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Review

A Review on the Dynamics of Prescribed Fire, Tree Mortality, and Injury in Managing Oak Natural Communities to Minimize Economic Loss in North America

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Abstract: The long history of fire in North America spans millennia and is recognized as an important driver in the widespread and long-term dominance of oak species and oak natural communities. Frequent wildfires from about 1850 to 1950 resulted in much forest damage, and gained fire a negative reputation. The lack of fire for the past nearly 100 years due to suppression programs is now indicted as a major cause of widespread oak regeneration failures and loss of fire-dependent natural communities. The use of prescribed fire is increasing in forest management and ecosystem restoration. An understanding of fire effects on trees can provide the basis for the silviculture of restoring and sustaining oak ecosystems. We present an overview of fire-tree wounding interactions, highlight important determinants of fire injury and damage, and discuss several practical situations where fire can be used to favor oak while minimizing damage and devaluation of the forest. We also identify stages in stand development, regeneration methods, and management objectives for which fire has the potential of causing substantial damage and recommend preferred alternative practices.

Keywords: prescribed fire; tree injury; tree decay; tree volume; tree value; oak; silviculture; tree mortality; stand development

1. Introduction

Fire has played a major role in shaping the composition and structure of vegetation for millenia in North America. Fossil records of *Quercus* extend back to 50–55 million years BP [1–3], and oaks were widespread by the end of the Paleogene (~23 million years BP) in the northern hemisphere [3,4]. During the Holocene, increasing fire occurrence, often due to Native American land use practices, favored the dominance of oak-pine (*Quercus/Pinus*) natural communities such as forests, woodlands, and savannas in North America [5–8]. In historic times, fire frequency was highest in the oak region during the early European settlement period [9–11] when settlers saturated the landscape with fire and initiated a wave of fire that rolled from the eastern seaboard to the tallgrass prairies [12,13]. Widespread catastrophic fires, which burned in logging slash circa the 1850s to 1920s, caused severe destruction on millions of acres and took thousands of lives, bringing the need for wildfire control to national attention. In fact, wildfire control was a major purpose for forming state and federal forestry agencies in the early history of forestry in America [14–16]. Wildfire suppression programs have been successful for minimizing the role of fire on the landscape in the short-term. Occasionally, large wildfires (e.g., >4000 ha) break out in severe drought years and high fire danger weather. But for the last 100 years, the influence of fire on forest composition and structure has been minimal, perhaps leading to the creation of novel forest conditions. Once prominent, fire-dependent natural communities such as woodlands and savannas are now rare throughout the US, and oak-pine forests are changing in composition toward other species and developing more complex structure [17–19]. The use of the terms forest, woodland and savanna in this paper follows the definitions of a previous paper [20], and represent categories that span the continuum of increasing tree density, tree canopy cover, tree canopy strata, dominance of woody understory vegetation, and dominance of shade tolerant herbaceous species along the progression from savanna to forest community. The loss of oak forests is a national and global concern [21]. Now, land management agencies and conservation organizations and individuals are increasingly adopting the goals of restoration and sustainable management of oak savannas, woodlands, and forests using prescribed fire in combination with other forestry practices. However, the reintroduction of fire into hardwood forests is a controversial topic due to the potential negative effects of fire on timber volume, quality, and value [22–24].

The history of wildfires during the industrial logging era of the mid-19th to early 20th centuries is widely recognized as the source of high levels of decay and cull (without commercial economic value) timber in eastern hardwood forests [25–28]. Forest fires affect wood volume, quality, and value of individual trees by causing mortality, or wounding tree boles, thereby promoting wood decay and degrade; or of forest stands by causing shifts to less commercially valuable species [22,29]. Wounds can become quite large with increasing fire intensity such as is experienced when wildfire burns through cured logging slash, or in drought years. Decay fungi can infect trees by colonizing wound surfaces and potentially cause substantial loss of wood volume and value over time [22,30–32]. The cumulative negative effects of fire injury persist and exponentially increase over decades in forests because trees are long-lived organisms and decay takes time to advance in them. Therefore, it is not surprising that there is a trend toward a higher proportion of cull percent in stands with increasing historic wildfire frequency in the eastern United States (Figure 1). The highest levels of live cull in standing timber today occur in the Southern, Great Plains Border, and former Prairie Peninsula regions where wildfires were historically more frequent. The Great Plains Border Region commonly experiences annual seasonal drought in late summer and cyclical periods (e.g., 21 to 22 years) of severe drought [33] that promote higher intensity fires and potentially more severe tree wounding. Another contributing factor to high cull percent in forests of Southern and Midwestern hill country is that woods burning persisted longer there than in other regions of the eastern United States [15].

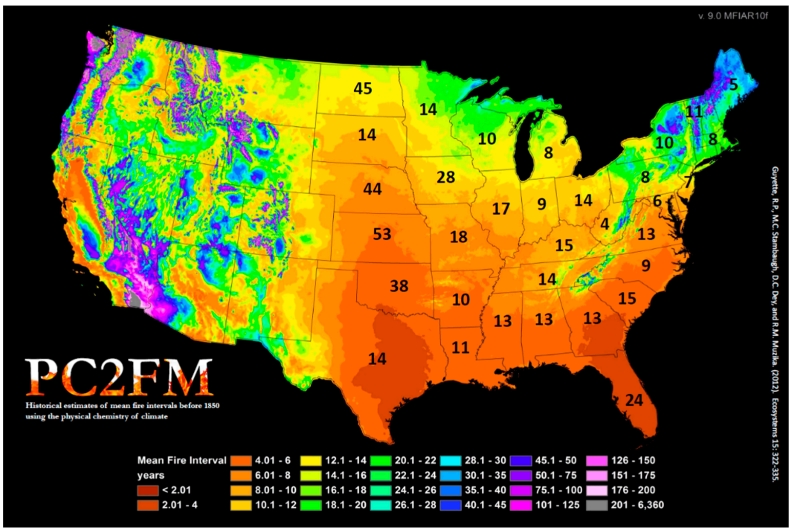

Figure 1. Estimated mean fire interval for low-intensity wildfires before European settlement circa 1650–1850 [34] and percent of total net timber volume that is live cull in modern times according to a national forest inventory [35].

Efforts by federal, state, and county forest fire fighting agencies have been successful in substantially reducing the forest area burned by wildfires through suppression and education in regions of oak forests. Changing economies and demographics in rural areas have also led to a change in the use of fire and cultural attitudes that have resulted in fewer fire ignitions. Even in the face of relatively high fire ignitions, ranging from 2000 to 5000 per year in states like Missouri, Alabama, Florida, Georgia, Tennessee, and North Carolina, effective fire suppression limits the average size of wildfires to <10 ha in most years, and fire has been marginalized in most other states in the eastern US [36]. Consequently, the percent of cull live timber in the East has decreased, for example, from about 50% to 18% since the 1950s in states like Missouri [28,37]. In the past 10 to 30 years, prescribed burning to restore oak/pine savannas and woodlands has increased on public and private conservation lands driven by ambitious goals to restore fire-dependent ecosystems, especially in the Great Plains Border Region [38–40]. In addition to these efforts, other federal and state agencies including The Nature Conservancy, National Wild Turkey Federation, and other NGOs are using prescribed burning to restore woodlands and savannas throughout the Midwest and South.

Efforts to restore native communities at such a large-scale followed several decades of debate among resource professionals over the reintroduction of fire, especially in regions where it was a hard-won fight to get people to quit burning their woods. Improvements in timber quality and decreases in the amount of cull in forests following fire suppression were strong testimony to the benefits of keeping fire out of the woods. However, it is also recognized that the loss of fire from oak-pine ecosystems is a major contributor to the loss of savannas and woodlands, and the problem managers are struggling with in sustaining oak-pine forests.

Oak-pine forests, woodlands, and savannas are fire-dependent systems. Their presence on the landscape is essential to conserving native biodiversity, maintaining ecosystem productivity, and promoting resilience and health of landscapes [41–45]. Restoring oak woodlands and savannas on a broad scale increases landscape diversity that is important to the recovery and conservation of threatened and endangered species [46–48]. Lack of early successional habitat in the eastern US, which savannas and open woodlands provide, is a major concern in wildlife conservation [49–51]. Savannas and woodlands support some of the highest levels of plant diversity [52–54], which begets a greater abundance of varied resources and habitats needed to conserve threatened and endangered wildlife species [55–58]. Both the dominance of oak tree crowns in the canopy and oak litter on the forest floor increase ecosystem productivity by supporting a greater diversity and abundance of invertebrates involved in energy and nutrient cycles than those communities without oak [59–62]. In this era of ecosystem restoration, using fire to restore native communities puts emphasis on ecological benefits such as increased native plant diversity and improved habitat quality for species that prefer woodlands and savannas. However, age-old concerns about fire damage to trees and forests remain and should be considered when planning management approaches and silvicultural prescriptions for restoring and sustaining these highly valued oak forest, woodland, and savanna ecosystems.

This paper provides an overview of prescribed fire-caused damage in oak-dominated systems in North America, the factors that influence damage to trees, and how management can be modified to minimize financial loss of the oak component in forests, woodlands, and savannas. Several management scenarios are used to explore the appropriateness of fire at key stages in the process of restoring and managing oak regeneration and development of oak ecosystems. A previous paper [63] published an excellent synthesis of the role of fire in the life cycle of an oak forest with an emphasis on biology and ecology. We used a similar life cycle approach to select the scenarios for discussion. They are common stand conditions and developmental stages that are key break points in sustaining oak forests, woodlands, and savannas.

2. Types of Fire Injury and Damage

2.1. Tree Mortality

Prescribed surface fires in eastern hardwood forests are capable of killing large mature trees of any species if the intensity and duration of heating is sufficient to cause death of the cambium and foliage (Figure 2). Temperatures (e.g., at 25.4 cm above the ground) in low-intensity, dormant season (e.g., March–April) fires can average 149 °C to >204 °C [64–66], i.e., high enough to kill living organisms and plant tissue, and cause tree mortality by stem girdling [67–69]. However, bark is capable of protecting trees from complete girdling of the stem [70,71]. In mixed-oak forests, relatively high percentages of overstory trees (>11.4 cm dbh) may be scarred on the lower bole from low-intensity fires but usually mortality is relatively low (e.g., <5% basal area or <8% of stem density) after single or repeated low-intensity fires [68,72–74]. Mature, large diameter pines are more resistant to fire mortality than are most hardwood species of similar sizes [75]. Higher fire intensity and increased exposure to high temperatures are needed to kill large trees (e.g., >25 cm dbh), which may occur locally during low-intensity fires where accumulations of fuels occur near the base of individual trees [76]. Tree mortality due to burning increases with decreasing tree diameter and is highest in the seedling size class; and increasing numbers of fires and fire frequency results in higher mortality in species that are able to resprout after being top-killed (i.e., where fire kills the shoot but not the root or adventitious buds clustered near the root collar) [77–79].

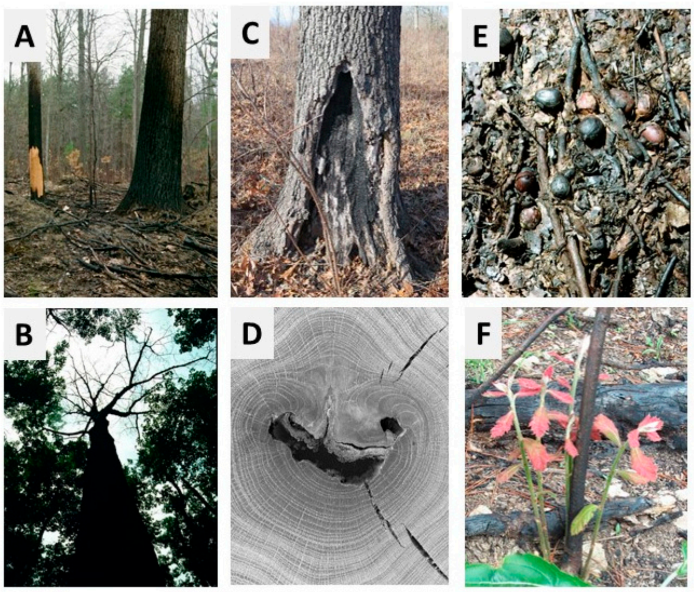

Figure 2. Injury and damage from prescribed burning may include (**A**,**B**) mortality of large overstory trees, though this occurs infrequently, and is usually associated with large concentrations of slash fuels around the base of the tree. Small to large wounds at the base of the tree (**C**), where the heat of fire has killed the cambium, may permit wood decaying fungi entry into the tree. Some tree species, such as those in the white oak group, are able to compartmentalize the injury and minimize the area of damage by decay (**D**). Low intensity fires cause high mortality in oak acorns that are mixed in the surface litter (**E**). Young seedlings of most species are at high risk to fire mortality but larger seedlings and saplings are able to resprout after fire top-kills the main stem (**F**), oaks have a relatively high capacity to do this, even in frequent fire regimes.

2.2. Stem Top-Kill

Low-intensity fires are capable of causing death of the entire cambium on smaller diameter trees of any species. The bark of saplings and seedlings is relatively thin and offers less insulating protection to the cambium than mature, large diameter trees of most hardwood species [80]. Complete stem girdling by fire results in the death of the main stem above the damage. Many hardwood species are able to produce vegetative sprouts after girdling of the stem by one fire [67,72]. Whether top-kill by fire is considered a benefit or damage depends on management goals, silvicultural objectives and the stage of stand development [63]. In sustaining oak forests, top-kill is a positive fire effect when used to favor the development of large and competitive oak reproduction by increasing available light to oak reproduction through decreases in the overhead canopy density in the mid- and overstory and competition in the regeneration cohort [81]. In restoring oak woodlands and savannas, repeated fires that cause mortality or top-kill of woody stems are desirable when trying to reduce stem density and forest cover to promote native ground flora diversity and desirable open woody structure. In contrast, repeated top-kill of hardwood sprouts can adversely retard the recruitment of oaks and other desirable reproduction into the overstory [82], causing years of lost growth and delaying maturity of a fully-stocked forest overstory.

2.3. Bole Wounding and Decay

Low intensity fires can kill cambial tissue at the base of overstory tree boles and create wounds, though not all trees are wounded in a fire [71]. Whether a tree is wounded or not depends largely on fire behavior (i.e., temperature, flame length, and duration of heating) at any one location within the burn unit, and tree characteristics such as species, size, and bark (see below). Numerous fire history studies, which sample the trees in a stand to document fire occurrence as evidenced by scars in tree rings, report that most fires in oak ecosystems are low intensity and scar on average about 10% of the sample trees, but occasionally 60% or more of the trees are scarred when moderate to high intensity fires burn [83]. The observed proportion of trees scarred in long-term frequent prescribed fire studies ranges from <20% to 70% of surviving trees (>11.4 cm dbh), depending on tree species and size, slope, aspect, fire season and frequency, and fuel loading [24,29,74]. The threat of scarring and scar size is substantially reduced in larger, thick-barked tree species. The probability of scarring is higher on southern aspects and steeper upper slopes and ridgetops where fire intensity may be higher than on mesic sites and flat terrain [74,84,85]. Growing season fires have a greater potential to cause scarring because plants are physiologically active and ambient temperatures are closer to lethal temperatures that cause plant tissue necrosis [86]. A regime of annual burning often results in less scarring than less frequent fires (e.g., every 4–5 years) because fuel loading is kept low and fine fuel continuity may be patchy [29,83,87,88]. When fires burn periodically in hardwood forests, fine fuel loading is able to recover to near maximum levels as defined by the decomposition equilibrium fuel loading for that system [89], hence fires burn with more intensity and longer duration. When overstory thinning is done to increase residual tree growth or to aid in developing woodland/savanna structure, subsequent fires usually increase the percent of trees scarred due to increased fuel loading from the thinning [74]. However, a previous paper [84] found that burning immediately after thinning in upland mixed-oak forests, before the newly added fuels had cured, actually reduced fire temperature, rate of spread and, hence, intensity. When heavy fuels from shelterwood harvesting are allowed to cure, e.g., 2 to 4 years, before prescribed burning, then severe mortality and bole damage is probable when heavy slash is within 1 m of the boles of oaks, hickories and yellow-poplar [76].

Open fire scars provide opportunities for wood decaying fungi to colonize and infect trees. Large scars with exposed wood that remain open and moist for long periods provide good environments for fungal colonization and development. However, fire scars are often small and the bark commonly remains intact, covering the injury after low-intensity fires in upland oak forests of the Central Hardwood region [71]. Loss of volume and value in fire scarred oak trees may be relatively minor in the short-term (<10 years), but with time, advanced decay can result in substantial value losses [22,32]. Although larger diameter trees are less likely to scar, when they do suffer wounding that results in open-faced scars, the potential is high for loss to decay over the ensuing decades [31]. If young, vigorous trees are able to rapidly enclose the open wound in a relatively short period of time, then the loss to decay can be minimized. Pole (dbh ranging from approximately 13 to 28 cm) and small sawtimber (dbh > 28 cm) trees are at risk of losing substantial volume and value in the lower log when they suffer open-faced scars because they will remain in the stand for decades before reaching maturity, which allows for advanced decay to develop. Considering that about one-third of the total standing volume is in the lowest 2.4 m log of mature trees, fire injury leading to wood decay at the base of a tree has significant potential effects on merchantable volume and value. Even where timber production is not the primary management concern such as in woodland and savanna restoration, the longevity of mature overstory trees may be compromised by advance decay in the boles of fire-scarred trees because trees are more susceptible to stem breakage and blowdown during wind and ice storms [70]. However, there are positive ecological benefits to scarring and decay development in large trees that lead to an increase in number of wildlife den and cavity trees. This is important to recovery of biodiversity in second growth mature forests because they have significantly fewer cavity and den trees than primary old growth forests [90].

3. Determinants of Fire Injury and Damage

Trees can resist being injured by fire, or they can minimize the damage following injury by defensive responses that confine damage (e.g., wood decay) to the area of initial injury.

3.1. Tree Species

Species-specific growth strategies and morphological characteristics result in different responses among species following fire, with oaks generally better adapted to persist following burning than many competitors. The susceptibility to cambial death and top-kill by a single fire is nearly equal for seedlings and smaller sapling-sized stems, almost regardless of species [67]. Mortality is high in the smallest of seedlings and new germinants, even in the oaks [91]. However, large oak seedlings and saplings are better able to persist with repeated burning than their major competitors [81]. In general, oak species have a distinct advantage over competitors for surviving fire because they preferentially allocate carbohydrates to root growth and have an abundance of dormant buds commonly located in the soil where they are insulated from the heat of a fire [19,66,84,92,93]. Nonetheless, oak stems < 10 cm dbh are susceptible to top-kill, but the larger stems have a high capacity to persist by sprouting [94], especially when there is adequate light for growth during the fire-free period. However, sprouting ability varies by species and begins to decline beyond a species-specific diameter threshold, which is usually in the pole-sized and small sawtimber size classes [19,95]. Lastly, species differences in ability to resist fire mortality and injury become more pronounced in the larger diameter size classes, and this has much to do with differences in bark characteristics (see below).

3.2. Tree Size

Size influences a tree's ability to sprout after fire-caused top-kill, as do the amount of root carbohydrate reserves and the presence of viable dormant vegetative buds after the fire [67]. Low-intensity fires commonly cause top-kill of hardwood trees < 10 cm dbh and a significant proportion of trees < 20 cm dbh [74,75,77,96]. A previous paper [70] found that post oak (*Q. stellata* Wangenh.) trees that were most likely to be scarred and survive a low-intensity dormant season fire were 10 cm dbh to 20 cm dbh at the time of burning; smaller trees were either top-killed or died. Larger seedlings and saplings of most hardwood species are able to sprout after top-kill caused by a single fire [67,93]. It is in the smaller seedling size classes where oaks are generally better able to persist after repeated fires than similar sized stems of their competitors, provided there is adequate light and time between fires for oak sprouts to continue building their root systems [67,97,98]. However, even oak seedling sprouts can be eliminated from a stand by long-term annual or biennial fires [77,79]. Red maple (*Acer rubrum* L.) can be a troublesome species that competes with oak. If it is allowed to grow to sapling or pole-size, it becomes either resistant to being top-killed, or a persistent sprouter even after several low-intensity fires in the dormant season [99,100]. When large diameter oak trees in the overstory are girdled by fire, they are completely killed, as large diameter oaks, regardless of species, have low sprouting potential [19]. However, as tree diameter increases, so does bark thickness, and this increases a tree's resistance to scarring or girdling of the cambium by fire [101]. But, if a large tree is fire scarred, the potential for volume and value loss from decay is increased because the decay may advance throughout the entire existing bole [31]. The rate of decay and extent of value loss depends, in part, on time and the decay resistance of the heartwood of the species, which varies [102]. Smaller trees, when scarred, may be able to compartmentalize the decay column in the center of the bole (Figure 2D), where wood quality is lower to begin with and where value loss can be minimized during the manufacture of the log [31].

3.3. Bark Characteristics

There are many properties of a tree's bark that influence its ability to insulate the cambium from the heat of a fire: thickness, texture, thermal conductivity, specific heat, and thermal diffusivity. However, it is bark thickness that largely determines the degree of protection of the cambium from lethal temperatures [103]. As trees grow, small increases in bark thickness provide exponentially greater protection from high fire temperatures [80,104]. A previous paper [70] found that the probability of fire scarring and the percent of bole circumference scarred were significantly and negatively related to tree diameter, bark width, radial growth rate, and tree age in post oak (dbh range 10 cm to 71 cm). Another previous paper [105] reported that the probability of surviving a fire increases at the sapling size (5 cm dbh to 10 cm dbh) when the bark starts to achieve sufficient thickness to prevent top-kill, depending on species. Similarly, the authors of a previous paper [70] observed that post oak trees > 10 cm dbh were more likely to survive low-intensity fires without top-kill. There is however a substantial variation in bark thickness, rate of bark growth on the lower bole, and bark texture among species [105–107]. Even with thick bark, scarring can occur in areas of bark fissures [70].

In general, upland species have thicker bark than bottomland species for similar sized trees in eastern North America [105]. Bark thickness is greatest in white oak group species (*Quercus* Section *Quercus*) followed by the red oak group species (*Quercus* Section *Lobatae*). Resistance to scarring decreases in upland oaks from post oak - bur oak (*Q. macrocarpa* Michx.) > white oak (*Q. alba* L.) > black oak (*Q. velutina* Lam.) > southern red oak (*Q. falcata* Michx.) - scarlet oak (*Q. coccinea* Muenchh.) [74,85,101,107]. Species with inherently thinner bark include American beech (*Fagus grandifolia* Ehrh.), flowering dogwood (*Cornus florida* L.), black cherry (*Prunus serotina* Ehrh.), maple (*Acer* spp.), and hickory (*Carya* spp.). The rate of bark thickening during growth is important because faster growth rates allow trees to reach critical thresholds of thickness earlier that are associated with protection of the cambium and survival. Eastern cottonwood (*Populus deltoides* Bart. ex Marsh.) and yellow-poplar (*Liriodendron tulipifera* L.) are both thin-barked, fire sensitive species when trees are small and young, but they have rapid rates of bark growth and are considered resistant to fire scarring as large mature trees [107,108]. In contrast, silver maple (*A. saccharinum* L.) has a slow rate of bark growth all its life and is vulnerable to fire injury even when it is a large tree. Species that have smooth bark texture, such as water oak, are more vulnerable to fire injury to the cambium than are deeply fissured, rough textured species such as chestnut oak (*Q. montana* L.) and bur oak. The bark of southern yellow pines confers a high degree of resistance to fire scarring [74,85]. Once a tree is scarred by a fire, it is more vulnerable to additional scarring in future fires because the bark is thin on the callus wood forming over the original scar.

3.4. Defense against Decay

Diameter growth rate determines how long an open fire scar may provide entry of fungi into the tree's stem. Trees with faster rates of diameter growth are able to close open wounds sooner, thus minimizing the time the wound face is available for fungal colonization. By sealing the wound, the tree also creates an unfavorable anaerobic environment for wood decay organisms, most of whom are aerobic [105,109]. High rates of diameter growth more rapidly restore structural support in the tree's bole and vascular cambial functioning after fire scarring of the bole [73,109]. Growth near the area of injury (wound wood ribs) can be faster than on other portions of the bole [71]. However, frequent fires commonly decrease diameter growth in most species, prolonging the time wounds may remain open for decades if fires are frequent enough (<5 or 10 years) [24,74,101].

3.4.1. Compartmentalization

Compartmentalization is a process whereby trees are able to establish a protective boundary surrounding cells injured by fire [109] (Figure 2D). The boundary is the result of the formation of tyloses and production of waxes, gums, and resins to form a barrier that inhibits cell desiccation and microbial infection. The ability to compartmentalize injuries varies by species. The birches (*Betula* spp.) are less effective at compartmentalizing stem wounds than maples and oaks [105]. Oak species, especially those in the white oak group, have an unusual ability to rapidly compartmentalize fire injuries [71,105]. Authors of a previous paper [71] found that low-intensity dormant season fires produced relatively small scars (scorch height < 102 cm above the ground) that were often concealed by intact bark and were effectively and rapidly compartmentalized in black oak and chestnut oak trees (dbh range 10 cm to 56 cm).

3.4.2. Heartwood Decay Resistance

Resistance to the spread and development of decay in the heartwood due to such factors as the production of toxic biochemicals (e.g., phenolic compounds) or tyloses [110] varies by species and is important to retarding decay that originates from fire scarring. Species of the white oak group (Figure 2D), black locust (*Robinia pseudoacacia* L.), catalpa (*Catalpa* spp.), black cherry, cedar (*Juniperus virginiana* L.), and cypress (*Taxodium* spp.) have heartwood that is resistant to very resistant to decay [102]. Red oak group species, hickories, maples, sweetgum (*Liquidambar styraciflua* L.), yellow-poplar, birches, eastern cottonwood, and American beech have only slight to no resistance to heartwood decay.

3.5. Scar Size and Time Since Wounding

Fungi that infect tree boles through logging or fire scars can cause substantial loss of value and degradation in timber quality over several decades [111]. The authors of a previous paper [30] found that one third of the volume can be defect in white oak, black oak, and scarlet oak butt logs (i.e., the lowest log in a standing tree) within 25 years after the trees received a fire scar. The proportion of butt log that was defect after fire scarring increased with increasing size of fire scar (from 1000 square cm to 6000 square cm) and decreased with increasing size of tree (from about 20 cm dbh to 56 cm dbh) at time of scarring.

Wider scars (Figure 2C) take a longer time for a tree to close by diameter growth. The authors of a previous paper [24] observed that fire scars in mature white oak averaged 8.9 cm in width and took on average 10 years to close in a Missouri oak woodland managed by prescribed burning, but larger scars (23 cm wide) took up to 24 years to close. Fire frequency has an effect on potential scar sizes, with percent of trees scarred and scar size decreasing in annual fire regimes compared to periodic, i.e., every 4 to 5 years [29,83,101]. And burning in thinned stands with slash increases not only percentage of trees scarred but also increases average scar size in oaks [74].

The authors of a previous paper [22] reported that both value and volume loss to decay and lumber degrade in black oak, northern red oak (*Q. rubra* L.), and scarlet oak butt logs increased with increasing prescribed fire severity and initial fire scar size as represented by scar height and scar depth. Most of the devaluation in the butt log resulted from declines in lumber grade and not from volume loss. However, they found that scaled volume loss averaged only 4% and value loss averaged 10% after 14 years from fire injury. They concluded that where <20% of the bole circumference was scarred and scar heights were <51 cm that value loss would be insignificant within 15 years of scarring, and that harvesting the most severely injured trees (e.g., Figure 2C) within 5 years limits value loss. The authors of a previous paper [31] reported also that value and volume loss increased with increasing fire scar size (wound width and length), time since wounding, and tree diameter at the time of scarring. Similar evidence of the extent of fire injury was noted by the authors of a previous paper [71] who measured scorch height on oak boles and found that it was generally <102 cm after low-intensity prescribed fires in Ohio. They observed that most wounds occurred near the ground and were covered by intact bark, small in size, and rapidly and effectively compartmentalized within 2 years of the fire. Thus, losses due to wood decay can be minimized if fire intensity is low and scarred trees are harvested before decay enters the log scaling cylinder and becomes advanced.

The stage of stand development and tree size at the time of fire scarring may influence the probability that decay will substantially reduce wood volume or value by the time the tree is harvested. Fire scars on small diameter trees that survive the injury are necessarily small in size because they are limited by tree size. Closure of the wound is rapid if the tree is vigorous and free-to-grow; this minimizes the likelihood of fungal infection and value loss is negligible [31]. Large diameter trees are better protected from fire scarring by their thick bark, and wounds tend to be small and low on the bole in low-intensity fires. These trees are merchantable and may be removed in a timber harvest soon after the fire (within 10 or 15 years) should fire injury occur, thus minimizing decay development that results in value loss [22,31,108]. In larger sawtimber, injuries on trees generally occur on the large end of the butt log and therefore they are often outside of the scaling cylinder where defect is removed in the slabwood resulting in minimal, if any, decrease in product recovery and value [22]. Fire-scarring of pole-sized and small sawtimber trees that will remain in the stand for 30 years or more are most at risk of advanced decay development and significant loss of volume and value by the time they are harvested. Pole-sized and small sawtimber trees can sustain large-sized scars that take time to heal, during which time they are prone to fungal infections, especially on mesic sites, where fungi populations thrive and moist scar surfaces may be more receptive to infection. Also, prolonged moisture in scars is more likely to occur when scars are in contact with the ground or when they are shaped such that they trap water.

4. Fire in Oak Management

In the next section we present several common scenarios in oak forest, woodland, and savanna management where managers may want or need to use fire, and they are concerned with avoiding or minimizing fire damage to trees. We also discuss the consequences of burning stands at various times in the life cycle of oak in terms of fire damage to trees that results in economic losses [59].

4.1. Scenario 1: Mature Forest with No Oak Advance Reproduction

Prescribed fire can be used to prepare the seedbed in advance of a good acorn crop or in preparation for artificial regeneration of oak by direct seeding or planting seedlings (Figure 3) [112,113]. Fire can reduce: (1) the physical barrier to oak seedling establishment created by deep litter (i.e., >5 cm), (2) seed of competitors stored in the forest floor, and (3) woody competitor density and structure in the mid and understory. Prescribed burning to reduce deep litter layers may need to be repeated because oaks have a periodicity in seed production and good acorn crops occur every 3 to 10 years depending on species. This may allow enough time for hardwood litter to accumulate to pre-burn levels before an abundant seed crop. In Central Hardwood forests, litter can return to 75% of its pre-burn levels in 4 years [89].

Prescribed fire can reduce the supply of viable seed of oak competitors such as black birch (*Betula lenta* L.), yellow-poplar, red maple, and grapevines (*Vitis* spp.) that occur in the seedbank, but repeated fires are needed to effectively lower seed supply, especially if seed-bearing trees occur in and around the stand to continuously add to the seedbank [114]. Removal of seed trees of undesirable competitors in conjunction with a regime of prescribed burning can help to deplete competitor seedbank supply. However, once an adequate supply of acorns falls to the ground, prescribed burning should cease until oak seedlings establish and begin developing a root system (e.g., $\geq$3 years) because even low intensity fires can kill the majority of an acorn crop and cohort of new seedlings [91,115,116].

Figure 3. Mature mixed-oak forests with complex vertical structure, and lack of oak advance reproduction are common starting conditions for managers interested in sustaining oak forests. The role of prescribed burning is to prepare the site for a good acorn crop and begin reducing the regeneration potential and vigor of oak competitors by diminishing their presence in the seedbank, understory, and midstory.

Shade tolerant midstory trees can dominate regeneration after overstory removal and prescribed burning in this scenario can begin the process of reducing the density of midstory competitors. Low intensity fires are capable of reliably top-killing hardwood trees up to about 10 cm in diameter but many of these stems will resprout after one fire. Although the rate of recovery in growth of competing sprouts is low under the high overstory stocking, repeated burning will be needed to control growth of competing sprouts and to increase their mortality [67,117,118]. The process of preparing the site to receive an abundant crop of acorns and developing a competitive cohort of large oak advance reproduction from that seed crop may take 10 to 30 years using combinations of stand thinning or shelterwood harvesting and prescribed burning [21,81]. Thus, scarring of merchantable stems or trees that will become merchantable by the time of harvest may lead to substantial loss of volume and value due to decay over 20 to 30 years [32,86]. Caution should be used when burning a forest for the first time due to high fuel loading that may have accumulated over decades of no fire. Subsequent fires, if frequent enough (<3 years), will be burning in lighter amounts of litter. Alternative methods for preparing the site for oak regeneration may include mechanical scarification to break up litter barriers and mechanical or herbicide treatment of the midstory. An herbicide application to individual midstory stems has benefits including the avoidance of stem wounding by fire, the prevention of hardwood sprouts from undesirable species, and fewer treatments required for sustained control of competing species. Midstory stems treated by mechanical cutting avoids fire scarring of residual trees, but does not prevent sprouting from cut stems, and it adds immediately to fuel loading that needs to be considered in future burning.

4.2. Scenario 2: Mature Forests with Abundant Small Oak Advance Reproduction

This is a common situation in eastern oak forests that have not been burned in decades. A multitude of seedlings may establish following a bumper acorn crop (Figure 4). Small oak advance reproduction (<30 cm tall and 6 mm in basal diameter) have low regeneration potential, and midstory removal or shelterwood harvesting are often recommended to reduce stand density and deliver more light to the forest floor to promote oak seedling growth [119]. This scenario is not to be confused with the situation where an abundance of oak advance reproduction with small shoots occur as sprouts following a fire that may be arising from larger root systems in stands managed with frequent fire over decades. Prescribed fire can be a useful tool for controlling competing woody stems that are <10 cm dbh, but it has the potential to cause high mortality in oak seedlings with small root systems. Therefore, authors of previous papers [81,120] recommended encouraging oak seedling growth with a shelterwood harvest that removes about 50% of the initial stand basal area, to about B-level stocking, and burning either just before or several years after final overstory removal. Once oak seedlings have become large (e.g., ≥19 mm basal diameter), then moderate- to high-intensity fires can increase the relative abundance of competitive oak reproduction, especially when conducted in the early growing season [81,121]. Waiting as long as possible to conduct the release burn to allow the oak seedlings to grow increases their capacity to sprout vigorously following top-kill from the fire. In unburned forests, basal diameter in oak is an indicator of the size of the root system, which drives sprout growth [122,123]. For several years after each shelterwood harvest, oak seedlings will benefit from increased light levels. Monitoring the reproduction helps determine the need for and timing of prescribed burning. If the shelterwood is completely removed in 3 to 5 years after the initial cut, then fire scarring is not an issue. Scarring of residual trees that are retained for the long-term for wildlife or aesthetic purposes may reduce their longevity due to advanced decay in the lower bole, which renders trees more susceptible to breakage or blowdown in storms. Logging slash that lies within 1.0 m of a residual tree bole may result in mortality or severe scarring after a prescribed fire. Directional felling and managing slash piles during skidding to remove slash from the base of mature trees retained for the long term can greatly reduce the risk of fire damage [76].

Figure 4. Mature mixed-oak forests sometimes have abundant but small oak advance reproduction in the low light environment of the forest understory. The oak seedlings have low regeneration potential and are at risk of mortality by burning, hence efforts to promote their growth usually begin with increasing light by reducing the midstory by thinning or the overstory by shelterwood harvesting. Prescribed fire has a role to play in oak management once oak seedlings grow to larger sizes that are indicative of large root mass and carbohydrate reserve.

4.3. Scenario 3: Stand Initiation Stage after Final Shelterwood Removal or Clearcutting

During the stand initiation stage [124], following clearcutting or final removal of the shelterwood, prescribed burning is effective in promoting oak dominance over competing woody vegetation, as long as the oak advance reproduction is present in sufficient density before harvesting (Figure 5). Periodic fires (e.g., every 3 to 5 years) are useful for increasing the relative abundance of competitive oak seedlings [81]. Moderate to intense fires during early leaf out discriminate more in favor of oak if the oak reproduction is large [121]. As long as the majority of competing stems are <10 cm dbh, burning, within typical prescriptions, will cause top-kill throughout the stand of reproduction, which with time will favor oak dominance. There are no long-term deleterious effects of burning at this stage of stand development unless there are large overstory trees retained for wildlife habitat, aesthetics, or other long-term purposes, such as maintenance of hard mast production. The fire will top-kill the regeneration and new sprouts will be free of fire injury. Scarring in large trees may reduce their life span and compromise their purpose for retention, although while they exist, stem decay may increase their usefulness and value as habitat for den and cavity dependent wildlife species. When the oak regeneration is determined to be adequate and competitive, burning must stop for a sufficiently long period to allow seedling sprouts to recruit into the overstory. This may take 10 to 30 years depending on growth rates and source of reproduction. For example, reproduction from stump sprouts grow initially more rapidly than seedling origin reproduction, reaching 5.8 cm dbh to 7.9 cm dbh in 10-year-old clearcuts in the Missouri Ozarks [125]. White oak saplings that are codominant in Missouri clearcuts grow 3.8 cm in diameter per 10 years on sites of average site quality (SI 18 m to 20 m for oak); at this rate it would take 20 years for a small diameter (2.5 cm dbh) sapling to reach 10 cm dbh and begin to improve its chances of surviving being top-killed by a low-intensity fire [126]. A sufficient fire-free period is crucial to permit recruitment into the overstory before burning is resumed. If timber management is a major objective, there may be no role for fire for the rest of the rotation until it is time to begin again the regeneration process. However, there may be a purpose for periodic fire if required to meet wildlife habitat, conservation of native diversity, control of invasive species, or other objectives.

Figure 5. In the stand initiation phase of forest development, following release of regeneration by clearcutting or final removal of the shelterwood, prescribed burning is highly effective to further promote oak dominance by taking advantage of their superior adaptations to fire when large oak seedling sprouts are competing in open environments.

4.4. Scenario 4: Stem Exclusion Stage, Crown Closure

When regenerating stands reach the stem exclusion stage [124], continued use of prescribed burning indiscriminately causes top-kill and retards stand development (Figure 6). Setting back a stand at this point results in the loss of 15 to 20 years of growth. If oak trees still require release to maintain adequate stocking of dominant stems at this stage, it is better to use mechanical or chemical release methods applied as a crop tree or area-based thinning. The risk of fire scars in larger saplings at this stage can result in substantial degradation and volume loss at the time of harvest, especially if the wounds are large enough to remain open to fungal infections for a decade or more. And practically, it may be difficult to conduct a prescribed burn due to lack of adequate fine fuel loading in the understory, low wind speeds, high fine fuel moisture, and high relative humidity within these dense sapling stands.

Figure 6. Using prescribed burning to thin dense sapling stands is hard to do and is ineffective in releasing individual crop trees since it is rather indiscriminate in what stems are top-killed. Alternative methods such as mechanical cutting or stem injection of herbicides are much more effective in releasing individual oak trees and other desirable species. This is a critical time in stand development where managers can substantially modify future stand composition.

4.5. Scenario 5: Stands Managed by Uneven-Aged Methods

The use of uneven-aged methods, primarily single-tree selection, is not recommended for sustaining oak forests on mesic and hydric sites (Figure 7); however, there is evidence in the xeric forests of the Missouri Ozarks that it may be possible to sustain white oak forests by this method [19,127]. Application of prescribed burning with single-tree selection management is highly likely to cause a large amount of defects in trees by the time they reach sawtimber size. In this silvicultural system, trees are harvested to simultaneously promote regeneration and recruitment into the overstory. Trees of all sizes exist in the stand, and sapling, poles and small sawtimber that sustain fire scars are likely to remain in the stand for decades before being harvested, thus, permitting time for advanced decay to develop. Also, the growth of trees in the mid- and understory is reduced by overstory stocking and this increases the time it takes for fire scars to heal. Burning in uneven-aged stands also can disrupt the distribution of age classes because seedlings and saplings are susceptible to being top-killed or dying. With repeated burning, the regenerating cohort will be concentrated into a single (or few) age classes. The use of group selection has been advocated for oak regeneration because it provides more light to the regeneration than the single-tree method. However, controlling competing vegetation before and after harvesting is problematic in small, random openings located throughout the forest. Without large oak advance reproduction at time of harvest, and control of competing vegetation, group openings typically become dominated by non-oak species [128,129]. The use of fire to control competing vegetation in isolated group openings is operationally impractical due to the small size of openings, lack of natural fire breaks around openings, and group openings are commonly imbedded within a matrix of single-tree selection forest that is vulnerable to fire injury and decay.

Figure 7. In managing forests by uneven-aged methods such as single-tree and group selection the manager is simultaneously developing regeneration, and promoting the recruitment of sapling and pole-sized trees into the overstory at fine scales, i.e., individual and small patch tree gaps. Using prescribed burning to favor oak regeneration in such stands may retard the recruitment process by causing top-kill of saplings, and initiate the decay process by basal scarring saplings and poles, which may develop substantial decay in the lower bole over the decades to maturity.

4.6. Scenario 6: Savanna and Woodland Restoration

Savannas and woodlands were once much more abundant across the landscape in the eastern United States, especially in the border region of the tallgrass prairie and eastern deciduous forests (Figure 8) [130,131]. An increasingly common management goal is to restore these ecosystems where forests now prevail. A primary objective is to reduce stand density using prescribed fire to promote development of native grass and forb ground flora typical of these communities [20]. A challenge in restoration is how to reduce the density of larger overstory trees that have developed over the past 50 years or more since the commencement of fire suppression programs. Moderate- to high-intensity fires are needed to reduce overstory density in the larger size classes, which incidentally have the potential to severely scar the residual overstory trees and reduce their longevity in the overstory. Fire is also less specific about which trees are removed and which remain compared to other methods of stand density management. An alternative to using fire to reduce stand density is to conduct a timber harvest. This permits recovery of wood products, avoids the problem of fire scarring residual trees, and provides better control over the distribution and composition of the final overstory. In addition, timber harvesting produces revenues that can be used to help pay for the management of the unmerchantable woody material, invasive species, or reestablishment of native ground flora. Lower intensity fires can be combined with timber harvesting and mechanical/chemical thinning to achieve other ecological objectives and control small hardwood sprouts. Even though timber quality and value are not foremost on the mind of restoration managers, it is well worth realizing that closed woodlands have nearly the volume of merchantable sawtimber trees as a forest does. And it goes without saying that minimizing fire damage that leads to timber volume and value loss is prudent management in woodland management. When it is time to replace the overstory in woodlands and savannas, a fire-free period is necessary for recruitment. Often there is large oak advance reproduction present because partial overstory density and periodic fire promote oak reproduction.

Figure 8. Managing mature oak forests (**A**) to restore woodlands (**B**) and savannas (**C**) involves reducing tree density in all size classes. Prescribed burning is effective in reducing tree density in the smaller diameter classes (e.g., <10 cm dbh) in the understory and midstory (**B**). Mechanical cutting or herbicide application methods are better for reducing density of larger midstory and overstory trees (**C**).

5. Conclusions

The use of prescribed fire in restoring and sustaining oak ecosystems does not have to have the same negative outcomes as the history of wildfires, with the damage they caused resulting in high amounts of standing live cull volume, especially that which arose out of European settler wildfires burning through a landscape of logging slash generated by regional logging and timber exploitation. Historically, fire was an integral driver of the widespread distribution and dominance of oak in forests, woodlands, and savannas, especially on mesic, high quality sites. And it is a necessary and often unique disturbance that is needed to sustain oak forests and restore woodlands and savannas today.

There are alternative management practices that can achieve similar outcomes in managing woody structure, but sometimes fire is the most effective tool for achieving specific management objectives, and at times there is no substitute for fire in achieving certain ecological objectives or for restoring ecosystem function. Fire can be compatible in oak management if understood and used properly because oak species have several morphological characteristics that make them well adapted to fire, and these can be exploited to improve oak regeneration success and set it on course to rise to dominance in mature stands. Nonetheless, prescribed fire still has the potential to do damage to trees and the forest if misapplied or used at the wrong stage of stand development. The extent of damage that develops in forests after fire depends on the use of fire in the silvicultural system, and ultimately management goals. It is important to time fire use and control its severity by managing fire intensity and applying it judiciously when it is appropriate given stand structure, composition, and desired stand developmental trajectory. It is imperative to know what the positive and negative consequences are when using fire to sustain oak ecosystems. Fire can provide many ecological benefits; it can also cause much damage and value loss. Wise decisions on fire use derive from knowledge of fire effects on the array of biological, ecological, economic, environmental, and social values, goods and services that come from oak ecosystems.

Small diameter trees that survive being burned can only have small wounds, because if they had large wounds they would be completely girdled and suffer top-kill or mortality. If they are in a dominant competitive position and are vigorous, they can heal quickly, preventing fungal infection and rapidly compartmentalizing the injured tissue. If the damage is to sprouting species such as the oaks, then sprouts following top-kill are free of injury and have room to grow, at least temporarily. Large diameter trees are harder to scar by fire due to their thicker bark. Should they be scarred, these trees are merchantable and may be harvested to limit wood decaying fungi from causing much volume or value loss. Fire scars on the lower end of the butt log are often outside the scaling cylinder and therefore do not affect product recovery or value. It is pole and small sawtimber-sized trees that are at greatest risk of sustaining large scars and remaining in the stand long enough to develop substantial decay. In oak forests and woodlands, prescribed fire is most useful to prepare for and manage regeneration of desirable species. It can be used without causing considerable loss in stand volume or value when incorporated as part of an even-aged silvicultural system. Intermediate-aged stands are at high risk to fire injury and damage; alternatives to fire are preferred for managing stand composition, growth, and quality in these stands. In any case, individual large-diameter trees are at risk of fire damage if the intention is to retain them for the long-term and they are subjected to high-intensity fires. We can manage the timing and application of fire, fuels, and hence fire intensity and duration to minimize the risk of fire damage and mortality.

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