# POST-HARVEST PRESCRIBED BURNING OF OAK STANDS: AN ALTERNATIVE TO THE SHELTERWOOD-BURN TECHNIQUE?

**Patrick H. Brose**[1]

**Abstract.—**Prescribed burning of two mixed-oak (*Quercus* spp.) stands in northwestern Pennsylvania 4 and 5 years after the final removal cut of a three-step shelterwood sequence was investigated. One stand was burned with hot mid-spring fire in May 2005 and the other treated likewise in May 2006. Understory inventories 3 years later showed reductions in black birch (*Betula lenta*) and red maple (*Acer rubrum*) seedlings and sprouts by 90 and 50 percent, respectively. Conversely, northern red oak (*Q. rubra*) reproduction was largely unchanged, as was that of black cherry (*Prunus serotina*). These stands now appear headed towards becoming northern red oak and black cherry stands instead of being dominated by black birch and red maple.

## INTRODUCTION

In the past 10 to 15 years, many managers of oak (*Quercus* spp.) forests throughout the eastern United States have begun incorporating prescribed fire into their management plans and activities (Dickinson 2006, Hutchinson 2009, Yaussy 2000). Generally, these prescribed fires are one of two types: site preparation (restoration) burns or oak release burns (Brose et al. 2006, 2008). In the former, fire is used in mature oak stands to reduce understory shade, prepare a seed bed for future acorn crops, and stimulate the herbaceous plant community. The latter uses fire in the stand-initiation stage to free existing oak reproduction from that of taller, faster-growing hardwoods such as black birch (*Betula lenta*), red maple (*Acer rubrum*), and yellow-poplar (*Liriodendron tulipifera*). To date, almost all research and operational use of release burning have focused on fires during a shelterwood sequence, an approach commonly called the shelterwood-burn technique (Brose et al. 1999a, b), although fires conducted after the final removal harvest may also meet the competition control objective.

When applied correctly, the shelterwood-burn technique provides excellent control of competing hardwoods (Brose 2010, Brose and Van Lear 1998, Brose et al. 1999a). However, it does have a downside. Because the burning occurs during a shelterwood sequence, there is the possibility of damaging or killing some of the remaining overstory trees that are being saved for the final harvest. Fire has a well-deserved reputation for damaging and killing mature hardwood trees (Berry and Beaton 1972, Brose and Van Lear 1999, Franklin et al. 2003, Hutchinson et al. 2005, Loomis 1973, Paulsell 1957, Regelbrugge and Smith 1994, Yaussy and Waldrop 2010). Of these papers, Brose and Van Lear (1999) specifically addressed burning during a shelterwood sequence and reported a 20-percent mortality rate following spring fires. They attributed this mortality to logging slash at the base of the fire-killed residual trees and recommended preburn slash control to minimize fire damage. Additionally, unscorched residual trees after a prescribed fire can be perceived as a risky purchase by log buyers, causing reduced revenues to the landowner.

Another approach to avoiding fire damage to the residual trees is to harvest them before conducting the prescribed burn. In other words, complete all the shelterwood harvests; then burn the stand (a

[1]Research Forester, U.S. Forest Service, Northern Research Station, 335 National Forge Rd., Irvine, PA 16329. To contact the author, call 814-563-1040 or email at pbrose@fs.fed.us.

post-harvest burn). This approach would mimic the sequence of timber cutting and fire of the early 20$^{th}$ century that created many of our current oak stands, yet it has had little research to document the responses of the oak reproduction and the many competing hardwood species.

Two studies report the results of wildfire in young hardwood stands. Carvell and Maxey (1969) investigated the effects of a fall wildfire in a 14-year-old sapling stand in West Virginia. They found a decrease in the density of basswood (*Tilia americana*), cucumbertree (*Magnolia acuminata*), and yellow-poplar stems relative to an adjacent unburned sapling stand whereas oaks and hickories increased in number. Ward and Stephens (1989) found the effects of a wildfire in a 32-year-old stand in Connecticut to still be evident 55 years later as decreased abundance of black birch and increased amounts of oak relative to an adjacent unburned area. Additionally, two studies report the results of prescribed fires in young hardwood stands. In Alabama, McGee (1979) found that fall and spring prescribed fires in 4-, 5-, or 6-year-old clearcuts increased red maple stems and had negligible impact on the oak reproduction. Ward and Brose (2004) reported that spring burning of young sapling stands in Connecticut resulted in differential mortality rates among the principal hardwood species: 7 to 18 percent for oak, 9 to 45 percent for red maple, and 75 to 79 percent for black birch, depending on fire intensity.

In 2005 and 2006, the opportunity arose to add to this small set of fire papers by studying the effects of a single spring prescribed fire conducted 4 and 5 years after the final harvest of a three-cut shelterwood sequence. Specific research objectives were (1) to document the declines in density of the various hardwood species to the fires and (2) to document the fuel loadings and fire behavior in these young stands.

## STUDY AREA

This study was conducted from 2005 to 2009 in the Allegheny High Plateau Region of northwestern Pennsylvania (Schultz 1999). This part of Pennsylvania is a dissected plateau characterized by broad, flat hills with deep valleys and steep slopes. Plateau-top elevations range from 1,700 to 2,000 feet above sea level; valley bottoms are 1,000 to 1,300 feet above sea level. Climate is classified as humid continental with warm, moist summers and cold, snowy winters. Average annual temperature is 48 °F with an average minimum mean of 17 °F in January and an average maximum mean of 82 °F in July (Cerutti 1985). Annual precipitation averages 43 inches of rain and 74 inches of snow distributed evenly throughout the year. The growing season averages 140 days. The region is extensively forested with a mix of oak and northern hardwood tree species.

The specific study site was a recently regenerated 43-acre northern red oak stand on State Game Land 29, a property of the Pennsylvania Game Commission. The stand is situated on a broad, flat hilltop so slope is almost zero and aspect is inconsequential. Soil is a Cookport silt loam (Aquic Fragiudults) formed in place from sandstone, siltstone, and shale parent material (Cerutti 1985). The site was never glaciated but is underlain with a fragipan that restricts water drainage and rooting depth. Site $index_{50}$ for northern red oak is estimated at 76 feet.

The parent stand of the study stand originated in the early 1900s when the entire region was logged and burned within a span of three to four decades (Marquis 1975). It was unmanaged until the early 1990s, when gypsy moth (*Lymantria dispar*) defoliated the stand, causing scattered mortality and some salvage harvesting. These two disturbances essentially served as a shelterwood preparatory cut as stand stocking was slightly reduced by removing some of the low-vigor trees. The cutting also coincided with an acorn crop, resulting in the abundant establishment of oak and other hardwood reproduction. In 1996, a shelterwood release cut occurred that removed approximately half the overstory trees. Shortly thereafter, the stand was divided into two sections, a 13-acre eastern block (EastBlock) and a 30-acre western block (WestBlock), and both sections were surrounded by 8-foot-high woven wire fencing to exclude white-tail deer (*Odocoileus virginiana*) from the new reproduction. The remaining overstory was harvested from both blocks in 2000.

After the final harvest, the abundant hardwood reproduction (20,000 to 30,000 stems per acre, of which 10 percent was oak) grew rapidly. By 2004, birch, cherry, and maple seedlings were overtopping the oak reproduction by several feet. The differences in abundance and size between the oaks and other hardwoods concerned the Game Commission foresters because only 125 to 150 oaks per acre could be expected to become codominant trees by age 20 in the new stand on a site of this quality (Loftis 1990). Anticipated oak mortality after age 20 would further reduce the oak component (Ward and Stevens 1994), resulting in a mixed-hardwood forest with few oaks in the main canopy. Therefore, the foresters decided to try prescribed fire to enhance the competitive position of the oaks in the regeneration pool.

## METHODS

For Objective 1, fifty 0.0025-acre (1/400-acre) regeneration sampling plots were systematically located to uniformly cover both blocks (20 in EastBlock and 30 in WestBlock) and permanently marked. In each plot, all hardwood stems >1 foot tall were identified to species and tallied by height class: 1 - 3 feet (oak only), 3 - 5 feet, 5 - 10 feet, 10 - 15 feet, and >15 feet. The EastBlock plots were established in early spring 2005 and the WestBlock plots were established in early spring 2006.

For Objective 2, nine 30 feet by 30 feet fire behavior plots were established in the two blocks (three in EastBlock and six in WestBlock) in areas visually judged to have uniform fuel conditions representative of the entire block. A thermocouple was positioned in the corner and center of each plot to measure fire temperatures 1 foot above the ground at 1-second intervals. Each thermocouple was attached to a datalogger buried in the soil. Woody fuels near each thermocouple were inventoried by size class by using three 15-foot transects and the planar transect method (Brown 1974). Size classes were <0.25 inch, 0.25 - 1.0 inch, 1.0 - 3.0 inches, and >3.0 inches for 1-hour, 10-hour, 100-hour, and 1,000-hour fuels, respectively. Fuel loading in tons per acre was calculated by using equations in Brown (1974). Leaf litter and dead herbaceous fuels were collected from the end of each third transect by using a 14 inch by14 inch square and oven-dried to a constant mass to determine fuel loading in tons per acre.

The prescribed fires were conducted on May 9, 2005 (EastBlock) and May 3, 2006 (WestBlock) by Pennsylvania Game Commission personnel in accordance with agency policy and state law. At the time of each burn, the oak reproduction was still dormant as the buds were still firm or slightly swollen. However, the leaves of the non-oak reproduction (birch, cherry, maple) ranged from dormant to fully expanded with considerable variation among and within the species. Before each fire, fuel moisture was measured by using a hand-held wood moisture probe and weather conditions were monitored every 15 minutes during the burns with a belt weather kit. EastBlock was ignited as a single unit by using drip torches and a ring-fire pattern. WestBlock was divided into six subunits of approximately 5 acres, each of which was lit by using drip torches and a ring-fire pattern. When possible, the flaming front was photographed as it passed through or near each plot.

Data collection occurred at two distinct times after each burn. The dataloggers and thermocouples were collected the day after the fires. These data were used to determine the overall average maximum temperature in degrees Fahrenheit of each fire and rate-of-spread (ROS) in feet per minute. Rate-of-spread was calculated by dividing the distance between two thermocouples by the time difference between their respective maximum temperatures. Flame length (FL) was estimated to the nearest foot in each plot from the photographs by comparing the flaming front to saplings of a known height or the diameter of an occasional residual tree. The regeneration sampling plots were re-inventoried after the third growing season (early spring 2008 for EastBlock and early spring 2009 for WestBlock). Inventory procedures were identical to the preburn inventories.

For the statistical analysis, I condensed the regeneration data into six groups (black birch, black cherry, mixed-oak, pin cherry [*Prunus pensylvanica*], red maple, and miscellaneous species). The birch, two cherry, and maple groups were single species. Mixed-oak was almost entirely northern red oak, with a few black oak (*Q. velutina*) and white oak (*Q. alba*). Miscellaneous species was heavily dominated by serviceberry (*Amelanchier arborea*) but also included an occasional American beech (*Fagus grandifolia*), cucumbertree, and sassafras (*Sassafras albidum*). Mean height for each species group was estimated by multiplying the midpoint (2.0, 4.0, 7.5, 12.5, and 17.5 feet) of each height class by the number of stems in that height class, summing these results, then dividing by the total number of stems of that species group. I used paired T-tests with unequal variances (Zar 1999) to test for differences between the preburn and postburn densities and heights of these species groups in each burn unit. For all tests, $\alpha = 0.05$.

## RESULTS

The two burn units were quite similar in their fuel loadings and despite being a year apart, the two prescribed fires behaved comparably to one another (Table 1). EastBlock averaged 31.4 tons per acre of fuels with nearly half in the largest fuel size class (1,000-hour). The Game Commission burned EastBlock in the early afternoon, when weather conditions were warm, dry, and sunny, with a light southwest breeze. Observed FLs were estimated between 2 and 4 feet with occasional flare-ups producing FLs of 5 to 10 feet, and ROS was measured at 3 to 5 feet per minute. The mean maximum temperature measured by the thermocouples was 969 °F with a range of 543 to 1,475 °F. WestBlock averaged slightly more fuel, 40.0 tons per acre, with half being in the 1,000-hour size class. Weather conditions during the burn were slightly warmer and drier than the EastBlock conditions. Fire behavior in WestBlock was slightly more active than in EastBlock with FLs of 5 to 12 feet, ROS of 4 to 9 feet per minute, mean maximum temperature of 1,223 °F, and a maximum temperature range of 810 to 1,667 °F. Both burns were completed without incident.

Before the fire, EastBlock averaged 15,317 stems per acre (Fig. 1). Red maple was the most abundant species at 3,938 stems per acre followed by pin cherry (3,110), mixed-oak (2,975), black birch (2,411), black cherry (1,644), and miscellaneous species (1,239). Stocking, the proportion of plots with at least one stem, for all these groups exceeded 80 percent, signifying that the regeneration

**Table 1.—Fuel and weather conditions and behavior of two post-harvest prescribed fires conducted in northwestern Pennsylvania**

| Conditions | EastBlock | WestBlock |
|---|---|---|
| Date | May 9, 2005 | May 3, 2006 |
| Time of burn | 12:00 to 13:30 | 10:00 to 15:00 |
| Size (acres) | 13 | 30 |
| Total fuels (tons/acre) | 31.4 | 40.0 |
| Leaf litter | 3.0 | 3.2 |
| 1-hour woody† | 2.3 | 3.3 |
| 10-hour woody† | 4.4 | 3.9 |
| 100-hour woody† | 7.8 | 9.6 |
| 1,000-hour woody† | 13.9 | 20.0 |
| Litter cover (%) | 90 | 100 |
| Fuel height (ft) | 2.5 | 3.3 |
| Fuel moisture (%) ‡ | 12 | 10 |
| Air temperature (°F) | 72 to 75 | 76 to 80 |
| Relative humidity (%) | 28 to 33 | 22 to 25 |
| Wind direction | Southwest | Northwest |
| Wind speed (mi/hr) | 1 to 3 | 1 to 3 |
| Cloud cover (%) | 0 | 0 |
| Days since rain, amt. | 3, 0.1 inch | 6, 0.25 inch |
| Flame length (ft) | 2 to 4 | 5 to 12 |
| Rate-of-spread (ft/min) | 3 to 5 | 4 to 9 |
| Mean thermocouple temp. (°F) | 969 | 1,223 |
| Thermocouple temp. range (°F) | 543 to 1,475 | 810 to 1,667 |

† Woody fuel size classes follow Fosberg (1970).

‡ Moisture of 10-hour woody fuels.

was well distributed throughout the burn unit. Pin cherry and black birch were the tallest species, averaging 10.0 and 9.7 feet, respectively, while mixed-oak was the shortest at 1.8 feet (Fig. 2). Black cherry, red maple, and the miscellaneous species were intermediate in height with averages ranging from 4.5 to 8.2 feet.

Three years after the fire, species composition in EastBlock had changed substantially (Fig. 1). Stem density decreased by a third to 10,309 stems per acre. Oak was the most common species at 2,907 stems per acre followed closely by pin cherry (2,734). Both densities were similar to preburn values. Red maple, black cherry, and miscellaneous species were intermediate in abundance with 1,906, 1,521, and 1,001 stems per acre respectively. Of these three, only red maple had decreased from preburn levels ($p < 0.01$). Black birch was the least common postburn species, with 240 stems per acre, and had significantly decreased from preburn values ($p < 0.001$). Generally, stocking rates for all groups remained unchanged except for black birch. It was found on only 25 percent of the plots, down from 80 percent before the burn. Heights of the hardwood stems were less varied after the fires (Fig. 2). Pin cherry was the tallest at 11.3 feet, whereas red maple was the shortest at 4.4 feet, a significant decrease ($p < 0.01$) from its preburn height. Birch, black cherry, mixed-oak, and the miscellaneous species were intermediate in height with means ranging from 6.8 to 8 feet. Of these, only the mixed-oak height (7.6 feet) was significantly different ($p < 0.01$) from its preburn height (1.8 feet).

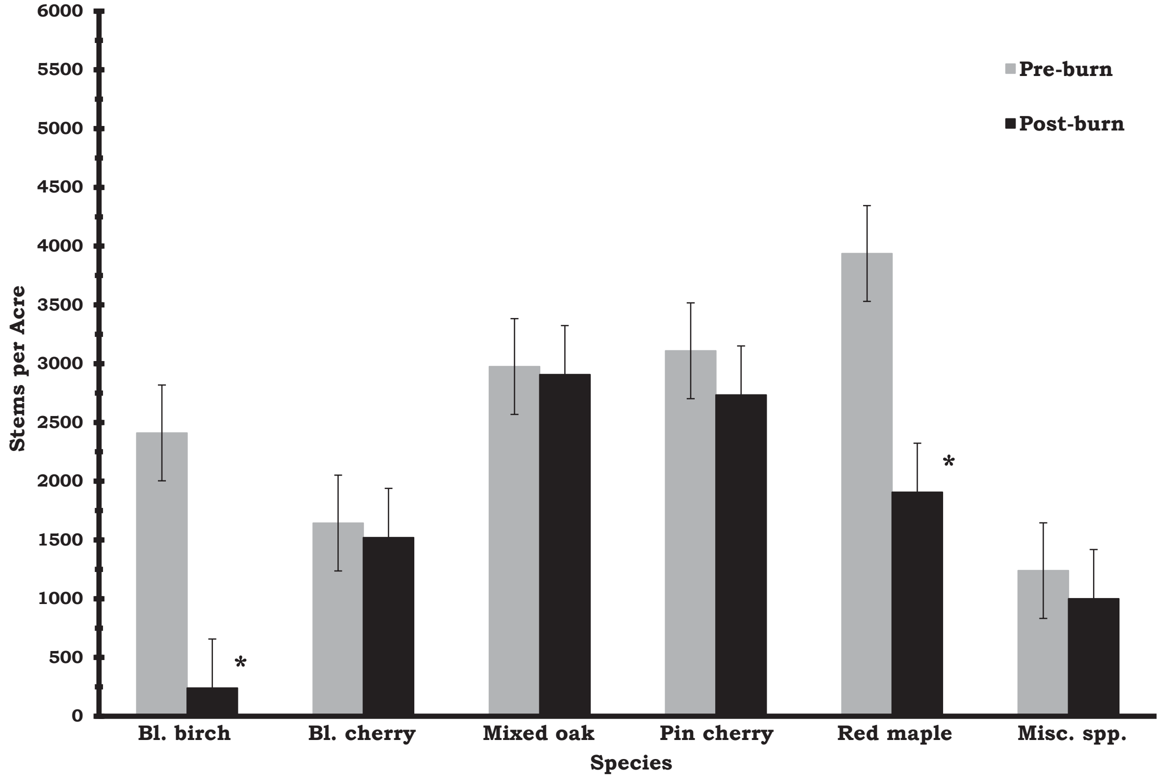


Figure 1.—Preburn and third-year postburn densities (stems per acre) of hardwood reproduction in the EastBlock unit on State Game Lands 29 in northwestern Pennsylvania. Asterisks denote postburn densities that are significantly different ($p < 0.01$) from their corresponding preburn densities.

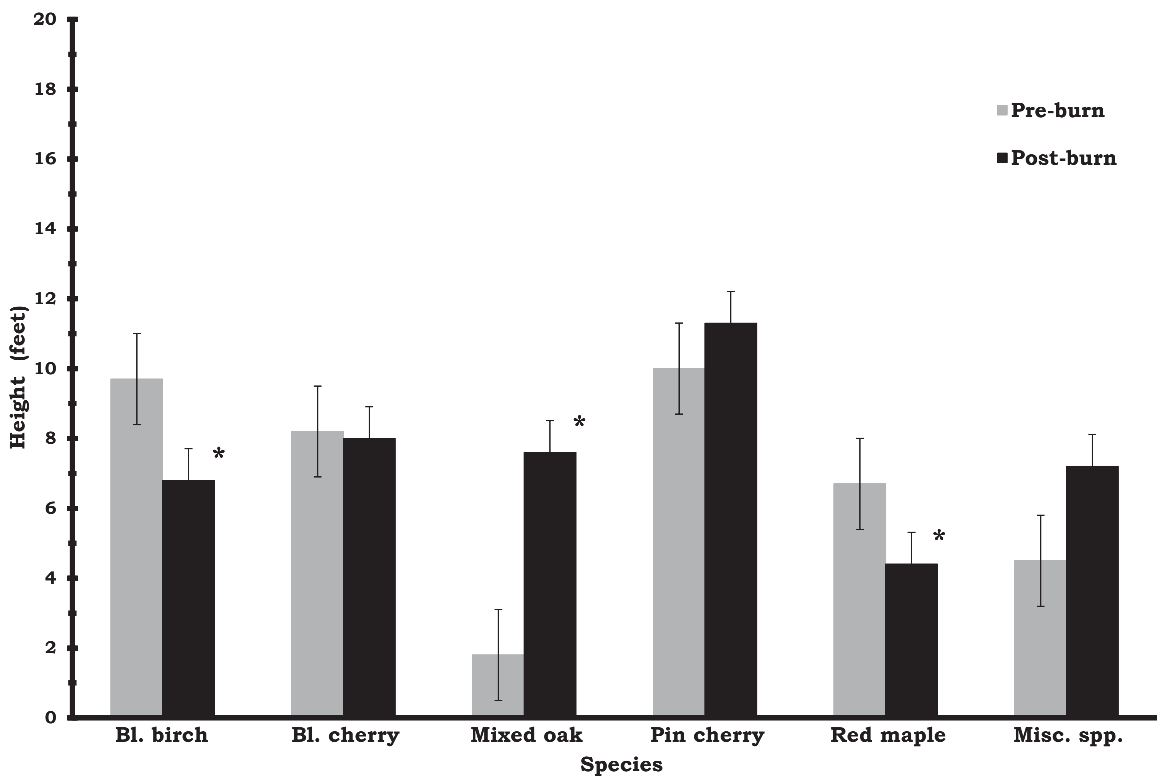


Figure 2.—Preburn and third-year postburn stem heights (feet) of hardwood reproduction in the EastBlock unit on State Game Lands 29 in northwestern Pennsylvania. Asterisks denote postburn heights that are significantly different ($p < 0.01$) from their corresponding preburn heights.

Preburn regeneration densities in WestBlock were quite similar to those of EastBlock (Figs. 3 and 4). Total regeneration density was 14,941 stems per acre, more than half of which was pin cherry (4,569) and red maple (4,054). Densities for the other species were comparable to those of EastBlock, except for black cherry, which averaged 518 stems per acre. Generally, stocking for all species exceeded 80 percent, except for black cherry, which was found on 30 percent of the plots. Pin cherry was the tallest species with a mean height of 16.5 feet, followed by black birch (13.0 feet). Black cherry, red maple, and the miscellaneous species were medium in height with means ranging from 8.0 to 10.4 feet. Oak was the shortest at 2.4 feet.

The response of WestBlock regeneration to the prescribed fire was similar to that of EastBlock regeneration a year earlier (Figs. 3 and 4). Three years after the fire, total regeneration density was 9,580 stems per acre. Pin cherry was the most abundant species (3,792), followed by mixed-oak (2,522), red maple (1,771), miscellaneous species (982), black cherry (347), and black birch (166). Of these postburn means, only black birch and red maple differed from their preburn means ($p < 0.001$ for both). Third-year postburn heights in WestBlock displayed the same interspecific distribution as those in EastBlock. Pin cherry was the tallest at 13.5 feet and red maple was the shortest at 3.5 feet. The other four species groups were intermediate in height, ranging from 5.5 to 7.7 feet. Comparing postburn heights to the corresponding preburn heights showed that black birch and red maple were significantly shorter and oak was significantly taller ($p < 0.01$ for all three). Stocking was largely unchanged except for black birch, which was found on only 27 percent of the plots 3 years after the burns.

## DISCUSSION

One drawback to the shelterwood-burn technique is that the hot spring fire can cause considerable damage and mortality to the remaining overstory trees. One approach to mitigate this problem is proper slash management, which prevents fuel from accumulating at the base of valued overstory trees or removes such fuel before the fire. Another approach is to complete all harvests before burning. However, this post-harvest burning method is largely theoretical as there is little published information on fire effects in recently regenerated stands. One exception to this knowledge gap is the study by Ward and Brose (2004) that found spring fires burned readily in young hardwood stands and provided good control of black birch with little negative impact on oak reproduction. This case study helps narrow this knowledge gap by validating the findings of Ward and Brose (2004) while providing additional insights into how the reproduction of different hardwood species responds to hot spring fires.

In this study, only a few oaks, less than 5 percent, failed to sprout after the fires, even though both fires burned with high intensity. Growth of these sprouting oaks averaged 2 to 2.5 feet per year over the next 3 growing seasons with numerous stems totaling 10 to 12 feet at the time of data collection. This high survival rate and rapid height growth are explained, in part, by some of oak's silvical characteristics (Brose and Van Lear 2004) and their interaction with the timing of the treatments. Acorns have hypogeal germination, resulting in the root collars and accompanying dormant buds being located below ground where they are protected from fire. In addition, oak seedlings emphasize root development. In this study, the young oaks had 8 or 9 years of partial to full sunlight and protection from deer to develop large root systems. The fires occurred just as the oaks were breaking dormancy so their root carbohydrate reserves were at or near their maximum.

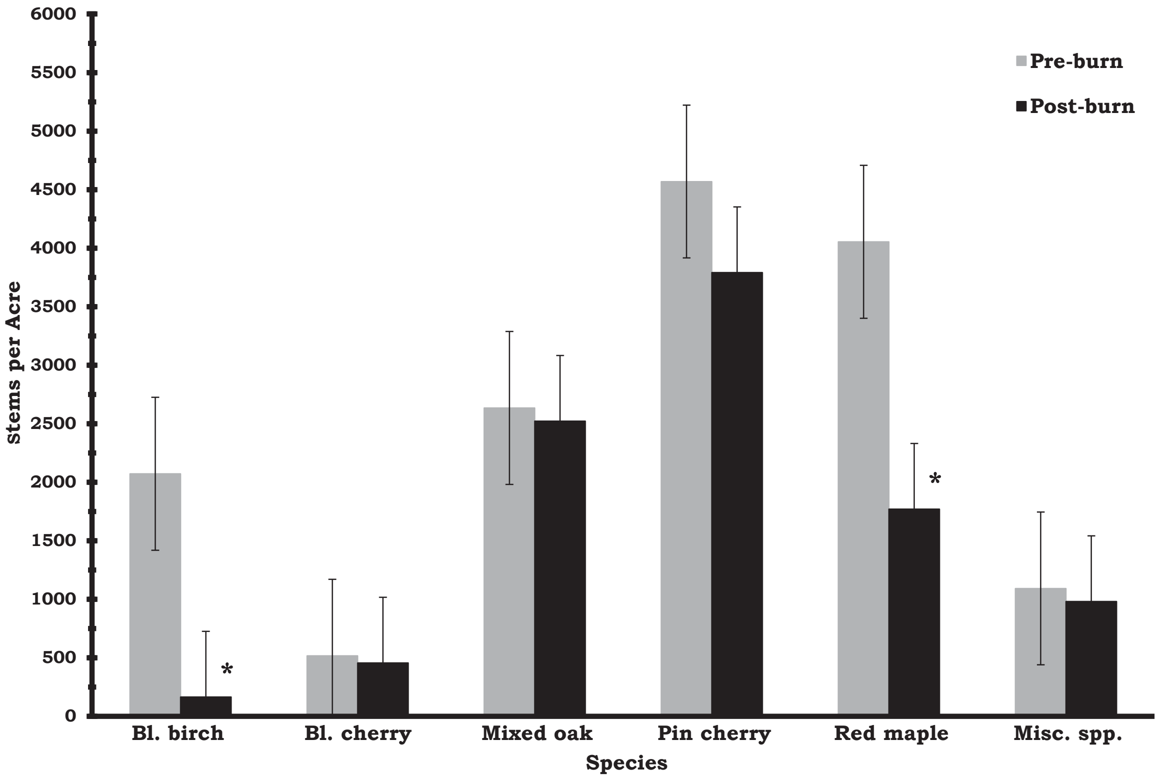


Figure 3.—Preburn and third-year postburn densities (stems per acre) of hardwood reproduction in the WestBlock unit on State Game Lands 29 in northwestern Pennsylvania. Asterisks denote postburn densities that are significantly different ($p < 0.01$) from their corresponding preburn densities.

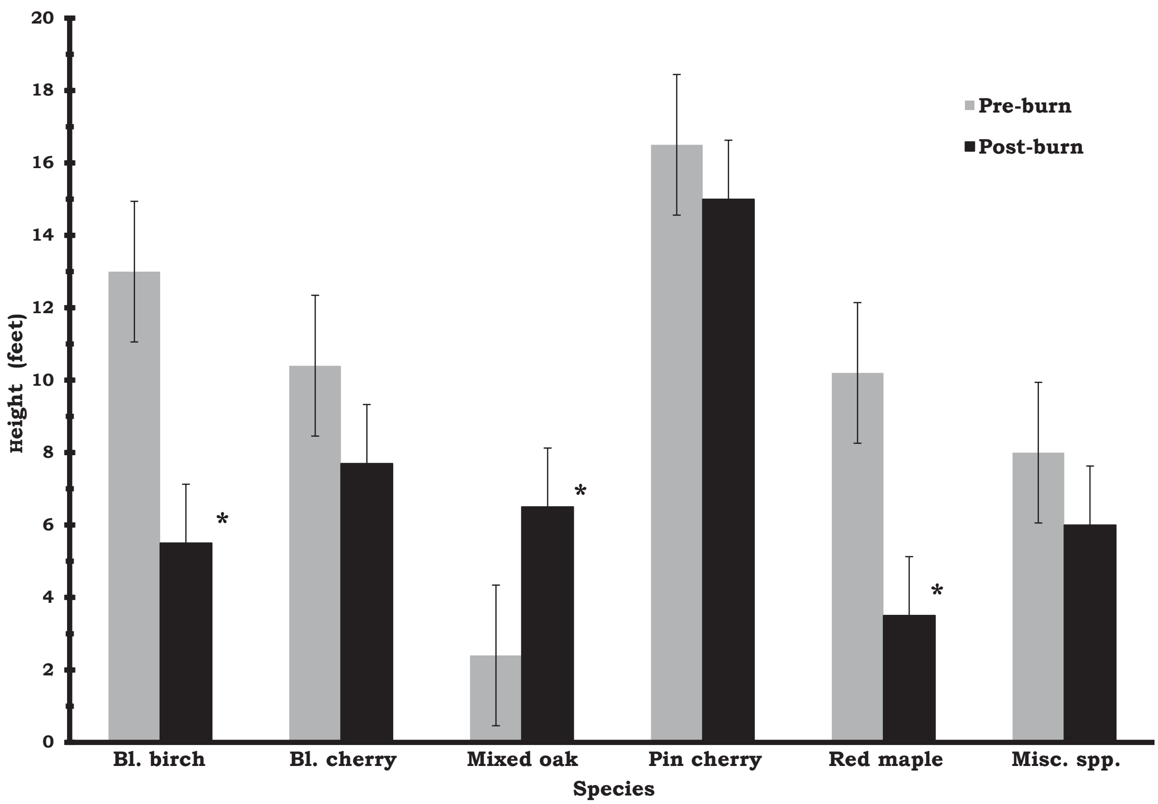


Figure 4.—Preburn and third-year postburn stem heights (feet) of hardwood reproduction in the WestBlock unit on State Game Lands 29 in northwestern Pennsylvania. Asterisks denote postburn heights that are significantly different ($p < 0.01$) from their corresponding preburn heights.

Conversely, more than 90 percent of the black birches failed to sprout postfire. This high mortality for birch confirms the finding of Ward and Brose (2004), when they reported a 76-percent mortality rate for black birch after a hot spring fire in Connecticut. Black birch has small, shallow roots and virtually all stems had already fully leafed out when the fires in the current study occurred. Consequently, they were highly susceptible to fire at that time. The birch that did survive and sprout were confined to small areas that did not experience high fire intensity. However, those survivors were growing just as fast as most of the other species so they will be formidable competitors in parts of these burn units for years to come (Heggenstaller 2010).

Only about half the red maple sprouted postfire, which is consistent with the 45-percent mortality rate reported by Ward and Brose (2004) after one burn. Like black birch, red maple has a small, shallow root system. However, at the times of the burns, red maple stems were in various stages of leaf expansion. Some were still dormant or with swollen buds, but many had leaves that were 25 to 50 percent expanded and there were a few with nearly fully expanded leaves. This wide variety of leaf expansion coupled with variations in fire intensity probably accounts for the 50-percent mortality rate. Red maple height growth was substantially slower after the fires relative to the other species. This result can be attributed to the degree of leaf expansion, the subsequent weather (the summers following the fires were dry), and the abundance of pin cherry, a species known for capturing much of the soil nitrogen following a disturbance. Red maple will likely not become a dominant species in these stands as they mature over the coming decades (Heggenstaller 2010).

The black cherry, pin cherry, and serviceberry (the dominant species of the miscellaneous group) responded to the fires in a manner comparable to the oaks. Stem densities declined from 10 to 15 percent across both fires for these three species. Pin cherry, also known as fire cherry, can sprout from the roots in addition to the root collar. Therefore, even though the fire killed virtually all the stems, most were simply replaced by a root sucker. Additionally, pin cherry seed in the forest floor likely germinated and contributed new seedlings that reduced the overall density decline. Postburn height growth was rapid for pin cherry with most stems nearly regaining their preburn heights within 3 years.

The low density decline and relatively rapid height growth of black cherry and serviceberry were somewhat of a surprise as there is no literature on their responses to fire. The finding of a low mortality rate for both is good because black cherry is the premier timber species of northwestern Pennsylvania and both species provide soft mast to a wide variety of wildlife.

Preburn densities of black cherry differed widely between EastBlock and WestBlock (1,644 and 518 stems per acre) likely because WestBlock had nearly 50 percent more pin cherry than EastBlock. In full sunlight, pin cherry outcompetes black cherry, causing the latter to have lower stem densities and reduced height growth (Ristau and Horsley 1999).

Before the fires, Game Commission personnel expressed concerns about the fuel loadings and expected fire behavior. One concern was that the lack of leaf litter (~3 tons per acre) would make conducting the burn difficult, requiring frequent ignitions and causing a patchy burn. The other was that the heavy loading of large fuels (22 to 30 tons per acre) would cause extreme fire behavior and lead to spot fires outside of the control lines. Neither concern became a problem. Fire easily carried through both units so the paucity of leaf litter was not an obstacle to a complete burn. The large fuels did cause long flame lengths, upwards of 20 feet in some cases, but spotting was minimal due to light winds and good smoke dispersal. Recently regenerated oak stands can be burned easily, safely, and without incident by practicing sound principles of prescribed fire planning and implementation.

These burns were a management success. Before the burns, only about 5 percent, or 125 to 150 stems per acre, of the northern red oak seedlings could be expected to survive and become codominant by age 20 (Loftis 1990). Additional oak mortality during the ensuing decades would further reduce these numbers and eventually result in a mixed hardwood forest containing few oaks in the main canopy (Ward and Stephens 1994). The fires changed these dominance probabilities in favor of oak. The suppressed oak reproduction was freed from the larger competition, and the undesirable black birch and red maple regeneration was markedly reduced from preburn levels. As of 2011, the oaks are still of equal height with all other species except pin cherry, which is the tallest. Now Loftis' (1990) dominance probability model predicts more than 400 codominant oak saplings at age 20, and stand development beyond that point will culminate in an oak-dominated stand like the one harvested in the 1990s.

The abundance of pin cherry is a concern as this species can dominate a site during early stand development to the detriment or exclusion of most other species (Ristau and Horsley 1999). But crop tree management can be used to maintain oak in a competitive canopy position (Brose et al. 2008, Miller 2000, Miller et al. 2007).

Although these results are encouraging, post-harvest burning needs more research before it can be fully endorsed as a management technique. A long-term study at several locations comparing the post-harvest burning to the shelterwood-burn technique and clearcut/shelterwood prescriptions without fire would be beneficial in this regard. Furthermore, post-harvest burning has the same biological constraints as the shelterwood-burn technique in regards to the existence of sufficient numbers of oak seedlings <u>before</u> beginning the regeneration process and the same operational constraints of prescribed burning. However, based on the results reported in this paper, post-harvest burning appears to be a viable alternative to the shelterwood-burn technique when there is concern about fire damage and mortality to high-value overstory trees.

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## LITERATURE CITED

Berry, F.H.; Beaton, J.A. 1972. **Decay in oak in the central hardwood region.** Res. Pap. NE-242. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 11 p.

Brose, P.H. 2010. **Long-term effects of single prescribed fires on hardwood regeneration in oak shelterwood stands.** Forest Ecology and Management. 260: 1516-1524.

Brose, P.H.; Gottschalk, K.W.; Horsley, S.B.; Knopp, P.D.; Kochenderfer, J.N.; McGuinness, B.J.; Miller, G.W.; Ristau, T.E.; Stoleson, S.H.; Stout, S.L. 2008. **Prescribing regeneration treatments for mixed-oak forests in the mid-Atlantic region.** Gen. Tech. Rep. NRS-33. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 90 p.

Brose, P.H.; Schuler, T.M.; Ward, J.S. 2006. **Responses of oak and other hardwood regeneration to prescribed fire: what we know as of 2005.** In: Dickinson, M.B., ed. Fire in eastern oak forests: delivering science to land managers; 2005 November 15-17: Columbus, OH. Gen. Tech. Rep. NRS-P-1. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 123-135.

Brose, P.H.; Van Lear, D.H. 1998. **Responses of hardwood advance regeneration to seasonal prescribed fires in oak-dominated shelterwood stands.** Canadian Journal of Forest Research. 28: 331-339.

Brose, P.H.; Van Lear, D.H. 1999. **Effects of seasonal prescribed fires on residual overstory trees in oak-dominated shelterwood stands.** Southern Journal of Applied Forestry. 23(2): 88-93.

Brose, P.H.; Van Lear, D.H. 2004. **Survival of hardwood regeneration during prescribed fires: the importance of root development and root collar location.** In: Spetich, M.A., ed Proceedings, upland oak ecology symposium: history, current conditions, and sustainability; 2002 October 7-10; Fayetteville, AR. Gen. Tech. Rep. SRS-73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 123-127.

Brose, P.H.; Van Lear, D.H.; Cooper, R. 1999a. **Using shelterwood harvests and prescribed fire to regenerate oak stands on productive upland sites.** Forest Ecology and Management. 113: 125-141.

Brose, P.H.; Van Lear, D.H.; Keyser, P.K. 1999b. **A shelterwood-burn technique for regenerating oak stands on productive upland sites in the Piedmont region.** Southern Journal of Applied Forestry. 23: 158-163.

Brown, J.K. 1974. **Handbook for inventorying downed woody material.** Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Carvell, K.L.; Maxey, W.R. 1969. **Wildfire destroys!** West Virginia Agriculture and Forestry. 2(2): 4-5, 12.

Cerutti, J.R. 1985. **Survey of Forest and Warren Counties, Pennsylvania.** Washington, DC: U.S. Department of Agriculture, Soil Conservation Service. 148 p. + maps.

Dickinson, M.B., ed. 2006. **Proceedings, Fire in eastern oak forests: delivering science to land managers.** Gen. Tech. Rep. NRS-P-1. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 303 p.

Fosberg, M.A. 1970. **Drying rates of wood below fiber saturation.** Forest Science. 16: 57-63.

Franklin, S.B.; Robertson, P.A.; Fralish, J.S. 2003. **Prescribed burning effects on upland *Quercus* forest structure and function.** Forest Ecology and Management. 184: 315-335.

Heggenstaller, D. 2010. **Reconstruction of the competitive dynamics of mixed oak forests.** University Park, PA: Pennsylvania State University. 107 p. M.S. thesis.

Hutchinson, T.F. , ed. 2009. **Proceedings, 3rd fire in the eastern oak forests conference.** Gen. Tech. Rep. NRS-P-46. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 154 p.

Hutchinson, T.F.; Sutherland, E.K.; Yaussy, D.A. 2005. **Effects of repeated prescribed fires on the structure, composition, and regeneration of mixed-oak forests in Ohio.** Forest Ecology and Management. 218: 210-228.

Loftis, D.L. 1990. **Predicting post-harvest performance of advance red oak reproduction in the Southern Appalachians.** Forest Science. 36(4): 908-916.

Loomis, R.M. 1973. **Estimating fire-caused mortality and injury in oak-hickory forests.** Res. Pap. NC-104. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 6 p.

Marquis, D.A. 1975. **The Allegheny hardwood forests of Pennsylvania.** Gen. Tech. Rep. NE-15. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 32 p.

McGee, C.E. 1979. **Fire and other factors related to oak regeneration.** In: Fischer, B.A.; Holt, H.A. eds. Proceedings, John S. Wright forestry conference: regenerating oaks in upland hardwood forests; 1979 February 22-23; West Lafayette, IN. West Lafayette, IN: Purdue University: 75-81.

Miller, G.W. 2000. **Effect of crown growing space on the development of young hardwood crop trees.** Northern Journal of Applied Forestry. 17(1): 25-35.

Miller, G.W.; Stringer, J.W.; Mercker, D.C. 2007. **Technical guide to crop tree release in hardwood forests.** Publication SREF-FM-011. Knoxville, TN: University of Tennessee Press. 24 p.

Paulsell, L.K. 1957. **Effects of burning on Ozark hardwood timberlands.** Agric. Expt. Stat. Res. Bull. 640. Columbia, MO: University of Missouri. 24 p.

Regelbrugge, J.C.; Smith, D.W. 1994. **Postfire tree mortality in relation to wildfire severity in mixed oak forests in the Blue Ridge of Virginia.** Southern Journal of Applied Forestry. 11(3): 90-97.

Ristau, T.E.; Horsley, S.B. 1999. **Pin cherry effects on Allegheny hardwood stand development.** Canadian Journal of Forest Research. 29: 73-84.

Schultz, C.H., ed. 1999. **The geology of Pennsylvania.** Harrisburg, PA: Department of Conservation of Natural Resources, Geological Survey. 888 p.

Ward, J.S.; Brose, P.H. 2004. **Mortality, survival, and growth of individual stems after prescribed burning in recent hardwood clearcuts.** In: Yaussy, D.A.; Hix, D.M.; Long, R.P.; Goebel, P.C, eds. Proceedings, 14th Central Hardwood Forest conference; 2004 March 16-19; Wooster, OH. Gen. Tech. Rep. NE-316. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station: 193-199.

Ward, J.S.; Stephens, G.R. 1989. **Long-term effects of a 1932 surface fire on stand structure in a Connecticut mixed hardwood forest.** In: Rink, G.; Budelsky, C.A. eds. Proceedings, 7th Central Hardwoods Forest conference; 1989 March 5-8; Carbondale, IL. Gen. Tech. Rep. NC-274. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 267-273.

Ward, J.S.; Stephens, G.R. 1994. **Crown class transition rates of maturing northern red oak (*Quercus rubra* L.).** Forest Science. 40(2): 221-237.

Yaussy, D.A., comp. 2000. **Proceedings, Workshop on fire, people, and the central hardwoods landscape.** 2000 March 12-14; Richmond, KY. Gen. Tech. Rep. NE-274. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 129 p.

Yaussy, D.A.; Waldrop, T.A. 2010. **Delayed mortality of eastern hardwoods after prescribed fire.** In: Stanturf, J.A., ed. Proceedings, 14th biennial southern silviculture research conference. 2007 February 26-28; Athens, GA. Gen. Tech. Rep. SRS-121. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 609-612.

Zar, J.H. 1999. **Biostatistical analysis.** 4th ed. Upper Saddle River, NJ: Prentice-Hall Publishing. 628 p.