecological and economic implications (McShea and Healy, 2002). In mature, unmanaged oak (*Quercus* L.) dominated stands on intermediate and mesic sites, shade-tolerant trees typically occupy the midstory and understory strata, creating low light levels on the forest floor. These conditions reduce survival of oak seedlings and prevent the accumulation of larger oak advance reproduction (seedlings, seedling sprouts, saplings), which is necessary for successful oak regeneration after a timber harvest or natural disturbance (Johnson et al., 2009). As sites become more mesic, oak seedlings increasingly fail to persist and accumulate due to high mortality caused by competition for growing space by non-oaks (Johnson et al., 2009; Kabrick et al., 2014).

Scientists have proposed and tested variants of the shelterwood regeneration system to address oak regeneration challenges. The most successful outcomes (e.g., Loftis, 1990; Brose and Van Lear, 1998) have occurred when small oak seedlings are abundant before treatments are applied. A preliminary treatment, which we will call a shelterwood first removal cut, removes the midstory and a portion of the overstory to increase oak seedling survival and growth, and the final shelterwood removal cut takes place when there are abundant large oak seedlings. This system has also been shown to have wildlife habitat advantages by creating early successional habitat and maintaining overstory structure for a period of time (Perry et al., 1999; Bellocq et al., 2005). Thus, early- and late-successional wildlife species both occupy shelterwood stands (Newell and Rodewald, 2012).

However, without additional understory treatments (e.g., herbicide, fire), oak seedlings are often outcompeted after a

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shelterwood first removal cut by sprouts from shade-tolerant stems (Hill and Dickman, 1988; Martin and Hix, 1988), newly established but fast-growing shade-intolerant species (Loftis, 1983), or a mixture of both (Brose and Van Lear, 1998). Because oak seedlings invest more growth to roots than shoots, they become overtopped and shaded by competitors that concentrate growth aboveground. The success of the shelterwood system for sustaining oaks is dependent on several factors: (1) the initial density and size of oak advance reproduction, (2) the composition, abundance, and size of competing species in the understory, and (3) the effectiveness of additional treatments (e.g., herbicide, fire, fencing) to reduce the dominance of competing non-oak species and/or favor the survival and growth of oak (Brose et al., 2008).

On mesic northern red oak sites in southern Appalachia, intensive single-stem pre-harvest herbicide applications that treat midstory trees and also small stems of yellow-poplar (*Liriodendron tulipifera* L.) (<5 cm DBH down to 60 cm height), have been shown to effectively reduce competition and increase the survival and growth of oak advance reproduction that was abundant before the treatment (Loftis, 1990; Kass and Boyette, 1998). However, studies in West Virginia (Schuler and Miller, 1995) and Wisconsin (Povak et al., 2008) have reported poor to moderate oak regeneration even after intensive pre-harvest herbicide treatments of shade-tolerant species such as sugar maple (*Acer saccharum* Marsh); both of these studies began with low densities of oak advance reproduction. Other factors such as the effectiveness of the herbicide and the intensity of deer browsing may also affect regeneration outcomes. When small shade-tolerant stems occur at high densities, individual stem herbicide treatment may be very costly (Kochenderfer et al., 2004).

The shelterwood burn method has been tested as a cost-efficient and effective method to promote oak regeneration. Brose and Van Lear (1998) studied mixed oak stands in Virginia with abundant regeneration of small oak seedlings and other species. They found that a first removal shelterwood cut followed several years later with a single prescribed fire favored oaks as the fire caused higher mortality rates in competing understory species such as yellow-poplar and red maple (*Acer rubrum* L.) than among the oaks. The oaks gained the greatest advantage from moderate- to high-intensity fires conducted during the growing season.

In many stands, however, prescribed fire is not a management option. Even where prescribed fire can be used, growing-season burns may not be feasible due to fuel and weather conditions or may not be allowed due to concerns about the impacts of fire on wildlife. For example, on lands owned by the Ohio Division of Natural Resources, any prescribed fire conducted after 15 April requires a survey the previous year to determine whether the federally endangered Indiana bat (*Myotis sodalis*) may be present in the burn unit (ODNR, 2013).

In mature oak stands on intermediate quality sites (Oak SI ~ 18–21 m), oak advance reproduction often accumulates in the understory but remains relatively small and is typically overtopped by shade-tolerant saplings and poles. Under these conditions, we tested whether a moderate-intensity herbicide treatment of shade-tolerant saplings and poles (injection of stems >5 cm DBH), conducted just prior to a shelterwood harvest, could increase the proportion of oak (and hickory, *Carya* L.) in the regeneration layer after the shelterwood harvest. We hypothesized that the late-growing season herbicide treatment would increase the proportion of oak-hickory through reduced sprouting of competitors. We also hypothesized that greater densities of large oak-hickory reproduction would develop after the shelterwood harvest in herbicide-treated units, due to less competition from stump sprouts of competitors.

2. Methods

2.1. Study area

Four study sites of 26–43 ha are located in southeastern Ohio, in the Unglaciated Allegheny Plateau. All sites are on State Forests owned and managed by the Ohio Department of Natural Resources, Division of Forestry. The Ball Diamond (39°11′16″N, 82°24′27″W) and Wolf Oak (49°10′42″N, 82°23′27″W) sites are on the Vinton Furnace State Forest (VFSF), in Vinton County. The Zaleski (39°20′2″N, 82°18′33″W) and Richland Furnace (39°10′20″N, 82°36′24″W) sites are located on nearby Zaleski and Richland Furnace State Forests, in Vinton and Jackson Counties, respectively.

The physical setting and land use history are generally similar for all sites. Topography is dissected with steep slopes and narrow valleys. Elevations range from 200 to 300 m. Bedrocks are predominantly sandstones of Pennsylvanian age, with some siltstones and shales. The highly weathered soils are fairly similar among sites and are characterized as moderately deep (50–100 cm to bedrock) sandy loams and silt loams that are acidic and have low available water capacity; the primary soils are the Steinsburg–Gilpin Association (Wolf Oak and Zaleski), the Germano–Gilpin Complex (Ball Diamond), and the Rarden–Wharton Complex (Richland Furnace) (Kerr, 1985; Lemaster and Gilmore, 2004). Steinsburg soils are coarse-loamy, mixed, active, mesic Typic Dystrudepts. Gilpin soils are fine-loamy, mixed, active, mesic Typic Hapludults. Germano soils are coarse-loamy, mixed, active, mesic Aquultic Hapludalfs. Wharton soils are fine-loamy, mixed, active mesic Aquic Hapludults. The average temperature, precipitation and growing season length at VFSF are 11.3 C, 1024 mm, and 158 days, respectively (Sutherland et al., 2003). Each site is located on former "furnace lands" which were clearcut in the mid- to late-1800s to provide charcoal to fuel nearby iron furnaces.

Stands were even-aged: dominant trees were 80 years old at Richland Furnace, 100 years at Zaleski, and 130 years at Ball Diamond and Wolf Oak. Among the four sites, tree basal area averaged 22–29 m^2/ha, of which 74–85% was oak-hickory. White oak (*Quercus alba* L.), chestnut oak (*Q. montana* Willd.), and black oak (*Q. velutina* Lam.) were dominant species in the overstory. Site index (black oak) of mid- to upper-slopes, where plots were located, ranged from 18 to 21 m (Carmean, 1965). White-tailed deer (*Odocoileus virginianus* Zimm.) populations are estimated at 5–7 deer/km^2 after hunting season; at these densities, browsing does not have a large impact on the density or composition of advance reproduction (Apsley and McCarthy, 2004).

2.2. Experimental design and treatments

The experimental design is a randomized complete block. At each of the four study sites (blocks), the entire 26–43 ha area would receive a shelterwood harvest. Four 5–12 ha treatment units were established at each site, two control (shelterwood harvest only) and two herbicide (herbicide + shelterwood harvest) units. There were four units at each site in order to incorporate a future (post-shelterwood) prescribed fire treatment on two of the units: one shelterwood + prescribed fire treatment and one herbicide + shelterwood + prescribed fire unit per site.

In 2005, prior to the shelterwood harvest, stem-injection herbicide treatments were applied in late summer and fall. Herbicide treatment dates were August 11–29 at the Ball Diamond, Richland Furnace, and Zaleski sites, and October 3 and 4 at the Wolf Oak site. For all tree species other than oaks and hickories, all stems >5.0 cm DBH were injected with glyphosate (54% active ingredient) (Kochenderfer et al., 2012), within each sample plot (see below) and also within a 10 m buffer surrounding each plot. From our pretreatment data, we estimate that 350 stems ha^{-1} were treated, 60% of which were saplings 5–9.9 cm DBH and 40% trees ⩾10 cm DBH.

The shelterwood harvests were prescribed to reduce basal area by 50%, leaving primarily dominant and codominant oaks as residual trees, and cutting all other stems >5.0 cm DBH, including the stems that had been injected with herbicide. At the Ball Diamond and Richland Furnace sites, shelterwood harvests were conducted in the dormant-season after the 2005 growing season; at Wolf Oak and Zaleski, shelterwood harvests were in the dormant-season after the 2006 growing season.

Within each of the 16 treatment units, 10–12 circular 314 m^2 (10-m radius) plots were established in summer 2005, prior to any treatments ($N = 184$ plots). Plots were randomly located on mid- and upper-slope positions on a variety of aspects; though only 7% were on northeast-facing slopes (azimuth 0–90°). Plot centers were >40 m apart and recent canopy gaps were avoided.

2.3. Pretreatment data collection

Stems 3.0–9.9 cm DBH were recorded by species in the entire plot. Stems 30 cm tall to 2.9 cm DBH were sampled in three 4-m radius (50.3 m^2) subplots, each centered 6 m from the plot center. In each subplot we recorded the density of all tree species in three size classes: 30–69.9 cm height, 70–139.9 cm height, and 140 cm height to 2.9 cm DBH. For tree seedlings <30 cm height, we recorded densities by species in four 1-m radius (3.1 m^2) "microplots" in each subplot ($n = 12$ microplots per plot). The four microplots were centered 4 m from the subplot center in the cardinal directions.

2.4. Postharvest data collection

During the first growing season after the first removal shelterwood harvest, in 2006 at Ball Diamond and Richland Furnace and in 2007 at Wolf Oak and Zaleski, photosynthetically active radiation (PAR) was recorded within each subplot 1 m above the forest floor, with a Decagon ACCUPAR LP80 ceptometer (Decagon Devices, Pullman, Washington). PAR was recorded simultaneously in a nearby open field to obtain a percent of full sunlight in each subplot. Residual overstory trees were tallied on all plots in 2007, with a 10-factor (10-ft^2/ac) BA prism.

Two years after the shelterwood harvest, in 2007 (Ball Diamond and Richland Furnace) and 2008 (Wolf Oak and Zaleski), stump sprouts from cut stumps ⩾7.5 cm basal diameter were located and tagged in each plot. For each sprouting stump, we recorded the species, stump diameter, number of sprouts, and the height of the tallest sprout. These data were collected again on all sites in 2010.

Postharvest regeneration data were collected in 2010 at the Richland Furnace, Wolf Oak, and Zaleski sites and in 2011 at the Ball Diamond site. The staggered nature of the shelterwood harvests and the data collection schedule resulted in advance reproduction data that were collected 4 years postharvest at the Wolf Oak and Zaleski sites, and 5 and 6 years postharvest at the Richland Furnace and Ball Diamond sites, respectively. Due to the much greater densities of larger stems 4–6 years after the shelterwood harvest, the sampling area was reduced and minimum size classes were increased for postharvest sampling. In the central 12.6 m^2 (2 m radius) of each subplot, we recorded the density of stems >140 cm height, in three size classes: 140.0 cm height to 2.9 cm DBH, 3.0 to 5.9 cm DBH, and 6.0 to 9.9 cm DBH, for all tree and shrub species. For multi-stemmed "clumps", originating from stems <7.5 cm basal diameter (the stump sprout threshold), we recorded the number of stems >140 cm height per clump. In addition, for oaks and hickories, which were the focus of this study, we also counted smaller stems in two size classes: 30.0–59.9 cm height and 60.0–139.9 cm height within the central 12.6 m^2 of each subplot; here, each rootstock was counted as one individual.

2.5. Data analyses

For statistical analyses, all stem density data collected on plots (the sampling unit) were converted to stems ha^{-1}, and then averaged to the unit level, resulting in 16 experimental units across the four study sites. Generalized linear mixed models ([GLMM] SAS 9.2, PROC GLIMMIX; SAS Institute Inc., Cary, North Carolina) were used to test for treatment effects on stump sprouts and advance reproduction. Study site was treated as a random effect and herbicide treatment was a fixed effect. To define a best fit distribution for the dependent variable in each model, we used goodness of fit tests (SAS 9.2, PROC UNIVARIATE) for the normal, gamma, lognormal, and exponential distributions.

To test for the effects of herbicide treatment on the density of stump sprouts (2 years after the shelterwood cut), we grouped the stump sprouts into three species/groups: oak-hickory (untreated), red maple (treated), and all other species (treated). We separated red maple from other treated species for two reasons. First, red maple was by far the most abundant treated species. Second, the herbicide treatment was much less effective on red maple than on other treated species (see results). When calculating stump sprout densities, each sprouting stump was defined as one individual.

We also tested for the effects of the herbicide treatment and the shelterwood harvest on the proportion of advance reproduction belonging to five species groups: red maple, other shade-tolerants, oak-hickory, sassafras (*Sassafras albidum* (Nutt.) Nees), and poplar–aspen–cherry (see Table 1 for the individual species in each group). Together, these five species/groups comprised >99.5% of the advance reproduction, both before and after treatments. The pretreatment proportion of each species/group was calculated for all stems 30 cm height to 9.9 cm DBH. Because postharvest sampling was limited to stems >140 cm height, for all species but oaks and hickories, we calculated postharvest proportion for each species/group using only stems 140 cm height to 9.9 cm DBH. In these models, time (pre-shelterwood and post-shelterwood) was a repeated measure and served as the shelterwood harvest effect. The models contained the fixed effects of harvest, herbicide, and harvest × herbicide interaction. The covariance structure was autoregressive.

At the smaller subplot-scale (12.6 m^2), we tested for herbicide effects on the dominance of two major species groups, oak-hickory and competitors (all other tree species). We classified dominance based on stem densities in the largest size class present within each of the 552 subplots. For the largest size class present in each subplot (1.4 m height to 2.9 cm DBH, 3.0 to 5.9 cm DBH, or 6.0 to 9.9 cm DBH), we compared the density of oak-hickory stems to that of competitors. Based on the ratio of oak-hickory to competitors, we assigned three dominance classes: (1) competitors dominant: density of competitors ⩾2X that of oak-hickory, (2) oak-hickory dominant: density of oak-hickory ⩾2X that of competitors, and (3) mixed-dominance: density of oak-hickory and competitors <2X that of the other group. Twenty-four subplots (4.3% overall) were excluded from this analysis because no stems >1.4 m height were present; within units, the maximum number of excluded subplots was 7 of 36 (20%). For each of the 16 treatment units, we calculated the percentage of subplots in each of the three dominance classes. We then analyzed each dominance class by GLMM as described above.

3. Results

3.1. Pretreatment advance reproduction

In 2005, the mean pretreatment density of large seedlings (30 cm to 1.4 m tall) per unit ($n = 16$) was 6918 ± 774 (SE) stems ha^{-1} and species composition was similar among designated treatments (Fig. 1, Appendix A). The most abundant species group in the large seedling stratum was sassafras, comprising 33 ± 2.5% of stems. Oaks and hickories were 24 ± 3.2% of stems, and red maple and other shade-tolerants made up 24 ± 2.8% and 16 ± 1.9% of stems, respectively. Within the oak-hickory group, chestnut oak was the most abundant species, averaging 526 ± 217 stems ha^{-1}, while hickories, white oak, scarlet oak (*Quercus coccinea* Muenchh.), and black oak each had mean densities between 200 and 400 stems ha^{-1} (Table 1). The mean density of smaller oak-hickory seedlings (<30 cm tall) was 15,919 ± 2373 stems ha^{-1}; chestnut oak (6848 ± 2157 ha^{-1}) and white oak (3541 ± 855 ha^{-1}) were the most abundant species in this size class.

The mean pretreatment density of saplings (stems 1.4 m tall to 9.9 cm DBH) was 1558 ± 116 stems ha^{-1}. In contrast to the large seedlings, the sapling stratum was strongly dominated by shade-tolerant species, as red maple and the other shade-tolerant species comprised 88 ± 2.1% of stems (Fig. 1, Appendix A). In the other shade-tolerant group, the most abundant species were blackgum (*Nyssa sylvatica* Marsh.) and sourwood (*Oxydendrum arboreum* (L.) DC.). Species composition was similar among units designated for control and herbicide treatments. Oak-hickory saplings were present but occurred at low densities, averaging 118 ± 33 stems ha^{-1} (8% of saplings); oak saplings were particularly sparse, averaging just 37 ± 12 stems ha^{-1}.

3.2. Postharvest

3.2.1. Basal area and understory light

In 2007, one or two years after the shelterwood harvests, the basal area of residual trees averaged 13.1 ± 0.8 m^2 ha^{-1} on control units and 13.4 ± 0.5 m^2 ha^{-1} on herbicide units, and ranged from 10.1 to 15.9 m^2 ha^{-1} among the 16 units. Nearly all residual trees (96%) were oaks. Understory light averaged 50.1 ± 4.5% of full sunlight on control units and 57.1 ± 3.8% of full sunlight on herbicide treatment units.

3.2.2. Saplings

Four to six years after the shelterwood harvests, the mean density of saplings (stems >1.4 m height) was 6976 ± 821 stems ha^{-1}. Postharvest sapling density and species composition were similar on the control and herbicide units (Fig. 2). Across both treatments, the majority of saplings were poplar–aspen–cherry, other shade-tolerants, and red maple. Within the poplar–aspen–cherry group, yellow-poplar was the most abundant species, with a mean density of 1233 ± 322 stems ha^{-1} across treatments (Appendix A). Similar to pretreatment densities, blackgum and sourwood were the most abundant species in the other shade-tolerant group after the harvest. Oak-hickory sapling densities averaged 1107 ± 287 stems ha^{-1} (17% of all saplings) in the control units and 1680 ± 591 stems ha^{-1} (23% of all saplings) in the herbicide units. Chestnut oak and hickories comprised 60% of the saplings within the oak-hickory group (Appendix A). Tall woody shrubs and vines (>140 cm height) were also abundant postharvest, averaging 4630 ± 675 stems ha^{-1}, dominated by *Rubus* spp. (58 ± 5.8% of stems) and greenbrier, *Smilax rotundifolia* (27 ± 6.0%).

Species groups were analyzed to determine whether there were significant changes in the proportion of larger advance reproduction (large seedlings and saplings combined, 30 cm tall

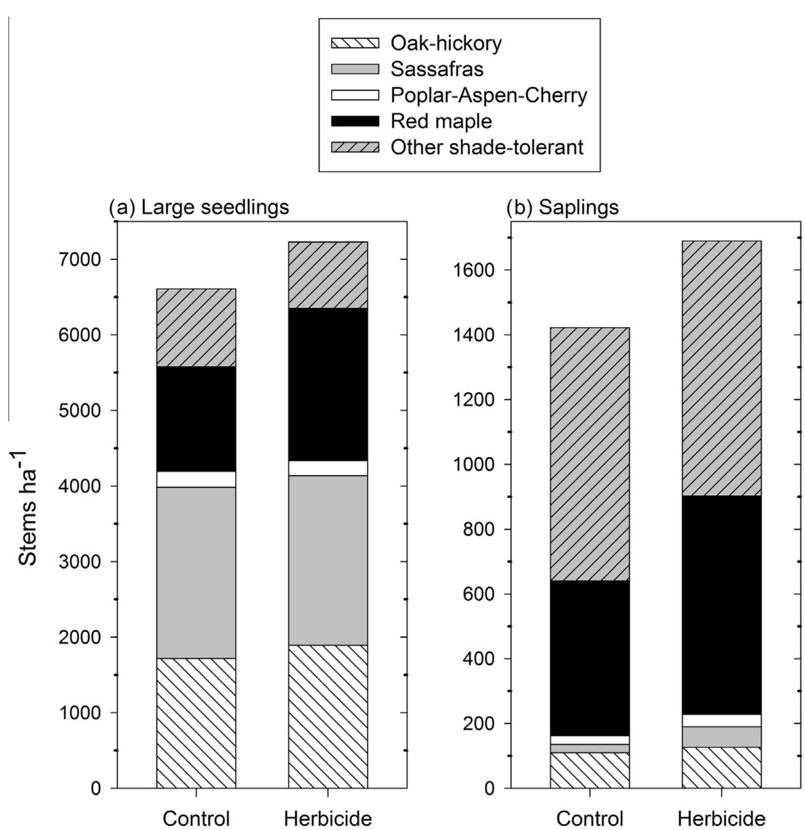

Fig. 1. Pretreatment mean density of (a) large seedlings (30 cm tall to 1.39 m height) and (b) saplings (stems 1.4 m tall to 9.9 cm DBH) for five species/groups on designated treatments.

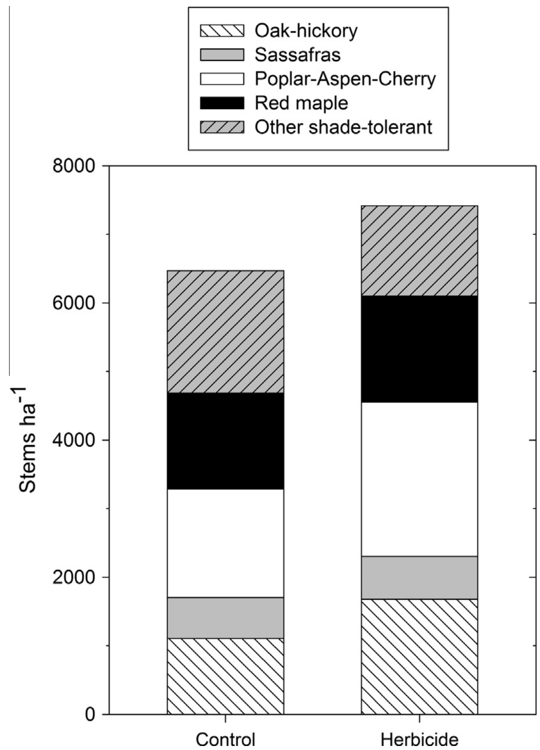

Fig. 2. Mean density of saplings (1.4 m tall to 9.9 cm DBH) in control and herbicide units 4–6 years after the shelterwood harvest, for five species/groups.

Table 1
Results of repeated measurements analysis for the effects of treatments on the proportion of species/groups in advance reproduction, from pretreatment to 4–6 years after the shelterwood harvest. The pretreatment proportions were calculated for all stems 30 cm height to 9.9 cm DBH; the postharvest proportions were calculated from all stems 140 cm height to 9.9 cm DBH.

Species/group	*p*-values		
	Harvest ($F_{1,14}$)	Herbicide ($F_{1,11}$)	Harvest × Herbicide ($F_{1,14}$)
Oak-hickory	0.260	0.484	0.328
Sassafras	<0.001	0.626	0.730
Poplar–aspen–cherry	<0.001	0.393	0.257
Red maple	0.068	0.562	0.321
Other shade-tolerant	0.756	0.010	0.394

to 9.9 cm DBH) from pretreatment to the proportion of saplings (stems >1.4 m tall) 4–6 years after the shelterwood harvest. For all five species groups, the herbicide × shelterwood harvest (time) effect was non-significant (*p*-values ranged from 0.257 to 0.730), indicating that changes in the proportion of a species group after the shelterwood harvest were not significant between the control and herbicide units (Table 1).

Despite a more than tenfold increase in the density oak-hickory saplings after the shelterwood harvest, the proportion of oak-hickory in the regeneration layer did not change significantly from pretreatment to postharvest (Fig. 3a). Also, the proportion of oak-hickory in the regeneration layer was not significantly different between control and herbicide units. Before treatment, oak and hickories comprised 20.8 ± 2.9% of the large seedlings and saplings, combined. By 4–6 years after the shelterwood harvest, oaks and hickories made up 18.7 ± 2.8% of the sapling strata.

Similar to oak-hickory, the proportions of red maple and other shade-tolerant species did not change significantly after the shelterwood cut (Table 1). Red maple comprised 26.3 ± 2.7% of the large seedlings and saplings before treatment and 22.3 ± 1.9% of the sapling strata postharvest (Fig. 2d). The other shade-tolerant group was 23.6 ± 2.3% of the advance reproduction before the harvest and 25.1 ± 2.7% of the sapling strata after harvest (Fig. 3e).

There was a significant increase in the proportion of stems in the poplar–aspen–cherry group after the shelterwood harvest (Table 1). Poplar–aspen–cherry comprised only 2.3 ± 0.5% of the large seedlings and saplings prior to the shelterwood harvest. The harvest initiated seed germination of these species, followed by seedling establishment and rapid growth. By 4–6 years after the cut, this group made up 21.9 ± 4.1% of the stems >1.4 m tall (Fig. 3c). Sassafras, on the other hand, exhibited a significant decrease after the shelterwood harvest. In 2005 sassafras made up 27.0 ± 1.8% of the large advance reproduction but postharvest its proportion in the sapling layer was only 11.9 ± 3.3% (Fig. 3b).

3.2.3. Large oak-hickory seedlings

Large oak-hickory seedlings (30–140 cm tall) occurred at mean postharvest densities of 5719 ± 894 and 5841 ± 1653 stems ha^{-1} on control and herbicide units, respectively. Across treatments, chestnut and white oak made up 61.8 ± 5.6% of the large oak seedlings. As expected, the density of all oak-hickory stems >30 cm tall, the majority of which were large seedlings, was significantly greater ($p < 0.001$) postharvest (5780 ± 908 stems ha^{-1}) than preharvest (1590 ± 332 stems ha^{-1}). However, the harvest × herbicide interaction was not significant, indicating that the postharvest increase in oak-hickory was not different between the control and herbicide units.

3.2.4. Stump sprouts

In 2010, four or five years after the shelterwood harvest, there were an average of 339 ± 17 sprouting stumps ha^{-1}, (defined as sprouts from trees >7.5 cm basal diameter), on the untreated control units (Fig. 4). Red maple was the most abundant species (144 ± 19.8 ha^{-1}), making up 42% of stump sprouts (145 ha^{-1}). After red maple, stump sprouts on control units were evenly distributed between oaks and hickories (30%) and all other species (29%), which were primarily blackgum and sourwood.

The stem-injection herbicide treatment, applied prior to the shelterwood harvest, resulted in significantly lower densities of red maple stump sprouts ($p = 0.015$; Fig. 4a). However, the effectiveness of glyphosate to reduce red maple stump sprouting was limited, as red maple stump sprouts were still present at moderate densities (89 ± 15.0 ha^{-1}) on the herbicide units, only a 38% lower density than on control units. By contrast, stump sprouts of the other species group had an 83% lower density on herbicide units than on control units ($p < 0.001$, Fig. 4c).

As expected, there was no herbicide effect ($p = 0.222$) on the density of stump sprouts from the untreated oaks and hickories (Fig. 4b). Oak stump sprout densities were variable among sites. Three of the four sites had relatively low densities of oak stump sprouts, averaging 49–60 stems ha^{-1}. By contrast, the Richland Furnace site, a younger stand with a greater proportion of chestnut oak, averaged 184 oak stump sprouts ha^{-1}, the majority of which were chestnut oak (59%).

3.2.5. Dominance at the subplot scale

We evaluated densities of saplings and stump sprouts within each subplot (12.6 m^2), to evaluate the post-harvest competitive position of oak-hickory versus competitors (here we include all other tree species), focusing on the largest size class of stems present in each subplot. In most subplots (77%), small saplings (stems 1.4 m height to 2.9 cm DBH) were the largest size class present. Across treatments, 65.4 ± 3.7% of subplots were classified as dominated by competitors, i.e., competitors were >2X the density of oaks and hickories in the largest size class (Fig. 5a). Competitors

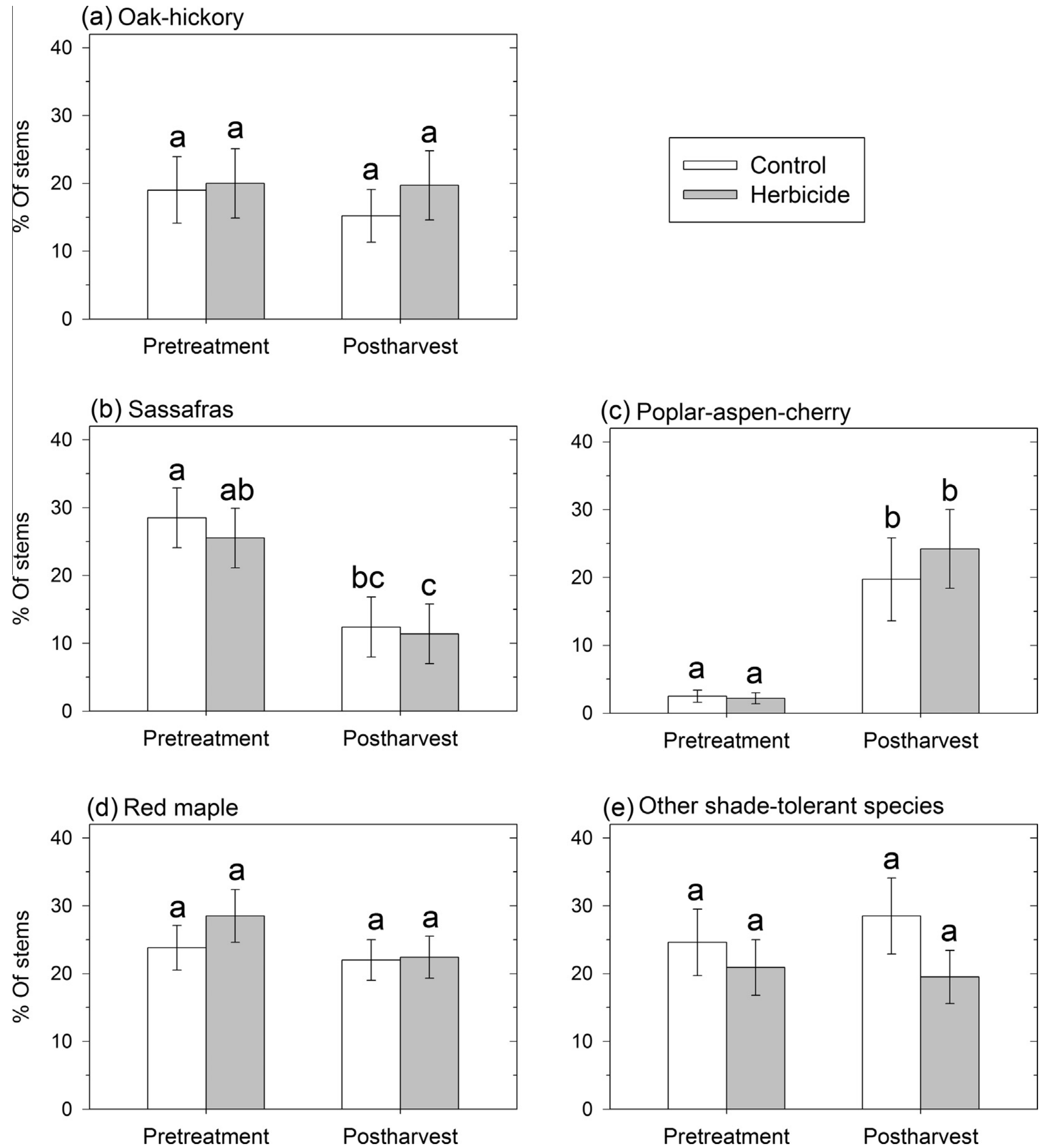

Fig. 3. Results of repeated measurements analysis for the effects of treatments on the relative density (% of stems) of species/groups from pretreatment to 4–6 years after the shelterwood harvest. The pretreatment proportions were calculated for all stems 30 cm height to 9.9 cm DBH; the postharvest proportions were calculated from all stems 140 cm height to 9.9 cm DBH. The bars show LS-mean values for each treatment × time combination. For each species/group, different letters above the bars indicate significant differences.

were dominant in a greater proportion ($p = 0.019$) of subplots in control units (73.1 ± 3.5%) than in herbicide units (57.7 ± 5.4%). Stump sprouts of competitors were present in 25% of subplots in control units and 15% of subplots in herbicide units. Although oaks and hickories were dominant in a small proportion of subplots overall, the percentage of oak-hickory dominated subplots was significantly greater ($p = 0.019$) in herbicide units (26.0 ± 3.1%) than in control units (13.4 ± 3.1%) (Fig. 5b). The proportion of subplots classified as having mixed dominance was not different between control and herbicide units (Fig. 5c).

4. Discussion

Prior to the shelterwood harvests, oak-hickory seedlings were abundant but small in stature. The first-removal shelterwood harvests greatly increased light to the forest floor; and by 4–6 years postharvest, larger oak-hickory stems (>70 cm tall) were present on the great majority (80.4%) of subplots. However, oaks and hickories made up <20% of the postharvest saplings (stems >1.4 m tall), as red maple, other shade-tolerant species, and the shade-intolerant poplar–aspen–cherry group often occurred at high densities and, across treatments, non-oak competitors were dominant in the majority of subplots.

The herbicide treatment, a late-season stem-injection of glyphosate (54% active ingredient) in all non-oak-hickory trees >5.0 cm DBH, was conducted just prior to the shelterwood harvests, and was intended to (1) limit the post-shelterwood sprouting of non-oak competitors, primarily shade-tolerant saplings and poles that occupied the midstory, and (2) be a cost-effective treatment for land managers. However, by 4–6 years after the shelterwood harvest, the competitive position of oaks and hickories in the sapling strata was largely similar in control and herbicide units. Specifically, the herbicide treatment did not decrease the proportion of red maple and other shade-tolerant saplings that were present after the harvest, resulting in the lack of proportional increase in oak-hickory in the herbicide units.

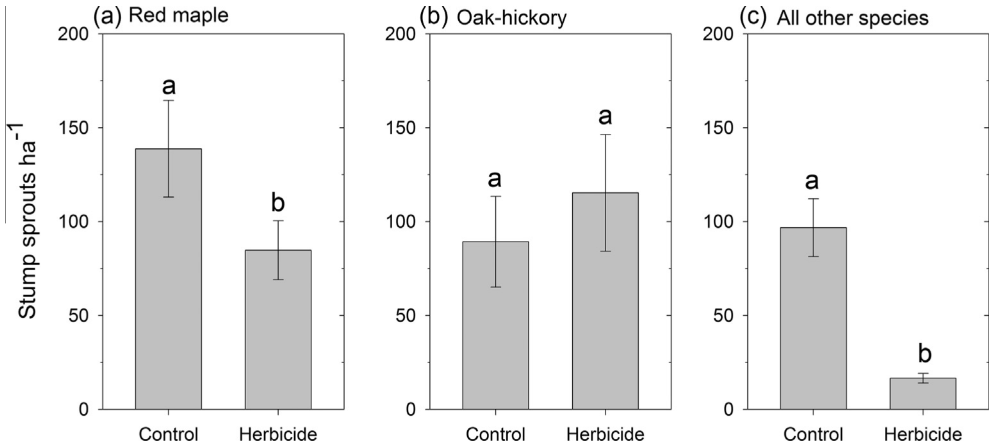

Fig. 4. Analysis of herbicide treatment effect on the density of sprouting stumps on control and herbicide units, 2 years after the shelterwood harvest, for (a) red maple, (b) oak-hickory, and (c) all other species. For each species/group, different letters above the bars indicate a significant difference between treatments.

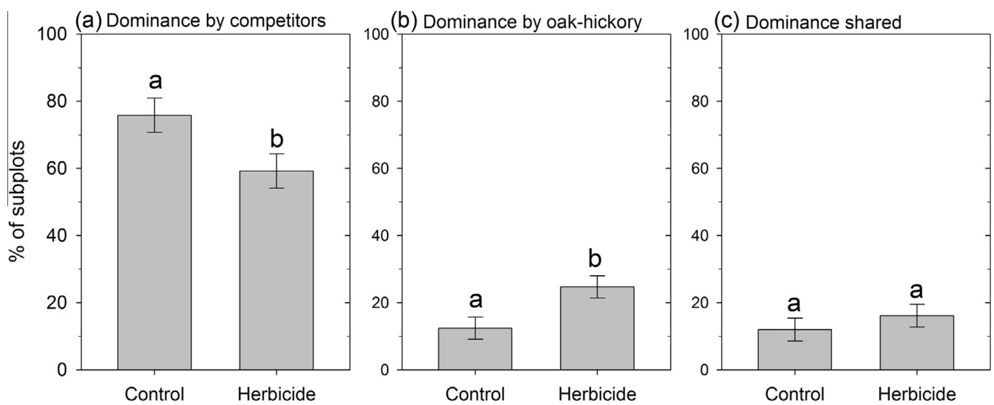

Fig. 5. LS-mean values for the percentage of subplots that exhibited: (a) dominance by competitors, (b) dominance by oak-hickory, and (c) dominance shared, between control and herbicide units, 4–6 years after the shelterwood harvest. Different letters above the bars for each type of dominance indicate a significant difference between control and herbicide units.

Two primary factors contributed to the limited effects of the herbicide treatment in this study. First, these stands had high densities of smaller shade-tolerant saplings that were not treated with herbicide because they were below the 5.0 cm DBH threshold. In the first removal shelterwood harvest prescription, all trees >5.0 cm DBH and not marked as residuals were to be felled. Immediately after the cuts, however, we observed that very few smaller saplings (<5.0 cm DBH) remained standing; presumably these stems were also cut or broken off during the harvesting operations. Therefore, although nearly all saplings and poles, which were primarily shade-tolerant species, were either cut or damaged during the harvest, a majority of those stems were small (<5.0 cm DBH), and thus remained untreated in the herbicide units and were capable of re-sprouting to form multi-stemmed clumps. In addition to the smaller saplings, non-oaks also comprised the majority of large seedlings (stems 30–140 cm tall) before the shelterwood harvest. In the herbicide units, these smaller stems were likewise not treated with herbicide and thus were either free-to-grow after the harvest if undamaged or were capable of resprouting if damaged. Parrott et al. (2012), in a midstory removal experiment in similar oak stands in Kentucky, found that even when all competing stems >2.54 cm DBH were cut and stumps sprayed with glyphosate (41% a.i), the smaller stems of competitors (primarily red maple) that were not cut/sprayed grew rapidly in the moderate light regime, overtopping oak seedlings.

Second, although the herbicide treatment (stem-injected glyphosate) greatly reduced stump sprouting in most non-oak competitors, it was much less effective on red maple, which was the most abundant species in the midstory. Red maple stump sprouts contributed to the dominance of non-oaks in both treatments at the subplot-scale. Glyphosate is commonly used in forestry applications due to its general effectiveness (Kochenderfer et al., 2004; Miller and Wigley, 2004), and lack of residual soil activity. However, recent management guidelines note the limited ability of glyphosate to prevent stump sprouting by red maple (Clatterbuck and Armel, 2011; Kochenderfer et al., 2012).

In addition to resprouting by established shade-tolerant species, the new establishment from seed germination and rapid height growth of yellow-poplar, and to a lesser extent bigtooth aspen (*Populus grandidentata* Michx.) and black cherry (*Prunus serotina* Ehrh.), also limited the proportion of oak-hickory in the sapling strata after the harvest. Prior to the shelterwood harvest, yellow-poplar was a minor component of the overstory, making up, on average, <3% of basal area per unit. In the high light environment after the harvest, these newly-germinated but fast-growing seedlings were able to overtop established oak seedlings. In oak stands on good quality sites, it is common for yellow-poplar to establish from the seedbank and become dominant in the regeneration layer after a clearcut or heavy shelterwood harvest (Loftis, 1983; Jenkins and Parker, 1998). On the intermediate quality sites in our study, future moisture limitations may limit the longer-term success of yellow-poplar (Hilt, 1985; Morrissey et al., 2008). However, even the short-term dominance of yellow-poplar in these stands may limit the survival of oak-hickory reproduction and thus its capacity to dominate the next forest.

In addition to analyzing treatment effects on the proportion of the major species/groups, we also examined dominance at the scale of the individual subplot. The herbicide treatment did have a statistically significant but modest effect on species dominance. In subplots located in the herbicide units, stump sprouts of competitors were less frequent and oak-hickory was dominant in twice as many subplots as in the control units. Presumably, oak-hickory dominance would have been greater yet on the herbicide units if we had used an herbicide that was more effective on red maple.

As this study was being conducted, managers and scientists in Pennsylvania were modifying the SILVAH system specifically to provide research and practice-based guidance for mixed oak stands in the mid-Atlantic region (Brose et al., 2008). While the size classes used in our data collection are not perfectly matched to those in the SILVAH system (SILVAH classes rely on root collar diameters as well as height, and we did not collect those data), we can scale the data from both systems to stem densities per unit area and make some general comparisons to the SILVAH-Oak guidelines. The situation in our stands prior to the start of the experiment was most comparable to stands with abundant "new" oak (<15 cm. tall) and modest stocking of "established" oak (15–90 cm. tall). Only 24% of our plots met the SILVAH:Oak stocking threshold for established oak, based on our 15–70 cm. height class. With this mix of seedlings, and the high abundance of larger competing stems, SILVAH:Oak would have recommended a non-commercial preparatory cut, which is very similar to the herbicide treatment that we implemented. However, SILVAH:Oak would NOT have recommended the shelterwood first removal cut until established oak stocking exceeded 50%. The recommendation to leave a high overstory stocking when small seedlings have accumulated is specifically intended to retard growth of competing stems and avoid germination of shade-intolerant stems while providing a reduction in low shade that will favor development of new oak seedlings to established sizes.

Despite the difference between our treatment and the recommended SILVAH:Oak treatment, our study area accumulated larger oak advance regeneration after the shelterwood harvest, with 46% of study plots adequately stocked with seedlings >70 cm in height, nearly comparable with the class SILVAH calls "competitive" oak (>90 cm height). As we have noted, however, this increase in larger oaks was accompanied by increases in the abundance and size of competing shade-tolerant and –intolerant competing stems. Even with the much improved stocking of competitive oaks after the shelterwood harvest, SILVAH:Oak would recommend additional treatments (herbicide, fire) to ensure that oak would be a significant component on these sites after a final harvest.

4.1. Management implications

On intermediate quality sites, small oak advance reproduction may accumulate but it is typically overtopped by shade-tolerant saplings and poles. In this study, a late-season stem-injection herbicide treatment on larger interfering stems, followed immediately by a shelterwood first-removal cut to 50% residual BA, had relatively modest effects on the composition and abundance of tree regeneration after the shelterwood harvest, as non-oaks continued to dominate the regeneration layer. The high understory light levels after the harvest favored enhanced growth of the surviving competitors that were below the herbicide size threshold along with the germination and rapid growth of new shade-intolerant competitors. In addition, herbicide effects were limited due to the ineffectiveness of glyphosate to limit red maple stump sprouting. Stem-injection of the herbicide imazapyr is recommended to reduce stump sprouting by red maple (Clatterbuck and Armel, 2011; Kochenderfer et al., 2012).

At least on public lands, the use of prescribed fire to control smaller stems will often be the best option for managers. In our study, by 4–6 years after the shelterwood harvest, competitive-sized oaks >70 cm tall were "stocked" on nearly one-half of all sample plots, sufficient stocking to ensure that oak should be a significant component of the next forest (Brose et al., 2008). However, these competitive oaks were typically overtopped and outnumbered by other species. Even with the herbicide treatment in our study, the stands appear to require further treatment for oak to remain competitive. Brose and Van Lear (1998) showed that a single moderate to high intensity growing-season burn, conducted in late spring or late summer 3–5 years after a shelterwood harvest, promoted oak dominance due to higher mortality rates of red maple and yellow-poplar reproduction. The competitive oaks (>70 cm tall) that have developed in our study will resprout vigorously, even after a high intensity growing season burn (Brose and Van Lear, 1998). The largest size class of regeneration in our study was predominantly stems 1.4 m tall to 2.9 cm DBH of competing species. Stems of this size remain highly susceptible to topkill by fire. However, if the fire is conducted in the dormant season, then resprouting rates of red maple, yellow-poplar, and other competitors will be high (Brose and Van Lear, 1998) as will their growth rates in the open conditions created by the shelterwood harvest.

Another option to reduce the number of small interfering stems is to conduct prescribed fires in the mature stand prior to shelterwood harvesting. Hutchinson et al. (2012a) showed that repeated low-intensity dormant-season prescribed fires, conducted over a 10-year period, reduced the density of shade-tolerant saplings in the understory, which led to greatly improved oak regeneration when natural canopy gaps formed. Also, fire stimulates germination of seed-banking species such as yellow-poplar and subsequent burns cause high mortality of the newly established seedlings, potentially reducing the density of seed stored in the soil (Hutchinson et al., 2005; Schuler et al., 2010). However, if the large seed-producing trees remain in or near the stand then the seed bank will be continuously replenished.

In mature oak stands with a midstory and understory dominated by shade-tolerant species, a treatment sequence of repeated prescribed fires followed by an herbicide application could be successful. Low-intensity fires will topkill most stems <10 cm DBH while causing relatively minor damage to overstory trees (Hutchinson et al., 2012b; Fan et al., 2012; Marschall, 2013). While many of the shade-tolerant stems will resprout after fire, the intact canopy will limit their resprouting vigor. After multiple burns have reduced the density of smaller understory stems, herbicide could then be applied to only the remaining larger undesirable stems that have not been topkilled by fire, thus greatly reducing the number of stems requiring herbicide treatment.

Our study adds to the growing body of evidence about effective treatments to sustain high oak components in current mixed oak stands with silviculture. Our stands had accumulated a substantial cohort of small oak seedlings and larger competitors. The combination of a late season medium intensity herbicide treatment to remove some of the competing stems with a heavy shelterwood first removal cut stimulated the growth of both oak seedlings and competing stems, resulted in only modest improvements in the competitive position of the oaks. However, because the oaks did survive and grow, additional treatments may still change the outcome on these sites. Our findings suggest that using either a series of low-intensity fires (Hutchinson et al., 2012b) or a more intensive herbicide treatment, with a lag period before a first-removal shelterwood harvest, would probably favor oak growth without similar stimulation of competitor growth. Our study also further highlights some challenges with use of glyphosate on red maple and the cost and effectiveness differences between fire and herbicide when competing stems are small and numerous.

Appendix A. Mean densities (± SE) of tree regeneration pretreatment and 4–6 years postharvest, for the five species/groups and individual species within the groups, for large seedlings (30–139 cm tall) and saplings (140 cm tall to 9.9 cm DBH)

			Pretreatment density, stems ha^{-1}		Postharvest density, stems ha^{-1}
A. Species group					
			Large seedlings	Saplings	Saplings
Red maple			1697 ± 270	577 ± 74	1473 ± 178
Sassafras			2256 ± 320	44 ± 10	611 ± 133
Oak-hickory			1804 ± 332	118 ± 33	1394 ± 326
Other shade-tolerant			956 ± 84	784 ± 68	1555 ± 145
Poplar–aspen–cherry			205 ± 58	32 ± 11	1915 ± 556
B. Species within groups					
Group	Species	Common name	Large seedlings	Saplings	Saplings
Oak-hickory	*Carya* spp.	Hickories	400 ± 92	82 ± 22	317 ± 83
	Quercus alba	White oak	299 ± 125	15 ± 6	196 ± 57
	Quercus coccinea	Scarlet oak	276 ± 75	3 ± 2	187 ± 42
	Quercus montana	Chestnut oak	526 ± 218	8 ± 4	519 ± 239
	Quercus rubra	Northern red oak	95 ± 31	2 ± 1	30 ± 12
	Quercus velutina	Black oak	208 ± 52	9 ± 4	144 ± 35
Other shade-tolerant	*Nyssa sylvatica*	Blackgum	558 ± 79	436 ± 37	831 ± 101
	Oxydendrum arboreum	Sourwood	205 ± 44	225 ± 48	518 ± 107
	Other species[1]		193 ± 24	122 ± 24	201 ± 25
Poplar–aspen–cherry	Yellow-poplar	*Liriodendron tulipifera*	182 ± 52	32 ± 11	1233 ± 322
	Bigtooth aspen	*Populus grandidentata*	2 ± 1	0 ± 0	570 ± 262
	Black cherry	*Prunus serotina*	21 ± 9	0 ± 0	112 ± 43

Note: In the pretreatment sampling, a mean of 102 total large seedlings and a mean of 32 total saplings were recorded per vegetation plot (n = 184). In the postharvest sampling, a mean of 26 total saplings was recorded in each vegetation plot.

[1] *Acer saccharum*, *Amelanchier arborea*, *Asimina triloba*, *Carpinus caroliniana*, *Cornus florida*, *Fagus grandifolia*, *Fraxinus americana*, *Ostrya virginiana*, and *Ulmus rubra.*

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