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Development of Prescribed Fire as a Silvicultural Tool for the Upland Oak Forests of the Eastern United States

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In the past 40 years, the perception of periodic fire in upland oak (*Quercus* spp.) forests in the eastern United States has changed dramatically. Once thought of as a wholly destructive force, periodic fire is now considered an important disturbance whose absence is a major contributing factor to oak regeneration problems. This change in attitude and the concurrent development of prescribed fire as an accepted oak regeneration tool are due to several research—management partnerships. Starting in the 1970s, cooperative research between the USDA Forest Service and various land management agencies examined fire effects in mature, uncut oak forests. These failed to regenerate oak but identified some key limitations leading to the failures. Subsequent research in the 1990s shifted to oak shelterwoods and ultimately identified hot spring fires as a treatment that would regenerate oak. Since then, other partnerships have expanded fire–oak research to include woodland restoration burning. This paper reviews the history of cooperative fire–oak research over the past 40 years and the key role partnerships have played in the development of current prescribed fire practices in upland oak forests.

Keywords: fire effects, hardwoods, *Quercus* spp., shelterwood, woodland restoration

Throughout the eastern United States, land managers increasingly recognize periodic fire as an important disturbance in upland oak (*Quercus* spp.) forests and are using prescribed fire to manage these ecosystems (Yaussy 2000, Dickinson 2006, Hutchinson 2009, Dey et al. 2012). These trends are evident in that the eastern national forests with significant areas of upland oak ecosystems have prescribed fire in their management plans and the number of burned acres in these forests has steadily risen over the past decade (National Interagency Fire Center 2013). Similar patterns of acceptance and use can also be found in land conservation organizations such as The Nature Conservancy, many state forestry and wildlife agencies, and some private land ownerships. This new acceptance and use of fire in upland oak forests of the eastern United States is in stark contrast to the long-standing view of fire in hardwoods.

In the late 1800s and early 1900s, fire was considered a scourge of forests throughout the eastern United States (Pyne 1982, DeCoster 1995). Fires were severe and widespread, causing damage to standing timber, degradation of soil productivity, destruction of human property, and loss of human life. The negative impacts of forest fires coupled with other abuses wrought by natural resource exploitation led to the conservation movement that spawned the USDA Forest Service and other federal/state land management agencies. The Weeks Act in 1911 authorized the purchase of degraded lands in the eastern United States to protect watersheds, restore forests, and form national forests. Many eastern states followed suit by purchasing abandoned tax-delinquent lands, thereby forming a network of state forests and other public lands. The foresters hired by these fledgling agencies to manage these lands were tasked with resource conservation and protection; chief among these responsibilities was controlling forest fires. Success came relatively quickly. Through a comprehensive approach of fire control laws, prevention programs, early detection networks, and interagency cooperative suppression, the occurrence, severity, and size of wildfires in eastern hardwood forests decreased substantially within a few decades (Pyne 1982, Brose et al. 2001). For example, in Pennsylvania the number of fires and

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acres burned decreased by more than 90% from 1910 to 1940 (Abrams and Nowacki 1992, DeCoster 1995).

By the 1950s, many parts of the eastern United States were 2–3 decades into the fire control era (Pyne 1982). At that same time, foresters began noticing that oak forests were not regenerating to the same species mix as had previously existed (Clark 1993). They complained of there being "too much" yellow-poplar (*Liriodendron tulipifera*) following harvests of oak stands or commented on the increasing abundance of red and sugar maple (*Acer rubrum* and *A. saccharum*) reproduction in maturing oak stands (Clark 1993). The question starting to surface was whether fire exclusion and oak regeneration difficulties were simply a correlative association or whether there might be a causal relationship, i.e., the fire–oak hypothesis (Abrams 1992, Brose et al. 2001), that could be developed into a silvicultural tool.

Hypothesis testing is the realm of scientific research, but the development of guidelines extends into management and that leads to partnerships. Forestry research is ideally suited for cooperative partnerships. Scientists need an ownership-stable land base on which to conduct experiments that may endure many years. Furthermore, scientists often need the personnel and resources that managers can provide to install treatments on large acreages. Managers need to understand how forests regenerate and develop through time, given the myriad of biotic and abiotic components and environmental interactions so that their management decisions are based in sound science and are likely to produce the desired outcome. The evolution of fire research in eastern oak forests illustrates how managers and researchers have worked together to move the science from theory to practice. The purpose of this paper is to chronicle the history of fire research in eastern hardwoods, highlighting some of the key research—management partnerships that were critical to the development of prescribed fire as a silvicultural tool for upland oak forests.

Methods

From 2010 to 2012, scientists from the Northern and Southern Research Stations conducted a meta-analysis and synthesis of the existing fire–oak literature of eastern North America (Brose et al. 2013, 2014). That project amassed 139 papers on fire history or fire effects on hardwood reproduction produced since 1950. These papers came from a wide variety of sources, including dissertations and theses, case studies in conference proceedings, and published manuscripts in refereed scientific journals. Criteria for inclusion were: The paper had to report quantitative data and the study had to have occurred in the hardwood biome of eastern North America (east of the 100th meridian). These criteria excluded the general fire ecology papers, literature reviews, published abstracts, and studies conducted in the pine forests of the southern United States and the boreal forests of eastern Canada.

For this paper, that synthesis was expanded to include literature reviews, papers published before 1950, and those reporting fire effects on other forest attributes such as herbaceous plants, overstory trees, soils, and wildlife. Criteria for accepting these other publications remained the same and this revised search resulted in an additional 45 papers. The resulting set of 184 papers was organized by decade (oldest to most recent) and examined for partnerships, commonalities in research objectives and design, major findings, and trends in all of these through time.

Results and Discussion

Early Fire–Oak Research

From the beginning of forestry research in the United States through the 1950s, fire research in eastern oak forests was limited and focused. Only 20 publications, primarily in the *Journal of Forestry*, met the criteria for inclusion (Figure 1). Nearly all of these addressed wildfire damage to overstory trees and the accompanying loss to wood value and volume (Lachmund 1923, McCarthy 1928, Nelson et al. 1933, Stickel 1935). An exception to this trend was Korstian (1927) who reported fire effects on acorn viability and showed that red oak acorns were more resistant to fire than white oak acorns. Partnerships were minimal. All that researchers needed for most studies was access to recently burned oak stands and these were still plentiful despite the gains made in wildfire prevention and control.

The initial research forays into fire effects on hardwood reproduction in oak forests took place in Missouri and Tennessee when long-term studies started in 1949 and 1962, respectively (Figure 1). In the former, researchers from the University of Missouri teamed up with Missouri Department of Forestry to implement a study of annual and periodic fire effects on upland oak forests (Paulsell 1957, Huddle and Pallardy 1996). In the latter, the University of Tennessee partnered with the Tennessee Agricultural Experiment Station to conduct a study of the effects of annual and periodic fires on oak barrens (Thor and Nichols 1973, DeSelm et al. 1991, Stratton 2007). In both of these, the state agencies provided the land and the labor and resources to implement the treatments while the university personnel designed the studies, collected the data, and analyzed the results. Like the previous fire studies, both studies reported on fire effects to overstory trees. However, researchers also collected data on hardwood reproduction, the understory plant community, and soil properties. Since the inception of these studies, 5 to more than 20 prescribed burns have been conducted, depending on the treatment. Results from both studies show a reduction in stem density and basal area, pri-

Management and Policy Implications

A chronological review of the scientific literature pertaining to fire–oak research shows how the science has developed through time and has produced several management guidelines for the upland oak forests in the eastern United States. Prescribed fire can be used in mature stands to begin the regeneration process by reducing dense understory shade and preparing a seedbed for new oak seedlings. However, care must be exercised so as to not destroy a recent acorn crop or kill small oak seedlings. Prescribed fire can also be used near the end of the regeneration process to release oak reproduction that is being outcompeted by taller, faster-growing mesophytic hardwood reproduction. This is best done during or after a shelterwood sequence using a growing-season fire. Finally, fire can be used long term to recreate open oak woodlands similar to those that used to exist in many parts of the eastern United States. In all scenarios, foresters must also be mindful that prescribed burning stimulates germination of the seed bank, encourages establishment of exotic and native plant species, and attracts deer. Therefore, landowners and managers of upland oak ecosystems will need to carefully use prescribed fire so as to accentuate its benefits while avoiding its negative effects.

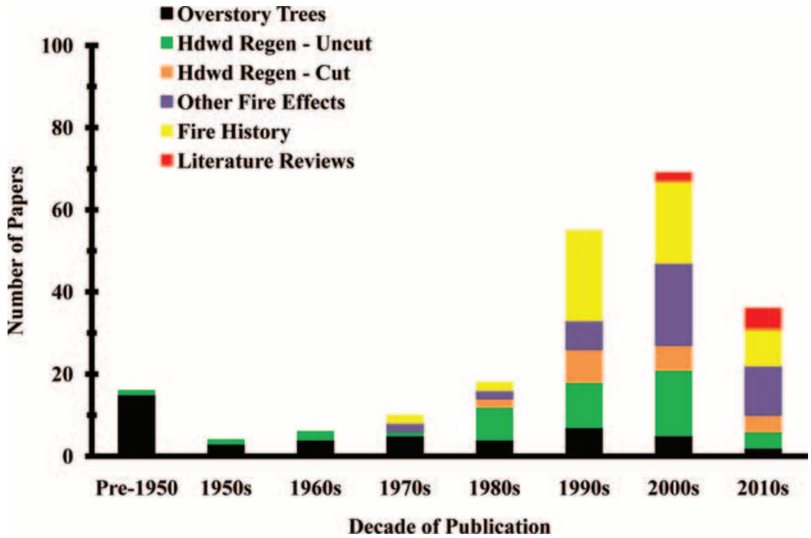

Figure 1. The distribution of fire–oak publications through time by their principal subject matter. Cut refers to oak stands that have been harvested or are undergoing a shelterwood sequence while uncut refers to mature, undisturbed stands. Fire history includes dendrochronology and paleoecology studies. Note how the subject matter expands through time and the number of publications increases starting in the 1990s.

marily in the sapling size class (< 5.0 in. dbh); widespread scarring of larger trees; increases in presence and abundance of forbs, grasses, and hardwood sprouts; and insignificant changes in soil *p*H and water-holding capacity. Unfortunately, both studies took place on low productivity sites (oak site index$_{50}$ ≈ 60 ft) where oak regeneration difficulties are minimal or nonexistent so applicability of these results to higher quality sites and their attendant oak regeneration challenges is ill advised.

Initial Fire–Oak Regeneration Research

By the 1970s and 1980s, the stage was set for research to begin into the role of fire in the oak regeneration process. By that time, the oak regeneration problem was obvious and widespread (Holt and Fischer 1979, Loftis and McGee 1993). Furthermore, emerging research indicated that many American Indian tribes and early European settlers used broadcast burning for various reasons and oaks had adaptations to resist fire and exploit the postfire environment, suggesting a long-term relationship between periodic fires and oak dominance (Komarek 1974, Pyne 1982). The number of fire–oak studies increased relative to previous decades and the emphasis broadened from overstory damage to regeneration response (Figure 1). Important prescribed fire studies conducted during these decades examined single fires in mature, undisturbed stands on medium-quality sites (oak site index$_{50}$ ranged from 65 to 75 ft) where oak regeneration difficulties could be expected to occur (Johnson 1974, Teuke and Van Lear 1982, Huntley and McGee 1983, Wendel and Smith 1986). Generally, these were case studies and some were burned/unburned comparisons. Of these, the Johnson (1974) and Wendel and Smith (1986) studies are noteworthy for their detail and findings.

The Johnson (1974) study took place in southwestern Wisconsin and involved the USDA Forest Service, North Central Forest Experiment Station and the Wisconsin Department of Natural Resources. The former provided the scientific expertise to conduct and analyze the study while the latter provided the study site and the technical expertise to implement the treatment. The study site was an 8-acre stand dominated by northern red oak (*Quercus rubra*). The stand was moderately thinned from below (basal area reduced from 120 to 80 square feet per acre) in fall 1969. At the same time, a large acorn crop occurred, resulting in the establishment of 7,000 new red oak seedlings per acre in spring 1970. A year later, the stand was divided and one section was burned with a low-intensity prescribed fire while the other served as an unburned control. Data collected that fall indicated that the burned seedlings had a 40% survival rate while the control seedlings had a 90% survival rate. The fire had killed approximately half of the northern red oak seedlings. The Wendel and Smith (1986) study occurred in east-central West Virginia and was a cooperative effort by the USDA Forest Service, Northeastern Forest Experiment Station, the Washington National Forest, and the West Virginia Department of Natural Resources with the former providing the scientific expertise and the latter two providing the land base and conducting the prescribed fire. Like the Johnson (1974) study, this stand was thinned from below to a basal area of 90 square feet per acre in spring 1979 and burned a year later. Prior to the fire, desirable hardwood reproduction was 3,814 stems per acre and 5 years later the density was 3,500 stems per acre. However, within these numbers the amount of oak dropped by nearly 80% while the amount of red maple and black locust (*Robinia psuedoacacia*) increased by 17 and 120%, respectively. Clearly, the fire had set back the oak regeneration process.

In theory fire favors oak reproduction, yet these renowned research foresters did more harm than good when they tried to promote oak regeneration through prescribed burning. The main problem probably was that the oak seedlings and sprouts were small and had been growing in dense understory shade for most of their lives. Consequently, they had small root systems with little root carbohydrate reserves and simply could not sprout postfire (Brose and Van Lear 2004, Brose 2011). Second, the prescribed fires were conducted in mid- to late April so the small seedlings may have already begun utilizing their root carbohydrate reserves. Finally, neither study controlled access of white-tail deer (*Odocoileus virginianus*) to the sites so excessive deer browsing may have subsequently eliminated many oaks that sprouted postfire. Regardless of why these studies failed to promote oak reproduction, it was evident that prescribed burning could impede the oak regeneration process under some circumstances.

The 1990s: A Decade of Change

The 1990s saw fire research transform from being a minor component of the overall oak research agenda to an important part of it. Fire–oak studies became much more prevalent than they had been, especially in subject matter such as different approaches to the oak regeneration problem, fire's effects on other attributes of oak ecosystems, and fire history (Figure 1). This transformation occurred due to several reasons. First, the fire–oak association via past cultural burning practices by American Indians and European settlers was becoming more evident and accepted (Abrams 1992, Denevan 1992). Second, forest managers and researchers that held the traditional perspective that fire was a negative disturbance in oak forests began retiring and their replacements did not hold to such a strict view. Third, funding for fire–oak research became more available through programs like the Joint Fire Science Program and the National Fire Plan. Finally, researchers started having success in their fire–oak regeneration studies.

The first change in fire–oak research was to move from single fire studies to investigating multiple burns. The rationale was simple; oak stands had lacked fire for decades so it was unreasonable to expect a single burn to substantially change the dynamics of the regeneration pool. Like the single-burn studies, these generally took place in mature, undisturbed oak stands. However, unlike the single-burn studies, these produced a wide variety of results; sometimes oak regeneration was favored (Barnes and Van Lear 1998), sometimes it was hindered (Arthur et al. 1998), and sometimes there was no demonstrable effect (Merritt and Pope 1991, McGee et al. 1995). These vastly different outcomes occurred because the studies differed in initial starting conditions, fire intensity, season-of-burn, and time between the two burns.

Of the prescribed fire studies of this time, the Barnes and Van Lear (1998) study stood apart from the others because it was the first to specifically investigate the ecological differences between dormant- and growing-season burns in a controlled replicated manner. Overall, they found that the understory composition shifted more toward oak domination and midstory density decreased more substantially after growing-season burns than after dormant-season fires. However, the benefits to oak reproduction from either type of prescribed fire accrued slowly, especially following dormant-season burns.

The next change involved studying fire effects in regenerating oak stands (Figure 1). That started in the mid-1990s when the Virginia Department of Game and Inland Fisheries (VDGIF) burned two oak shelterwoods in central Virginia during the summer (Keyser et al. 1996). These shelterwoods differed profoundly in at least three aspects from the mature stands typically used in earlier research. First, overstory density was markedly reduced; residual basal areas were only half of what they had been preharvest. Second, the harvested trees included nearly all the midstory stems and many of the dominant nonoaks. Finally, 4 years had passed between the harvests and the summer fires. They found that oak reproduction had a significantly higher survival rate than that of red maple and yellow-poplar. For the first time, foresters had used fire to favor oak over competing mesophytic species. This result spurred a partnership between VDGIF and Clemson University to more fully investigate the responses of oak shelterwoods to seasonal prescribed fires.

In the follow-up study, the VDGIF provided three oak shelterwoods in central VA and conducted the prescribed fires while Clemson University personnel designed the study, collected and analyzed the data, and reported the results (Brose and Van Lear 1998, Brose et al. 1999a). Fire seasonality was expanded to include spring and winter prescribed burns. Furthermore, fire intensity was classified into four categories (low, medium-low, medium-high, and high) based on measured fire behavior, stem charring, and fuel consumption. This cooperative study confirmed that oak reproduction in shelterwoods is less adversely impacted by summer fires than the reproduction of red maple and yellow-poplar. Additionally, it found spring burning to be similarly beneficial to oaks, but winter fires conferred less of an advantage to oak. Perhaps most notably, this study showed the importance of fire intensity within season-of-burn. Low-intensity fires in any season had little impact on the composition of the regeneration pool, but as fire intensity increased to medium-high and high, oak was preferentially favored over its competitors, especially in spring burns. A follow-up study showed that the fire effects on the reproduction last at least a decade (Brose 2010).

This approach increased the relative abundance of oak reproduction by what, in retrospect, appears to have been an ideal convergence of five factors. First, there was an abundance of oak reproduction before the shelterwood harvest. Second, the shelterwood harvest was heavy, removing approximately 50% of the basal area from below. Third, there was a 4-year interval between the cut and the burns that allowed the oak seedlings and sprouts to develop large root systems. Fourth, fire seasonality and fire intensity interacted resulting in differential mortality rates between oak and the mesophytic hardwood species, especially for the medium-high and high intensity spring burns. Finally, there were sufficient food sources for the local deer herd so they did not constantly browse the new oak sprouts. These findings led to the development of the shelterwood-burn technique (Brose et al. 1999b) that has been the basis for much of the subsequent fire–oak research and oak forest management on public lands.

Also in the 1990s, forest fire history research became common (Figure 1). This aspect of fire–oak research involved paleoecology studies of charcoal and pollen deposits in bog sediments and forest soils (Patterson 2006, Hart and Buchanan 2012) and dendrochronology studies utilizing fire-scarred trees, snags, and stumps (Guyette et al. 2006, Hart and Buchanan 2012). The paleoecology studies showed a multimillennial relationship between fire occurrence and oak dominance at a broad scale while the dendrochronology studies provided detailed fire histories spanning 100–500 years for specific sites. Collectively, these fire history studies indicate that fires have occurred throughout the eastern hardwood biome for millennia, there is a climatic gradient (more fires in the South than in the North), fires increased in frequency during European settlement, and fires have nearly vanished since the advent of fire control policies and practices (Brose et al. 2014). All of these points are important for justifying, planning, and implementing prescribed fire programs in oak forests.

Recent Developments in Fire–Oak Research

Beginning in the 1990s, but appearing in the literature in the 2000s, was a new generation of cooperative fire–oak studies conducted in mature stands (Figure 1). These studies grew out of existing projects (DeSelm et al. 1991, Huddle and Pallardy 1996) or began from scratch (Dey and Hartmann 2005, Hutchinson et al. 2005, Blankenship and Arthur 2006, Waldrop et al. 2008). These studies have several characteristics in common; they all: (1) considered periodic fire to be a missing ecological process from eastern oak forests; (2) had as a goal the recreation of open oak woodlands (intact main canopy with no/little subcanopy) similar to those described by many early Europeans; (3) used multiple fires conducted over at least a decade; (4) usually had treatment areas of 40–50 acres; and (5) sought to establish and maintain an oak-dominated regeneration pool for eventual replacement of the canopy trees when they die from natural causes.

Of these various long-term studies, the Ecosystem Management study in southern Ohio is quite instructive due to its size, scope, longevity, and attention to detail (Sutherland and Hutchinson 2003, Hutchinson et al. 2005, 2012). It began in 1995 as a partnership between the USDA Forest Service, Northern Research Station, Wayne National Forest, and the Ohio Division of Forestry. Like the previously described partnerships, the two land management agencies provided the stands for the study and implemented the treatments while the research station provided the scientific expertise. Four sites, each approximately 200 acres, were divided into three treatment units of 50–75 acres each. Treatments were annual burn, periodic burn, and an unburned control. The annual burns were carried out from 1996 to 1999 while the periodic burns were between 1996 and 2005. All fires were conducted in the early spring (dormant season). Like other fire studies in mature stands, the initial burns did not promote oak reproduction but did remove many of the midstory trees and created an open understory. However, cessation of the annual and periodic fires coupled with acorn crops led to the establishment of oak seedling cohorts. Subsequent formation of large canopy gaps has allowed some of these oak seedlings to grow into saplings that are positioned to eventually recruit into the main canopy (Hutchinson et al. 2012). Clearly, oak woodland restoration via prescribed burning is a long process and the fire regime must include formation of canopy gaps and fire-free periods of sufficient duration for the oak reproduction to be able to recruit into those gaps.

In some of the long-term oak restoration research projects, scientists have broadened their investigations to include direct and indirect fire effects on other forest components such as soil properties and wildlife (Figure 1). Because of the complexities of studying fire effects on a diverse array of subjects, numerous partnerships have been developed among researchers and land managers. This is best exemplified by the oak forest replicates of the Fire and Fire Surrogates Project in North Carolina and Ohio. At those locations, the North Carolina Wildlife Resources Commission and the Ohio Division of Forestry each provided three 200-acre stands and implemented prescribed fire and thinning treatments. Researchers from Clemson University, North Carolina State University, Ohio University, and Ohio State University worked with the USDA Forest Service scientists to examine the prescribed fire and thinning effects on herbaceous plants, neotropical songbirds, reptiles, and soil properties (Boerner 2000, Hutchinson 2006, Matthews et al. 2010, Greenberg et al. 2012). In an era of limited budgets, personnel, and resources, these types of interdisciplinary research-management partnerships are absolutely essential to address complex ecosystem management questions.

Figure 2. A seedbed preparation burn being conducted in northern Pennsylvania. The purpose of this type of prescribed fire is to remove the undesirable woody understory stems and reduce the litter layer so a subsequent acorn crop will result in the establishment of a cohort of oak seedlings. (Photo by Patrick Brose.)

A final development in fire–oak research is the appearance of reviews and syntheses of the pertinent literature (Figure 1). These publications explain differences among studies, highlight trends that are not readily apparent by examining the papers individually, and point out knowledge gaps for future research (Brose et al. 2006, Dey and Fan 2009, Arthur et al. 2012, Brose et al. 2013, 2014). The appearance of these review papers also signify that the fire–oak research has matured to the point of producing management guidelines for practitioners.

Fire-Oak Regeneration Guidelines

Landowners and managers of upland oak ecosystems in the eastern United States increasingly use prescribed fire to help meet a myriad of goals ranging from hazardous fuel reduction to improving wildlife habitat to regenerating forests to restoring overstocked woodlands. The fire–oak research studies over the past 40 years have recently been reviewed in detail (Brose et al. 2008, 2013, 2014) and can be summarized into the following oak regeneration guidelines.

Prescribed fire can be used in mature oak stands with little or no oak reproduction to help start the regeneration process. This is known as seedbed preparation burning (Figure 2). The goal of this type of prescribed fire is to create a suitable forest floor environment so that a future acorn crop results in a cohort of new oak seedlings. This goal is accomplished by the fire reducing the density of nonoak advanced regeneration, saplings, and shrubs so understory light levels are approximately 10% of full sunlight and decreasing the thickness of the O horizon to less than 1 in. Other benefits of this practice may include lessening the future influence of the seedbank (pioneer species germinate and then die in the shade), decreasing the populations of acorn insect pests, and xerifying the upper layers of the forest floor so that it is a less hospitable seedbed for mesophytic species (Wright 1986, Barnes and Van Lear 1998, Schuler et al. 2010).

The beneficial effects of seedbed preparation burns are transient so multiple fires done over a decade or more are often necessary to create and maintain understory conditions favorable for acorn germination and oak seedling establishment. Because of the need for multiple fires over several years, season of burn is not critical although growing-season fires will produce the desired open understory conditions faster than dormant-season fires. Similarly, fire intensity is not critical although hotter fires will remove the mesophytic understory stems faster than cooler fires. Generally in mature undisturbed oak stands, fire intensity is constrained by the paucity of fine fuels (litter and woody debris < 3 in. diameter) and repeat burning inhibits reaccumulation of these fuels. Once an oak cohort is established, fire is withheld so that the seedlings can grow to a suitable competitive size for that site and then the overstory is removed via a shelterwood sequence or final harvest. Crop tree management at crown closure will likely be a necessary treatment (Miller et al. 2007).

Figure 3. An oak release burn being conducted in northern Pennsylvania. Prescribed fires like this one are done to free existing oak seedlings and saplings from competing mesophytic hardwood reproduction. Note the degree of leaf expansion in the understory. (Photo by Patrick Brose.)

Prescribed fire can be used in oak shelterwoods to free existing oak reproduction from competing and interfering mesophytic species (Figure 3). This is called release burning and has as its goal the creation of a regeneration pool dominated by tall, vigorous oak reproduction. Minimum regeneration conditions for this prescribed burn are: (1) abundant oak reproduction (600 per acre) that are 2 ft tall (or have root collars 0.50 in diameter) and are well distributed throughout the stand (50% stocking of inventory plots) and (2) mesophytic competitors that are more numerous and taller than the oaks. These conditions generally occur 4–7 years after the shelterwood harvest, depending on site quality and the degree of cutting. Furthermore, as site quality increases, oak reproduction must be more numerous and taller. The optimal fire seasonality and intensity combination for releasing burning is mid to late spring with flame lengths of 2–4 ft although other seasons and cooler fires can also achieve acceptable results, but additional burning may be necessary. Once vigorous oaks dominate the regeneration pool, fire is withheld and the remaining overstory is harvested and the new stand is left to grow until crop tree management can be instituted at crown closure (Miller et al. 2007).

Release burning and seedbed preparation prescriptions can be adapted to restore open oak woodlands (Figure 4). In oak woodland restoration, the use of other silvicultural practices is important to supplement and enhance the fire effects. If logging is possible, harvest overstory trees so that the residual stocking is between 40 and 70%. If harvesting is not feasible, use stem-injection herbicides to reach the same level of overstory reduction. If herbicides and timber harvesting are not feasible, oak woodland restoration is still possible, but it is a slower, more protracted undertaking. Reducing overstory density to 40–70% stocking can be achieved via girdling of trees or by piling woody debris at their bases so the subsequent fires burn hotter than usual and kill them. Either approach is onerous but essential to restoring the open woodland conditions because burning, by itself, is unlikely to ever cause enough overstory damage and mortality given the weather conditions under which most eastern prescribed fires are conducted. After the structural restoration is complete, fire is reintroduced to stimulate forbs and grasses that are integral components of open oak woodlands. Generally, growing-season fire is preferred over a dormant-season burn because the former has more positive impact on the flowering of herbaceous plants and provides more control over woody species. The key differences to remember between restoration burning and release and seedbed preparation burning are that the overstory is never completely removed and fire reoccurs periodically in the former while in the latter two the overstory is harvested and burning ceases after the regeneration objectives are met.

When using prescribed fire to regenerate or restore oak ecosystems, foresters need to be mindful of several caveats. First, site quality matters. This affects competitive relationships between oak and the mesophytic hardwood species. At this time, prescribed fire should be limited to low- and medium-quality sites (oak site index$_{50}$ <75 ft). Second, prescribed fire will kill recently fallen acorns as well as small oak seedlings (less than 6 in. tall) so do not burn if these are essential to move forward in the oak regeneration process. Third, prescribed fire can exacerbate some invasive plant species problems and worsen deer browsing problems. Finally, prescribed fire can damage valuable crop trees, especially if there is a fuel accumulation at their bases.

These new prescribed fire uses and the negative caveats have been incorporated into management tools and forest policy. For example, the SILVAH decision-support system (Brose et al. 2008) now recommends seedbed preparation burning for mature oak stands with no or few oak seedlings on the ground to prepare for an eventual acorn crop and prescribes release burning in oak shelterwoods where existing oak reproduction is being outcompeted by mesophytic hardwood reproduction. Conversely, prescribed fire is not recommended for oak stands that have an adequate density of small oak seed-

Figure 4. Woodland restoration burning is done in eastern oak forests to re-create the open understory conditions frequently described by early European explorers and settlers and promote the herbaceous plant community. The photos show two oak woodlands in eastern Pennsylvania that are undergoing the restoration process (top) or have been restored (bottom). (Photos by Patrick Brose.)

lings to begin the regeneration process or in stands with a deer problem unless other practices such as fencing or increased hunting are also implemented. In terms of forest policy, many eastern states that previously lacked prescribed fire councils now have them. Similarly, prescribed fire consortiums have formed in the Appalachian Mountains, Midwest, and Great Lakes regions. These consortiums and councils have used this new fire–oak information to lobby for new fire laws such as Pennsylvania's Prescribed Burning Act of 2009 as well as promote prescribed fire in oak ecosystems via public education and training of natural resource personnel.

Future Fire-Oak Research

Even though a solid understanding of fire's role in the oak regeneration process now exists, the reviews and syntheses show several intriguing avenues for future research that will require partnerships of various types (Arthur et al. 2012, Brose et al. 2013). For example, what is the long-term success of prescribed fire as an oak regeneration tool? Studies documenting the decadal development of oak forests postfire are quite limited (Brown 1960, Ward and Stephens 1989) so it is not clear if the promising results of many short-term studies will persist. What is the relationship between fire characteristics, specifically heat per unit area, and the survival of seedlings of many hardwood species? Postharvest burning (Ward and Brose 2004, Brose 2013) offers a way to avoid damaging the boles of valuable crop trees when burning shelterwoods, yet this approach has received scant research attention. Investigations into fire effects on wildlife populations, wildlife habitat, and other attributes of forests will continue and will likely be a major area of study because of the ecosystem management approach of the public land management agencies. Similarly, methods such as broadcast herbicide spraying that can potentially serve as surrogates to prescribed fire will be studied due to the nonforestry factors (budget/resource constraints, liability issues, smoke management) that limit the amount of burning that is possible. In all of these future research endeavors as well as most others, partnerships between research and management will be essential to move the fire–oak science forward to serve practicing resource managers, forest landowners, and the general public.

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