MAKING SENSE OUT OF CONFUSION: A REVIEW OF FIRE-OAK PAPERS PUBLISHED IN THE PAST 50 YEARS

Patrick H. Brose and Thomas A. Waldrop[1]

Abstract—The existing fire-oak literature is contradictory on whether fire helps or hinders the oak regeneration process. This confusion occurs because the fire-oak studies have been conducted under a wide variety of conditions. In this paper, we review the fire-oak literature by stand age class, season of burn, and number of burns to identify commonalities and trends. Overall, prescribed fire reduces the density of small diameter stems in the midstory, preferentially selects for oak reproduction and against mesophytic hardwood reproduction, equalizes the height growth rates between these two species groups, and promotes the establishment of new oak seedlings. Generally, prescribed burning provides the most benefit to oak reproduction when the fires occur during the growing season and several years after a substantial reduction in overstory density. Single fires conducted in closed-canopy stands have little impact in the short term, but multiple burns eventually do benefit oaks in the long term, especially when followed by a canopy disturbance.

INTRODUCTION

Throughout the Eastern United States, mixed-oak (*Quercus* spp.) forests on upland sites are highly valued for many ecological and economic reasons. Generally, these upland forests consist of one or more oak species [black (*Q. velutina* Lam.), chestnut (*Q. montana* Willd.), northern red (*Q. rubra* L.), scarlet (*Q. coccinea* Muenchh.), and white (*Q .alba* L.)] dominating the canopy with a mix of other hardwood species in the midstory and understory strata. Despite widespread abundance and dominance of mixed-oak forests, regenerating them is a chronic challenge for land managers throughout eastern North America, and they are slowly being replaced by mesophytic hardwoods such as black birch (*Betula lenta* L.), black cherry (*Prunus serotina* Ehrh.), red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marsh.) and yellow-poplar (*Liriodendron tulipifera* L.) (Abrams and Downs 1990, Aldrich and others 2005, Healy and others 1997, Schuler and Gillespie 2000, Woodall and others 2008). Many factors contribute to this oak regeneration problem including loss of seed sources; destruction of acorns and seedlings by insects, disease, weather, and wildlife; dense understory shade; competing vegetation; and lack of periodic fire (Crow 1988, Johnson and others 2009, Loftis and McGee 1993). The implication of the lack of periodic fire as a cause of the oak regeneration problem arises from the fact that many of these oak forests exist in part due to past fires. This relationship has led to the creation of the fire-oak hypothesis (Abrams 1992, Brose and others 2001, Lorimer 1993, Nowacki and Abrams 2008).

The fire-oak hypothesis consists of four parts: (1) periodic fire has been an integral disturbance in the mixed-oak forests of eastern North America for millennia; (2) oaks have several physical and physiological characteristics that allow them to survive at higher rates than their competitors in a periodic fire regime; (3) the lack of fire in the latter 20th century is a major reason for the chronic, widespread oak regeneration problem; and (4) reintroducing fire via prescribed burning will promote oak reproduction. The scientific literature supports the first three parts to varying degrees. For example, paleo-ecological studies and historical documents indicate that American Indian tribes used fire for numerous reasons (Day 1953, Patterson 2006, Ruffner 2006, Wilkins and others 1991). Many studies report the growth strategy and physiological differences between oaks and mesophytic hardwood species (Gottschalk 1985, 1987, 1994; Kolb and others 1990) and the concomitant decline of fire and increase in mesophytic hardwoods during the early 1900s is evident from fire history research (Aldrich and others 2010, Guyette and others 2006, Hutchinson and others 2008, Shumway and others 2001). It remains hard to verify the fourth part of the fire-oak hypothesis—that prescribed burning promotes oaks—as the results reported in the literature vary widely. Results range from positive (Brown 1960, Kruger and Reich 1997, Swan 1970, Ward and Stephens 1989), to neutral (Hutchinson and others 2005a, Merritt and Pope 1991, Teuke and Van Lear 1982), to negative (Collins and Carson 2003, Johnson 1974, Loftis 1990, Wendel and Smith 1986). This confusion among findings inhibits resource managers from making more and better use of prescribed fire to regenerate and restore eastern oak forests. A systematic

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[1] Patrick Brose, Research Forester, USDA Forest Service, Northern Research Station, Irvine, PA 16329

Thomas Waldrop, Research Forester, USDA Forest Service, Southern Research Station, Clemson, SC 29634

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review of the fire-oak literature would cut through this confusion and shed light on the conditions under which prescribed fire helps or hinders the oak regeneration process.

METHODS

For this review, we obtained 59 fire-oak papers that have been published within the past 50 years in various conference proceedings and scientific journals (table 1). We sorted the papers by stand type (mature, young, or immature), season of burn (dormant or growing), and number of fires [single (1), dual (2), or multiple (>2)] based on the site descriptions and methods provided in the text. Mature stands were those in the understory re-initiation stage of development (Oliver and Larson 1990) and were characterized by an intact, closed-canopy, fully stocked overstory. These were stands that had been undisturbed for years or had only been recently disturbed by light, thin-from-below treatments. These stands were at the beginning of the oak regeneration process. They either lacked oak seedlings or the seedlings were quite small. Young stands were ones undergoing a shelterwood harvest sequence or had recently received a final harvest. In these stands, the oak and mesophytic hardwood reproduction was abundant and vigorous. They were near or at the end of the oak regeneration process. Immature stands are intermediate between young and mature stands. Their canopies had recently closed, but they were several decades from being mature. They were in the stem exclusion stage of stand development (Oliver and Larson 1990). Dormant-season fires occur between leaf abscission in autumn and leaf expansion the following spring. During this time, the hardwood reproduction is not photosynthesizing, although sap flow may be occurring, as early spring is included in the dormant season. Growing-season fires occur from leaf expansion in the spring to leaf abscission in autumn. The exact starting time of the growing season for prescribed burning purposes is highly variable, as it is governed by location, weather, and the physiological characteristics of the hardwood species.

After sorting the papers by stand type, season of burn, and number of prescribed fires, we examined the quantitative data provided in the results section of each paper to determine whether the fire treatment effects were positive, negative, or ambiguous for the oak reproduction. Positive results for the oak reproduction were absolute increases in oak seedling density via establishment of new germinants, relative increases to the oak portion of the regeneration pool via differential survival rates between oak and mesophytic hardwoods, and acceleration of oak seedling height growth postfire relative to that of other species. Negative fire effects to the oak reproduction were the opposite of the positive results, such as decreases in the absolute or relative abundance of oak reproduction or loss of the relative oak seedling height growth. Ambiguous results were when there was no or little meaningful change in competitive relationships between oak and mesophyitic hardwood reproduction from pre-burn to post-burn.

RESULTS

Mature Stands

As previously stated, these stands are in the understory re-initiation stage of development (Oliver and Larson 1990). The overstory is intact with stocking levels exceeding 80 percent. The midstory is ubiquitous and well developed. Dense shade covers the forest floor and strongly influences understory composition and growth. Generally, these stands have not experienced any substantial disturbance for decades. Of the 59 fire-oak papers, 39 (66 percent) took place in mature stands and 37 (95 percent) of those involved dormant-season fires (table 1). These were relatively evenly spread among the number of fires (11 single burns, 11 dual burns, and 17 multiple burns) and among effects on oak (11 ambiguous, 11 negative, 17 positive). However, when we combined these two groupings (number of fires and effects on oak), a pattern of improving benefit to oak as the number of fires increased was evident (table 2). The remainder of this section will review some of the noteworthy publications that are representative of the studies conducted in mature stands.

One fire—The effect of a single prescribed fire on existing oak seedlings was either negative or ambiguous (table 2). Of the 11 studies, 7 found that the number of oak seedlings decreased following the fire while the other 4 found no substantial change. Noteworthy negative studies include Johnson (1974), Huntley and McGee (1983), Loftis (1990), and Wendel and Smith (1986). Studies reporting ambiguous results include Albrecht and McCarthy (2006), Dolan and Parker (2004), Elliott and others (2004), and Teuke and Van Lear (1982). Of these, the Johnson (1974) study is fairly typical in terms of study design, implementation and outcome.

Johnson's (1974) study took place in southwestern Wisconsin and involved the Forest Service, U.S. Department of Agriculture (USFS) North Central Forest Experiment Station and the Wisconsin Department of Natural Resources. The study site was an 8-acre stand dominated by northern red oak. The stand was moderately thinned from below (basal area reduced from 120 to 80 cubic feet per acre) in fall 1969. At this same time, an acorn crop resulted in the establishment of 7,000 new red oak seedlings per acre in spring 1970. A year later, the stand was split in two 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 percent survival rate while the control seedlings had a 90 percent survival rate. The fire had killed approximately half of the northern red oak seedlings.

One of the criticisms of the Johnson (1974) study is that it reports results collected from one inventory conducted just a few months after the fire. A comparable study with a longer interval between treatment and inventory is Wendel and Smith (1986). That study occurred in east-central West Virginia and was a cooperative effort by the USFS Northeastern Forest Experiment Station, the Washington National Forest, and the West Virginia Department of Natural Resources. Like the Johnson study, this site was thinned to 90 cubic feet per acre basal area 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 percent while the amount of red maple and black locust (*Robinia psuedoacacia* L.) increased by 17 and 120 percent, respectively. Clearly, the fire had a negative impact on the oak regeneration process.

Why did these prescribed fires produce such negative results for the oak reproduction? The main factor in both of these studies was that the oak seedlings were small and had been growing in dense understory shade for all of their lives. Consequently, they had small root systems with little root carbohydrate reserves and simply could not sprout postfire. Second, the prescribed fires were conducted in mid- to late-April so the small seedlings may have already begun expanding their leaves, further lowering their root carbohydrate reserves. Finally, neither study excluded white-tailed deer from the sites so excessive deer browsing may have subsequently eliminated many oaks that sprouted postfire. Regardless of why these studies had a negative impact on oak reproduction, it is evident that prescribed burning could impede the oak regeneration process under some circumstances.

Another potential negative impact of prescribed fires on the oak regeneration process is their effect on recently fallen acorns. This facet of fire and the oak regeneration process was the earliest one reported in the scientific literature (Korstian 1927). He found that fires exceeding 400 °F readily killed acorns, but there was a mortality gradient among species with acorns of the red oak group surviving fire at a higher rate than those of the white oak group. Korstian surmised that this gradient was caused by the differences in germination timing (fall for white oaks, spring for red oaks) between the two groups. Subsequent research has confirmed that acorns are easily killed by fires (Auchmoody and Smith 1993, Dey and Fan 2009, Greenberg and others 2012).

***Two fires*—**The studies utilizing two prescribed fires showed varying responses (tables 1 and 2). Four papers reported ambiguous effects (Franklin and others 2003, McGee and others 1995, Merritt and Pope 1991) on oak reproduction with five showing positive outcomes (Barnes and Van Lear 1998, Schuler and others 2013) and two showing negative outcomes (Arthur and others 1998, Luken and Shea 2000). Illustrative of this confusion are the two oak sites that were part of the National Fire and Fire Surrogate Project as they report differing outcomes between sites as well as among topographic positions (Iverson and others 2008, Waldrop and others 2008).

The oak sites of the National Fire and Fire Surrogates Project located in western North Carolina and southern Ohio examined the responses of hardwood reproduction and many other variables to prescribed fire and mechanical fuel reduction treatments. Dormant-season strip-heading fires were conducted twice at both sites with and without a mechanical treatment. In North Carolina, the mechanical treatment was chainsaw felling of shrubs, while midstory and overstory thinning was the mechanical treatment used in Ohio. Oak regeneration varied by treatment at both the sites. In North Carolina, the oaks showed little response to any treatment during the first year after treatment but increased significantly in number between years 1 and 3 in the burn-only and mechanical + burn plots. A decrease was observed in year 5 after the second burn but the difference was not significant. The mechanical-only treatment had little initial impact on oak regeneration in North Carolina but a significant increase was observed between years 3 and 5. Oak reproduction decreased at Ohio in all treatment units during the first year after treatment, although the difference was not significant in the mechanical-only treatment unit. No changes occurred between years 1 and 4.

Competitors of oak tended to follow the same patterns at North Carolina and Ohio. Red maple showed little response to treatment during the first year in North Carolina, but in Ohio there were significant decreases in number of red maple seedlings in all treatments, including the control. Burning, with and without mechanical treatment, significantly increased red maple numbers at years 3 (North Carolina) or 4 (Ohio) but the second burn in North Carolina reduced numbers to pretreatment levels. Yellow-poplar increased over time in the mechanical-only plots in Ohio. However, this response was small in comparison to the large increase in numbers of yellow-poplar seedlings observed the first year after burning at both sites. These numbers decreased by the third measurement at both sites and even more after the second burn in North Carolina. This result agrees with the results of Brose and Van Lear (1998) who emphasized the need for prescribed burning after yellow-poplar seedlings become established. Oaks were four to six times more numerous after the second burn in North Carolina than were seedlings of yellow-poplar. The burn-only treatment changed stand structure by reducing the sapling/shrub layer but it did little to thin the overstory.

Iverson and others (2008) used the same study area in Ohio reported by Waldrop and others (2008) to compare treatment impacts as they varied across different positions of the landscape. Study plots in Ohio were larger than those in North Carolina (50 acres vs. 20 acres) thus allowing a comparison of treatment impacts across dry and mesic sites. The drier landscape positions generally had more intense fires, more canopy openness, and more oak and hickory advance regeneration; several other tree species also exhibited marked landscape variation in regeneration after treatments. Though advance regeneration of several competing species became abundant after the initial treatments, the second fires reduced the high densities of the two major competitors, red maple and yellow-poplar. The authors suggested that on dry or intermediate sites with at least 2,000 oak and hickory seedlings per acre, opening the canopy to 8.5–19 percent followed by at least two fires should promote oak and hickory to be “competitive” over about 50 percent of the area. However, no appreciable oak and hickory regeneration developed on mesic sites.

The study by Iverson and others (2008) on relatively large (>50 acres) treatment units showed some promise and also showed some of the problems that managers face. Though thinning and burning increased the density of oak advance regeneration, there also was ample competition from species that had different strategies in dealing with the new conditions brought about by the thinning and burning. There was a large spatial variation in oak regeneration across the large sites because topography, fire intensity, and canopy openness were also highly variable.

More than two fires—Even though prescribed burning in hardwoods has been discussed for several decades, it was not used on an operational scale until the 1980s (Van Lear and Waldrop 1991). Consequently, long-term studies involving multiple fires in hardwood forests are rare, but a number of new publications are available describing results after three or four periodic fires. Generally, these studies describe positive effects of multiple prescribed fires on oak reproduction, but a few report negative effects (tables 1 and 2).

One of the longest running fire studies in eastern hardwood forests is located in south-central Tennessee (Stratton 2007). Since 1962, an oak barren has been burned in late winter annually or every 5 years. During that time, oak has come to dominate the understory as mesophyitc hardwood reproduction gradually died out. An interesting finding is that none of the oak reproduction has ever successfully grown into the canopy in any of the fire treatments. Apparently, a 5-year fire return interval is too short for oak reproduction to grow large enough to withstand a surface fire without being topkilled and forced to sprout again.

Blankenship and Arthur (2006) used a study site on the Cumberland Plateau in eastern Kentucky to examine stand structure after prescribed burning two or three times. The same study site was used by Green and others (2010) after another set of burns (three and four burns) to examine oak and red maple seedling survival. Burning was conducted by backing fire down the ridge and by point source or strip heading fires if a higher intensity was desired. The first two fires were in the dormant season; later burns were in the growing season. Burning altered stand structure by reducing overstory stem density by 30 percent and midstory stem density by 91 percent (Blankenship and Arthur 2006). Midstory oak and red maple stem densities were reduced by 94 and 85 percent, respectively. Damaged or dead overstory and midstory stems sprouted to greatly increase the number of trees in the ground layer, with oak, red maple, and dogwood being most common after three burns. Green and others (2010) tagged chestnut oak, scarlet oak, and red maple seedlings to follow survival and growth through three and four prescribed fires. Burning reduced the numbers of seedlings of all three species, but scarlet oak had significantly higher survival than chestnut oak and red maple. Scarlet oaks burned four times were significantly taller than chestnut oak and red maple burned either three or four times. Overall, scarlet oaks had better survival and growth than red maples, but red maples were not eliminated as some continued to resprout. Both papers (Blankenship and Arthur 2006, Green and others 2010) emphasized that after several burns, oak regeneration was in a better competitive position than was red maple, but goals of producing predominately oak regeneration had not been reached. Additional trials with other burning regimes and/or silvicultural tools would be necessary to reach that goal.

Alexander and others (2008), also working in Kentucky, had similar results to Blankenship and Arthur (2006) and Green and others (2010). Numbers of mid-story trees were reduced by burning one or three times, but sprouting caused large increases in the numbers of trees in the smaller size classes. Both single and repeated prescribed burns increased understory light and reduced red maple survival. However, neither burning regime placed oaks in an improved competitive position. The authors suggest that successful oak regeneration is difficult to predict because it is controlled by three highly variable and interdependent factors: life history traits of oaks compared to competitors, pre-burn stature of oak seedlings, and variability of fire temperature and how it affects light. Although not suggested by these authors, other factors that also control oak regeneration are site quality and position on the landscape (aspect and position on the slope).

Hutchinson and others (2005a, b) studied regeneration after two and four dormant-season prescribed burns on xeric, intermediate, and mesic sites in southern Ohio. Burning, conducted by strip heading fires, had little impact on overstory trees over 10-inch diameter at breast height (dbh). Smaller trees (4 to 10 inch dbh) were reduced in density by 31 percent by burning twice and by 19 percent by burning four times. The two-burn treatment had higher fire intensity, resulting in greater mortality of small trees. Burning also reduced sapling density by 86 percent. Regeneration after burning was abundant and largely of the same species as were killed by burning. In this trial, results were similar among xeric, intermediate, and mesic sites. The largest change was brought about by the higher fire intensities associated with the two-burn scenario because they better opened the canopy to a greater degree. In addition, burning at longer intervals may allow greater buildup of fuels, as stems and branches of trees killed by one fire fall over and become fuel for the next fire. Waldrop and others (2010) found that after burning, fine woody fuels increase in abundance over time until the next prescribed fire. A factor often overlooked is delayed mortality, which can occur for several years after a single fire. Yaussy and Waldrop (2010) showed that the likelihood of mortality was related to prior tree health, size class, species, and first-order fire effects. Hutchinson and others (2012) concluded that periodic fire, coupled with natural gap dynamics, may be a feasible management strategy for perpetuating oak forests where harvesting is not an option.

Growing-season fire*—*In our survey of the fire and oak literature, we found only three studies reporting results of a single growing-season fire (foliage of mesophytic hardwood reproduction was more than 50 percent expanded) in a mature stand. The Barnes and Van Lear (1998) study occurred on the Clemson University Forest in South Carolina, while the Brose and others (2007) and Gottschalk and others (2013) studies took place in Pennsylvania on the Clear Creek and Moshannon State Forests, respectively.

Barnes and Van Lear (1998) compared a single growing-season fire in 1992 to three dormant-season fires conducted in 1900, 1992, and 1993. All burns began with backing fires and were completed with strip heading fires. Oak density was not significantly different between the two burning treatments. However, the single growing season burn was as effective at promoting open growing conditions, as were the three dormant-season burns. Burning in the growing season was also more effective at reducing competition from yellow-poplar. This study suggests that even though burning in the growing season is more difficult than in the dormant season because of increased humidity and shading, it can be more effective and, ultimately, less expensive.

In the two Pennsylvania studies, postfire sprouting of oak seedlings was 65 percent *less* than that of mesophytic hardwood reproduction. This large difference between the two species groups was likely due to the oak seedlings having much smaller root systems relative to the larger non-oak reproduction.

Two or more growing-season fires**—**None of the prescribed fire studies conducted in mature hardwood stands fell into this group. However, a long-term fire study conducted in pine-dominated stands on the Santee Experimental Forest of South Carolina does provide some insight into this type of fire regime (Langdon 1981, Lewis and Harshbarger 1976, Lotti and others 1960, McKee 1982). The study was established in 1946 with annual and periodic (3 to 5 years) burning conducted in summer and winter until Hurricane Hugo severely damaged the study in September 1989. Waldrop and others (1992) reported on changes to vegetation through 43 years of treatment. When plots were burned every 3 to 5 years, in either summer or winter, trees over 5 inches dbh were largely unaffected as they were too tall and their bark was too thick to be impacted by low-intensity burning. Hardwoods between 1 and 5 inches dbh were topkilled gradually over time. These stems then sprouted, resulting in a large increase in stems less than 1 inch dbh. Annual winter burning produced similar results but had the largest number of sprouts. With each of these treatments, vegetation had at least one growing season to recover from burning. It was only in the annual summer burn treatment that hardwoods were nearly eliminated from the forest floor, and that required many burns. The most resilient species were the oaks, which persisted through 18 to 20 annual summer fires (Langdon 1981). This result has been cited by many authors as an indication of the competitive advantage of oaks over other hardwoods in a regime of frequent burning. However, density of oak competitors increased in all fire regimes except annual summer burning, which is impractical for almost all land managers.

Young Stands

These stands received a complete or heavy partial harvest (≥50 percent basal area reduction) or comparable disturbance within the past 10 years. They are at the end of the understory re-initiation stage (overstory still somewhat intact, but it no longer controls understory development) or in the stand initiation stage (Oliver and Larson 1990). Examples of young stands include those that have recently received a final harvest, stands undergoing a two-cut shelterwood sequence, and stands heavily damaged by insects, weather, or wildfire. The key characteristics of these stands are that the event released the hardwood reproduction from dense understory shading and there has been sufficient time (≥3 growing seasons) for that reproduction to respond to the release.

We found 16 fire-oak papers involving young stands (tables 1 and 3). Unlike the papers reporting results of burning in mature stands, only six of these involved dormant-season fires, while eight used growing-season burns (note that three papers provided data on both seasons of burn). Similarly, the fire studies in young stands were not evenly distributed by number of burns and effects on oak reproduction like those conducted in mature stands. Rather, they were concentrated in the single fire and positive effects categories.

***Dormant-season fires*—**Just six papers reported results of single fires conducted during the dormant season and all of these originated from three studies. Huntley and McGee (1981) burned 3-year-old hardwood clearcuts in northern Alabama. They found that the dormant-season fire reduced the density of yellow-poplar reproduction, but had virtually no impact on that of red maple. Density of oak reproduction was also unaffected. In central Virginia, Brose and Van Lear (1998) investigated the impact of a single dormant-season burn on hardwood reproduction in oak shelterwood stands. Like the Alabama study, they found decreases in the density of yellow-poplar reproduction, but little reduction of red maple density, except where the fires were intense. A follow-up study (Brose 2010) showed that these initial findings persisted, especially on the more intensely burned plots, and were leading towards eventual oak domination.

***Growing-season fires*—**Research into the effects of growing-season fires (foliage of mesophytic hardwood reproduction was more than 50 percent expanded) is limited. We found eight papers that had growing-season prescribed fires as one of the treatments. In central Virginia, Keyser and others (1996) found that summer fires in oak shelterwood stands reduced the density of red maple and yellow-poplar seedlings by 82 percent and 97 percent, respectively, relative to the unburned controls. Oak reproduction decreased by only 11 percent following summer burning. Post-fire height growth among the species groups was equal. This small study spawned a more comprehensive research project, also conducted in central Virginia, that examined late spring and summer prescribed fires as treatments in oak shelterwood stands (Brose and Van Lear 1998, Brose and others 1999). The previous summer-burn results were verified. Densities of red maple and yellow-poplar reproduction declined by 46 percent and 72 percent, respectively, while oak seedling density dropped by only 5 percent. Additionally, late spring burning (foliage of mesophytic hardwood reproduction was more than 50 percent expanded) resulted in a 45 percent decline in stem density for the two non-oak species. The importance of fire intensity was evident in that the largest reductions in stem densities of maples and yellow-poplars occurred where the fires burned the hottest. These outcomes were still present 11 years later, especially the relationship between fire intensity and oak dominance (Brose 2010).

Besides burning in oak shelterwoods, growing-season fires after the final harvest have been studied to a limited extent. In Connecticut, Ward and Brose (2004) found that mortality of black birch ranged from 66 to 86 percent following late spring burning (foliage of mesophytic hardwood reproduction was more than 50 percent expanded) in a recently-regenerated, mixed hardwood stand. Mortality of red maple averaged 15 percent, but exhibited wide variability, 0 to 100 percent, depending on fire intensity and size of the red maple reproduction prior to the fires. Oak mortality averaged just 9 percent with low variability. In Pennsylvania, Brose (2013) investigated the effects of early-May prescribed fires on hardwood reproduction in former oak stands that had recently received the final harvest of a three-cut shelterwood sequence. Like in Connecticut, black birch exhibited large decreases in stem densities (~90 percent) while stem density of red maple declined approximately 50 percent. Density of oak reproduction was unchanged by the burning; virtually all oak stems sprouted after the fires. Likewise, densities of black cherry, cucumbertree (*Magnolia acuminata* L.), and serviceberry (*Amelanchier arborea* Michx.f.) Fern.) seedlings were the same after the fires as before. Besides reducing the stem densities of black birch and red maple, the growing-season fire equalized the height growth among the various species.

Immature Stands

Only four publications address fire effects during the stem exclusion stage (table 1). All are reviewed here.

In southern West Virginia, Carvell and Maxey (1969) studied a sapling stand partly burned by an autumn wildfire 5 years earlier. In the unburned portion, yellow-poplar was the dominant species in terms of density and size. However in the burned section, oak and hickory (*Carya* spp. Nutt.) dominated. They noted that 40 to 70 percent of the saplings that survived the fire had large basal scars and concluded that fire was a poor means to manipulate species composition in sapling stands given the loss of future timber value.

In southern Pennsylvania, Abrams and Johnson (2013) reported that an intense fall wildfire in a 15-year-old mixed oak stand resulted in a 43 percent reduction in stem density, including fewer oaks and black cherry and an increase in low-value trees like black locust. Additionally, the surviving oaks suffered major damage to their boles that will persist for decades and decrease the ultimate future value of the stand.

Maslen (1989) reported on a single high-intensity dormant-season strip-heading fire in a mixed hardwood pole stand in the Piedmont of North Carolina. This study looked at understory characteristics 7 years after burning, giving a slightly longer-term view of fire impacts. By then, there were no significant differences in the numbers of oaks and competitors less than 2 feet tall, as seedlings and sprouts had grown into the next larger size class. In the 2- to 12-foot height class, oaks, yellow-poplar, and all other species were significantly higher in number than prior to burning. Oaks over 12 feet tall at the time of the fire were essentially unaffected by burning; they survived the fire. The results of this study indicated that a single prescribed fire did little to the stand other than to remove small regeneration and allow sprouts to grow back over time.

In Connecticut, Ward and Stephens (1989) report the long-term (55-year) effects of a summer wildfire that burned through part of a 30-year-old mixed hardwood stand in 1932. Prior to the wildfire, the stand contained approximately 1,050 stems >1.0 inch dbh per acre and 74.0 square feet per acre of basal area. Oak and hickory comprised 21.3 and 6.4 percent of the stems, respectively, with the balance consisting of birch, maple, and other hardwoods. In the years just after the 1932 fire, stem densities and basal area in the burned area dropped by 84 and 38 percent, respectively, with few differences among species. In the subsequent decades in the burned area, stem densities quickly recovered due to sprouting of the fire-killed stems before declining due to natural stand thinning. At the same time, basal area gradually increased. By 1987, stem densities and basal areas were similar in the burned and unburned areas, but the burned area contained considerably more oak than the unburned area; 160 stems per acre versus 65 stems per acre. The negative effects of the 1932 fire were the widespread bole damage of the trees that survived the fire and the poor stem form of many of the sprouts that developed postfire.

DISCUSSION

From tables 1, 2, and 3, and the observations, insights, and interpretations provided in the reviewed fire-oak papers, several findings and trends emerge that are useful to managers of oak-dominated ecosystems. They are:

Many factors influence the outcome of a prescribed fire. Among these, the important biological ones are the developmental stage of the oak stand and the degree of root development by the oak reproduction. Important fire factors are season of burn, fire intensity, and their interaction. Finally, critical site factors include topography and the disturbance history of the stand, both of which influence fire behavior, fire size, and the species composition of the reproduction.

In mature stands (understory re-initiation stage), as the number of fires increases, so does the benefit to oak. Single fires and the initial burn of a multi-fire sequence will provide little, if any, benefit to the oak reproduction and may actually be detrimental in the short term. Conversely, multiple burns spread over a decade or more will generally benefit the oak component of the regeneration pool via an improved seedbed for oak seedling establishment and enhanced understory light conditions for the subsequent growth of the new seedlings and any existing oak reproduction.

In young stands (initiation stage), single fires can rapidly benefit the oak reproduction. This is likely due to differences in root development between the oaks and the competing mesophytic hardwoods that give the oaks a higher postfire sprouting probability.

In immature stands (stem exclusion stage), prescribed fire can increase the relative proportion of oak, but there will be large economic losses due to bole damage to the trees that survive the fire and stem defect (crook and sweep) of the new sprouts.

Among the various eastern species, post-fire sprouting ability of the reproduction varies widely. Some are non-sprouters (eastern hemlock (*Tsuga Canadensis* (L.) Carr.) and eastern white pine (*Pinus strobus* L.), some are poor sprouters (sweet birch and yellow-poplar), some are moderate sprouters (blackgum and red maple), and some are excellent sprouters (oak and hickory). A species' sprouting ability is a function of its capability to form dormant basal buds coupled with its germination strategy (epigeal or hypogeal), its juvenile growth strategy (root-centric or stem-centric), and its shade tolerance, i.e., the optimal light regime for juvenile growth. Sprouting ability is also influenced by season of burn, fire intensity, and their interaction.

Growing-season fires will have more impact, i.e., kill more stems, than dormant-season fires because the vegetation is physiologically active. Similarly, multiple fires kill more stems than single fires due to accumulated damage on midstory and overstory trees. Across the range of prescribed fire regimes, a single dormant-season fire will have the least impact on forest structure while multiple growing-season fires will have the most impact. Multiple dormant-season fires and single growing-season fires will have an intermediate impact. Within any of these, fire intensity will also play a role, as hotter fires have more impact than cooler fires.

Immediate mortality from a single fire is mostly confined to the regeneration layer and small saplings (<3 inch dbh). Midstory trees, large saplings (3 to 6 inch dbh) and pole-size trees (6 to 10 inch dbh), are periodically killed and some may succumb to delayed mortality. Overstory trees (>11 inch dbh) are generally unscathed unless there is an accumulation of fuel at or near their bases.

Long-term fire studies in young stands are needed. We found only 10 fire studies done in oak shelterwoods or recently regenerated oaks stands, and just one of them reported results more than 10 years postfire. While the vast majority of these studies reported positive results for the oak reproduction, more research is needed to understand the other ramifications of this approach.

In some situations, prescribed burning can make the oak regeneration process more difficult. If conducted shortly after a good masting event, fire will kill many of the acorns on the ground. Small oak seedlings with undeveloped root systems are virtually defenseless against a fire, especially a growing season burn. Prescribed fires can also cause a large influx of new non-oak seedlings from seed stored in the forest floor, exacerbate invasive species problems, and incite excessive browsing by white-tailed deer.

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Table 1—Prescribed fire papers reviewed for assessing fire effects on hardwood reproduction

Publication	State	Type of stand	Season-of-burn	Number of burns	Effect on oak
Ibrecht & McCarthy 2006	OH	M	D	1	A
Collins & Carson 2003	WV	M	D	1	N
Dolan & Parker 2004	KY	M	D	1	A
Elliott & others 2004	NC	M	D	1	A
Huntley & McGee 1983	AL	M	D	1	N
Johnson 1974	WI	M	D	1	N
Loftis 1990	GA	M	D	1	N
Teuke & Van Lear 1982	SC	M	D	1	A
Wendel & Smith 1986	WV	M	D	1	N
Arthur & others 1998	KY	M	D	2	N
Barnes & Van Lear 1998	SC	M	D, G	2	P
Franklin & others 2003	KY	M	D	2	A
Iverson & others 2008	OH	M	D	2	P
McGee & others 1995	NY	M	D	2	A
Merritt & Pope 1991	IN	M	D	2	A
Schuler & others 2013	WV	M	D	2	P
Waldrop & others 2008	NC	M	D	2	P
Waldrop & others 2008	OH	M	D	2	N
Wang & others 2005	SC	M	D	2	P
Will-Wolf 1991	WI	M	D	2	A
Alexander & others 2008	KY	M	D	3	N
Blankenship & Arthur 2006	KY	M	D	3	A
DeSelm & others 1991	TN	M	D	10+	P
Dey & Hartman 2005	MO	M	D	4	P
Fan & others 2012	MO	M	D	4	P
Gilbert & others 2003	KY	M	D	3	A
Green & others 2010	KY	M	D	3	A
Huddle & Pallardy 1996	MO	M	D	10+	P
Hutchinson and others 2005a, b	OH	M	D	4	P
Hutchinson & others 2012	OH	M	D	4	P
Luken & Shea 2000	KY	M	D	3	N
Paulsell 1957	MO	M	D	10+	P
Sassen & Muzika 2004	MO	M	D	4	P
Signell & others 2005	PA	M	D	4	P
Stratton 2007	TN	M	D	10+	P
Thor & Nichols 1973	TN	M	D	10+	P
Brose & others 2007	PA	M	G	1	N
Gottschalk & others[a]	PA	M	G	1	N
Huntley & McGee 1981, 1983	AL	Y	D	1	N
McGee 1979, 1980	AL	Y	D	1	N
Reich & others 1990	WI	Y	D	1	A
Brose 2010	VA	Y	D, G	1	P
Brose 2013	PA	Y	G	1	P
Brose & others 1999	VA	Y	D, G	1	P
Brose & Van Lear 1998, 2004	VA	Y	D, G	1	P
Geisinger & others 1989	SC	Y	G	1	A
Keyser & others 1996	VA	Y	G	1	P
Stottlemyer 2011	SC	Y	G	1	P
Ward & Brose 2004	CT	Y	G	1	P
Brose [a]	PA	Y	G	2	P
Kruger & Reich 1997	WI	Y	G	2	P
Abrams & Johnson 2013	PA	I	D	1	N
Carvell & Maxey 1969	WV	I	D	1	P
Maslen 1989	NC	I	D	1	A
Ward & Stevens 1989	CT	I	G	1	P

[a] Unpublished data on file at the Forestry Sciences Lab in Irvine, PA or Morgantown, WV.

Studies are organized by stand type (M=Mature, Y=Young, I=Immature), season-of-burn (D=Dormant, G=Growing), and number of fires (1, 2, or >2).

Effect on oak abbreviations are A=Ambiguous, N=Negative, P=Positive.

Table 2—Distribution of fire-oak publications by the number of burns and the effect on oak regeneration process for studies conducted in mature stands

|---------------- Number of Fires --------------------|

Effect on Oak	1	2	>2	Total
Positive	0	5	12	17
Ambiguous	4	4	3	11
Negative	7	2	2	11
Total	11	11	17	39

Note the trend line illustrating the increasingly positive effects on oak as the number of fires increase from one to more than two.

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Table 3—Distribution of fire-oak publications by the number of burns and the effect on oak regeneration process for studies conducted in young stand

|---------------- Number of Fires --------------------|

Effect on Oak	1	2	>2	Total
Positive	8	2	0	10
Ambiguous	2	0	0	2
Negative	4	0	0	4
Total	14	2	0	16

Note the clustering of studies reporting positive effects on oak after just one or two burns.