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REVIEW ARTICLE

Fire exclusion as a disturbance in the temperate forests of the USA: Examples from longleaf pine forests

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Abstract

Forest fires are a disturbance where the effects can range from benign to extreme devastation within a given ecosystem. The stage of stand development coupled with prior management dictates the amount and composition of potential fuels. Thus, fire policy exerts a strong influence on fire effects. Changes in cultural acceptance and use of fire typically drive fire policy. This linkage is perhaps exemplified by America's 300 year love/hate relationship with this powerful natural force. This article uses the four stages of stand development (stand initiation, stem exclusion, understory reinitiation and old-growth), as described by Oliver and Larson (1996), to present opportunities and constraints to fire use, and management options are suggested. Using a selective review of research in the USA that emphasizes the longleaf pine ecosystem in the south-east, the focus is on three themes presented from the viewpoint of a resource manager trying to attain a specific result. First, some high points in the history of fire in America and its ecological ramifications on the landscape are outlined, using examples to illustrate key concepts of behavior, intensity and periodicity. Secondly, examples are given of how people have sought to exclude fire from the landscape, often with disastrous consequences. Thirdly, the topic of prescribed fire in an ecosystem maintenance and restoration role is touched on. Some challenges associated with reintroducing fire into areas where past fire policy dictated its exclusion are also related.

Keywords: *Fire behavior, fire effects, fire policy, longleaf pine, restoration, stand dynamics, suppression.*

Introduction

Throughout time people have marveled at the many faces of fire and long ago discovered that they could use this natural force to enhance their standard of living. Over the millennia, this combination of natural and anthropogenic fire shaped the landscape mosaic of the Earth, creating and manipulating vegetative communities from open grasslands to dense forests.

In the USA, burning practices have shifted from: (1) widespread Native American use, which sustained fire-maintained ecosystems and did not appear to cause long-term ecological damage (Pyne, 1997), to (2) the ubiquitous use of fire by European settlers in conjunction with their introduction of exotic plants and animals, often resulting in unnatural/unsustainable vegetative communities, then to (3) attempted fire exclusion without regard for the ecological consequences, and finally to (4) recognition that fire must be returned to the landscape in the long run to avoid catastrophic ecological and human consequences.

(1) *Native American use.* Lightning fires have been occurring for millions of years (Robbins & Myers, 1992) and are often considered the primary selective force favoring development of fire-adapted traits in animal and plant communities of the south-eastern USA. At some point the indigenous people of the region began to set fires to augment the observed effects of lightning fires that favored their lifestyle, e.g. providing new forage for game, and driving or concentrating game so they might be more easily hunted (Pyne, 1997). These ignitions by Native Americans extended human influence out of proportion to the population size (Hudson, 1976) and expanded the burning season from several months in late spring/early summer to include all months of the

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year (Martin & Sapsis, 1992; Carroll et al., 2002). Occasional high-intensity, wind-driven fires (after hurricanes and insect epidemics) and severe drought fires were superimposed on the chronic lightning and Native American fire regimen, creating the open woodlands noted by early European explorers (Bartram, 1791; Landers et al., 1990; Olson, 1996; Pyne et al., 1996; Barden, 1997; Carroll et al., 2002). Lightning strikes, fires and/or smoke columns were often recorded in the writings of European explorers, beginning in the early sixteenth century (e.g. de Laudonniere, 1587), and there is no reason to suspect that the earlier pattern was any different.

(2) *European settlers*. The arrival of European settlers significantly changed the pattern of fire use. These early settlers were primarily pastoral herdsmen (Owsley, 1945) from the British Isles, Spain and France, where fire was an integral part of their livelihood. They brought this practice with them, blended their fire knowledge with that of Native Americans, and expanded the use and frequency of fire throughout the south, often burning every year (Wade et al., 2000). Fire was used to achieve a multitude of benefits (e.g. Wade & Lunsford, 1988) and little thought was given to containment. Extensive and often wasteful timber cutting combined with fires, both set and accidental, to create conflagrations that scorched hundreds of thousands of hectares and, by the early twentieth century, resulted in a public hue and cry (Pyne, 1997). The US federal government responded by passing laws prohibiting the use of fire and investing extensively in the detection and suppression of wildland fire (Pyne et al., 1996; Johnson & Hale, 2002).

(3) *Attempted fire exclusion.* The federal government pressured all southern states to follow suit and pass laws prohibiting the use of fire with the promise of fire suppression funding and the threat of withholding other funding (see Schiff, 1962, for a detailed account). This fire exclusion policy was initially effective, but as fuels accumulated, fires became increasingly more difficult to suppress. Early gains were soon replaced by fuel loads that far exceeded what had existed historically (Fulé et al., 2001). The resulting fires were more damaging and dangerous to control. A lack of labor for fire-fighting during World War II necessitated the reluctant approval of intentional fire to reduce fuel loads on some southern national forests, but the concept of fire as an ecological imperative was not organizationally embraced for another 50 years.

(4) *Ecological use of fire.* In the wake of fires that ravaged the northern Rocky Mountains in the 1980s, the public again demanded action, and federal land management agencies switched from attempted fire exclusion to a policy that recognized the ecological role of fire. The federal government implemented a plan to increase substantially the use of fire to sustain historic ecosystems on federal lands (US Department of Interior and US Department of Agriculture, 1996; US Department of Agriculture, 1997). It will, however, be many decades before the unnaturally high levels of fuel that accumulated under the fire exclusion policy are reduced through fuel reduction projects, or by wildfire (Parsons, 2000). In the meantime, catastrophic fires will continue to occur.

These informal and formal fire polices have all had dramatic effects on the structure and composition of forest vegetation. Attempted fire exclusion, in particular, has occasionally resulted in new successional pathways, and has created many of the untenable vegetative conditions that currently characterize many landscapes (Landers et al., 1995; Brennan et al., 1998). For example, once the herbaceous groundcover has been shaded out by the rank growth of various brushy species in the open longleaf/slash pine (*Pinus elliottii*) communities along the west coast of Florida, a wide swath of brush typically has to be cut and left to dry to provide enough fuel for a fire to develop the intensity necessary to ignite and burn through the flammable understory. Without periodic fire, these communities succeed into pure hardwood communities as the pine overstory dies out (Robbins & Myers, 1992). The same situation occurs in open longleaf stands across the sand hill region of the southern USA, where the scrub oak understory has to be cut to provide fuel for a fire to carry in this fire-maintained community. A western USA example occurs in the redwood region of California, where a dense midstory of various firs (*Abies* spp.) occurs with fire exclusion that precludes redwood (*Sequoia sempervirens*) regeneration (Oliver & Larson, 1996).

Another challenge, which in the long run will probably prove even more daunting, is the rapidly expanding wildland–urban interface (WUI), a boundary area where human occupation meets the open, wild landscape (e.g. Randall, 2003; Long et al., 2004). Prescribed fires at the WUI are much more complex, requiring more planning and coordination, more equipment and personnel, and more complete mop-up. In addition, although many people now conceptually accept the pivotal role that fire plays in maintaining healthy ecosystems, they appear to be more reserved the closer prescribed fire is to human settlements (Loomis et al., 2001; Winter et al., 2002, 2004; Brunson & Shindler, 2004; Brunson & Evans, 2005).

Patterns of persistence

Many forested ecosystems such as longleaf pine (*Pinus palustris*) are actually maintained by

disturbances such as fire and these forests might eventually disappear from a site if fire is withheld for long enough, particularly on fertile sites with vigorous hardwood competition (Hermann, 1995). Other forested ecosystems are influenced by periodic fire on a time-span ranging from several years to several centuries. See Brown and Smith (2000) for a description of fire regimens, and autecological and synecological effects of fire in various American ecosystems.

Tree species in general differ in their degree of fire tolerance and maintain their presence on a site through several distinctly different strategies. These strategies can be summarized under three general headings (from Bond & van Wilgen, 1996):

1. *Endurance*: the plant tends to survive even the most intense fires as long as its stem is not girdled and not too many of its buds are killed by heat. Examples include longleaf pine and south Florida slash pine (*P. elliottii* var. densa), which go through a grass stage where they develop a strong root system and then grow rapidly to put the apical bud above the typical flame zone. Both species thrive under a chronic fire regimen that ensures most fires are low intensity because of a lack of fine fuel; they typically survive such fires even as juveniles. Some western North American species, such as Douglas fir (*Pseudotsuga menziesii*) and western larch (*Larix occidentalis*), and many pines [e.g. loblolly (*Pinus taeda*) in the south and ponderosa (*Pinus ponderosa*) in the west] become resistant to understory fires as they mature and develop a thick bark.
2. *Sprouting*: this heading includes plants usually topkilled by fire when young, but their root systems survive and readily sprout; examples include many oaks (*Quercus* spp.).
3. *Seed-based*: species in this group are fire sensitive, especially when young, but some, such as Table Mountain pine (*Pinus pungens*) and lodgepole pine (*Pinus contorta*), are able to persist because they have serotinous cones that release their seed after extreme heat melts the resin bond, allowing the seeds to fall on the nutrient-rich ash bed below (Turner et al., 1999). Other species, such as yellow poplar (*Liriodendron tulipifera*), are able to persist because of seed buried in the soil or unburned duff that germinates after being heated by fire. In both of the above cases, these species recolonize the burn from seeds on the site. Finally, species such as birch (*Betula* spp.) have virtually no immunity to fire throughout their lifespans, but persist by quickly recapturing a site because nearby individuals release a copious amount of light seed that blows in to recolonize the ash bed.

Fire-maintained ecosystems

In this review the discussion is mainly tied to the fire-maintained longleaf pine ecosystem of the southeastern USA. Historically, it occupied more area dominated by a single species than any other ecosystem in the USA, stretching from the Atlantic Ocean and Gulf of Mexico to the foothills of the Southern Appalachians and Ozarks. Stands are typically open forests, woodlands and savannas comprising an overstory of longleaf pine above a herbaceous groundcover with occasional clumps of longleaf reproduction. These communities are noted for the diversity of their groundcover vegetation (Walker & Peet, 1983; Bridges & Orzell, 1989; Noss, 1989; Boyer, 1990; Peet & Allard, 1993), which is maintained by frequent fire, primarily during the growing season (Andrews, 1917; Wells & Shunk, 1931; Wahlenberg, 1946; Grelen, 1975; Platt et al., 1988*b*; Landers et al., 1995). Burning in such a forest type also facilitates the presence of wildlife such as bobwhite quail (Stoddard, 1931; Moser et al., 2002) and the endangered red-cockaded woodpecker (Conner et al., 1997), as well as maintaining or enhancing understory plant diversity (Glitzenstein et al., 2003; Moser & Yu, 2003). Landers and Wade (1994) hypothesized that this ecosystem persists because a climate–site–fire–plant interaction reinforces dominance of the longleaf pine–bunchgrass ensemble.

Under such conditions, it is not a question of whether to use fire, but rather at what frequency, season and intensity (e.g. Grelen, 1978; Platt et al., 1988*a*). Although longleaf pine growth can be reduced by fire (Boyer, 2000), the longleaf ecosystem evolved under a chronic fire regimen (Landers, 1991; Frost, 1993), and the continued presence of fire is required to keep the various vegetative associations healthy and maintain their typical two-tiered nature (Christensen, 2000). Many students of fire history think that typical longleaf sites burned every 2–10 years before Europeans arrived (Frost, 1993; Christensen, 2000) and then every 1–3 years until aggressive fire-suppression activities began in the 1920s (Landers et al., 1990; Landers, 1991). Xeric sites burn as soon as enough fuel accumulates to carry fire, generally every 3–8 years.

Longleaf roots, bole and crown all possess traits that make this species very fire resistant. These traits include a juvenile grass stage that focuses on root growth; a thick root collar which, along with the taproot, stores enough food reserves so that when

the seedling initiates height growth, it will grow 1 or 2 m during the first year, often placing its terminal bud above the flames of the inevitable fire; enormous buds with a high heat capacity that help to keep cell temperatures below the lethal threshold; tufts of long needles concentrated at branch tips which envelop and shield the buds; and thick bark that protects the cambium from heat once the ground-line diameter exceeds about 1.5 cm. Forest managers can take advantage of these traits to facilitate achievement of resource management objectives.

Stand development principles

Why focus on stand dynamics?

Depending on the species, age and structure of the forest, as well as fire intensity and severity, postburn recovery to the preburn sere can take from months to centuries. For example, the fire regimen in some northern coniferous ecosystems is characterized by stand-replacement burns with a return interval measured in centuries, while some southern coniferous ecosystems are characterized by low-intensity surface fires with a return interval of only a few years (e.g. Duchesne & Hawkes, 2000; Wade et al., 2000).

The behavior and intensity of a fire are functions of the fuel complex, burning conditions, and cause and location of ignition, whereas the impact or severity of a fire is also a function of the proportion of the forest floor and coarse woody debris consumed, the proximity of live tissue to lethal temperatures and the time for which this lethal threshold was exceeded (Pyne et al., 1996). The fuel complex is, in turn, defined by stand structure, composition, nature of the last disturbance and length of time since it occurred. Thus, before fire is intentionally applied to a vegetative community, one should have a good idea of the present state of the community, how it got there and where it might be heading with or without disturbance (Christensen, 1988).

Fire effects

Activities that maintain forest structure often overlap the stages of stand development: fire that thins dense vegetation in the stem exclusion stage often results in growing space for regeneration in the understory reinitiation stage, and fire that maintains an open forest character in the old growth stage may also encourage regeneration. The judicious use of fire thus requires that the manager not only understand how to use this tool to achieve the management objective at hand, but also recognize the ancillary stand effects that every fire will produce. The following sections look at how different fire policies—fire exclusion, prescribed fire and reintroducing fire to previously fire excluded forests—impact forests in different stages of stand development.

Effects of stand structure

For a fire to start and spread, there must be enough fuel of the right size and arrangement, weather conditions must be favorable and there must be an ignition source, either natural or human. The structure of the forest influences the first two by dictating the fuel array, its vertical and horizontal continuity, and the amount of live and dead fuels. Forest structure also affects stand microclimate. The amount of sunlight reaching the forest floor, fuel temperature, relative humidity and subcanopy wind profiles are all controlled by the presence and density of overstory, midstory and understory canopies (Rothermel, 1972; Miller & Urban, 2000).

Fewer fires start in very dense stands because the forest floor takes much longer to dry than it does in more open stands. The more humid conditions dampen fire intensity and result in less severe fires, although when conditions are dry enough, or when intense fire enters such a stand, the close proximity of tree crowns facilitates the formation and spread of crown fires. As these dense stands mature and reach senescence, both fire intensity and fire severity tend to increase. Lodgepole pine (*P. contorta*) stands that burned in the 1988 wildfires in Yellowstone National Park, Wyoming, represent one example (Christensen et al., 1989).

Back in the south-eastern USA, in contrast, longleaf pine savannas support an abundant groundcover that dries quickly and ignites easily, but generally results in lower fire intensities and less severe fires. When this ecosystem is not burned frequently (every few years), a dense, flammable understory forms, which under adverse weather conditions can result in a catastrophic crownfire (Robbins & Myers, 1992; Landers et al., 1995), as happened during the 1998 drought in Florida.

Basic to this discussion is the premise that stand structure and composition are not static concepts, but change both spatially and temporally. Oliver and Larson (1996) categorized these changes into four stages or generalized categories of stand development; this model is one from among a suite of different classification schemes (see Bormann & Likens, 1979; Spies & Franklin, 1996; Carey & Curtis, 1996; Franklin et al., 2002). Although Figure 1 suggests a linear transition between discrete phases, in fact it represents a convenient mental demarcation of what is really a continuum with multiple potential transition pathways.

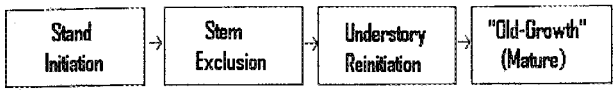

Figure 1. The four stages of stand development (Oliver & Larson, 1996).

The length of time an ecosystem spends in any one of the four stages varies depending on factors such as species, site (e.g. soils and aspect), presence of insects or disease, weather (e.g. drought), and the timing and severity of both the previous and next disturbance. The advantage of examining fire in light of stand development patterns is that the structure at certain times can be grouped into categories that are similar in fire susceptibility, fire behavior and fire effects.

Stand initiation stage

After a disturbance, new individuals and species continue to appear for several years. In short fire-return interval ecosystems such as longleaf pine, the overstory usually remains intact, although groundcover species abundance and dominance vary. The stand initiation stage can last from 1 or 2 years to many decades. A second fire during this stage will have significant impacts on ecosystems that are perpetuated by stand replacement fire regimens, often extirpating species from the site and requiring anthropogenic intervention to ensure the same successional pathway used before the untimely second fire. For a manager, this stage is the opportune time to affect stand composition easily.

Fire-adapted species tend to be less tolerant of shade than those not adapted to fire (Pyne et al., 1996). Thus, an obvious effect of fire exclusion is to promote species that are not fire adapted to regenerate and grow. Once sunlight is severely curtailed at the forest floor, shade-intolerant species, including most pioneer species, will not regenerate, ultimately resulting in plant community strata composed solely of shade-tolerant species (Oliver and Larson, 1996). In longleaf pine communities, fire exclusion for only a few years will limit longleaf regeneration (Landers et al., 1995), but this process takes much longer for other species at higher latitudes such as in boreal forests.

Fire-maintained ecosystems depend on disturbances such as fire at the stand initiation stage to ensure their continued presence in a stand. Prescribed fire at this stage rids the site of brown spot disease, a debilitating pathogen of juvenile longleaf pine; consumes accumulated litter and dead woody debris on the forest floor, releasing the nutrients stored in these fuels for use by soon-to-establish germinants; and removes understory and groundcover canopies, allowing sunlight to reach the newly exposed mineral soil seedbed.

Timing of a burn should be considered when establishing a new stand to ensure that the desired results are achieved (Gagnon et al., 2004). For example, managers desiring to establish a crop of longleaf pine will watch the overstory for a good cone crop, which takes 2 years to mature; when it materializes, they burn in late summer of the second year to prepare a mineral soil seedbed. This procedure allows enough vegetative recovery to hide the large longleaf seed from rodents, but not enough to provide undue competition to the seedlings that will appear soon after autumn seed fall.

A second example from the northern USA pertains to ensuring enough viable seed when desiring to regenerate red pine (*Pinus resinosa*) or eastern white pine (*P. strobus*). Cone beetles (*Conophthorus resinosae* and *C. coniperda*) can destroy close to 100% of the cone crop of these two pines, resulting in little regeneration. Low-intensity fire can be used to kill this pest, which overwinters in cones in the litter beneath the fire-resistant mature pines (Miller, 1978; Wade et al., 1990).

A major traditional use of fire has been radically to change the vegetation to prepare for establishing a new suite of vegetation. Often a regeneration burn will control competing vegetation. On sites where fire long has been excluded, the challenge is finding enough of the desired fire-tolerant species that may be promoted by fire. Frequently, the desired species must be augmented, or completely established, by planting.

Stem exclusion stage

Eventually (1 or 2 years in longleaf stands depending on the season of burn), the rate at which new stems appear will drop precipitously and some of the newly established seedlings will die, the result of competition for moisture, light and nutrients as the available growing space is claimed by plants with well-established root systems. The surviving seedlings grow larger and express differences in height and diameter. In a stand replacement fire regimen, early successional or ruderal species will progressively dominate the various strata within the stand, eventually followed by a more shade-tolerant species. In contrast, ecosystems maintained with understory fire regimens (low-intensity fires generally of 1–3 m flame length that rarely burn tree crowns) (Robbins & Myers, 1992; Pyne et al., 1996), such as longleaf pine, continually go through only the first two or three stages, so changes in dominance are confined

to the herbaceous groundcover and woody understory plants, many of which developed from basal hardwood sprouts. In general, stand patterns are the result of growth and responses to individual interactions, although subtle variations in stand condition can change the competitive balance.

Fire exclusion in the stem exclusion stage eliminates fire as a force for creating spatial variability. While the actual practice of using fire as a deliberate thinning tool is not widely accepted (but see Wade, 1993), natural fire in the stem exclusion state can create irregular habitat patches, allowing individuals that escape or survive burning to capture the growing space of their dead neighbors, and hastening differentiation within a forest. Because longleaf pine seedlings usually survive low-intensity fires while other southern pines take a few years to develop fire-resistant stems, fire exclusion during the stand initiation stage will favor other faster growing pine species such as *P. taeda* and *P. elliottii*, at the expense of longleaf pine.

The same situation presents itself in other fire-mediated ecosystems. For example, in a stand containing oak and hickory (*Carya* spp.) seedlings, fire exclusion would favor regeneration of hickory species (Johnson et al., 2002). Above-ground growth of oak germinants is slower than most competitors because oaks expend much of their energy to develop a strong root system; they are thus quickly overtopped. Periodic low-intensity fires, in contrast, favor oak seedlings because, although they are topkilled and resprout along with their competitors, the oak sprouts now have a better root system and will therefore outgrow most competitors including hickory (Brose et al., 1999; Van Lear, 2004).

If prescribed fire is used at this stage, often the goal is either to promote understory fire-dependent forbs and herbs in forest types with relatively open canopies (like longleaf pine), or to keep the accumulation of debris on the forest floor at a manageable level. Fire can cause some spatial variation owing to localized concentrations of fuel, or act like a thinning from below (Pyne et al., 1996). Fire is also used in longleaf pine stands during the stem exclusion stage to eliminate seedlings of competing species, including other pines (Moser & Jackson, 2005).

Reintroducing fire to a fire-excluded stand in this stage of stand development, with the goal of bringing fire back to the ecosystem, runs the risk of a stand-replacement fire. With crowns relatively low to the ground, stems close together and often 1- and 10-hour fuels in the form of dead branches and stems, such fires have a good chance of causing substantial mortality.

Understory reinitiation stage

As the stand develops and trees grow larger, the base of the live crown moves up and distances between crowns increase owing to branch abrasion caused by swaying, thus releasing growing space in the understory (Oliver, 1978). Into this newly available environment come herbs, forbs and woody understory regeneration. In longleaf pine ecosystems, longleaf reproduction will survive the frequent fires that topkill its competitors, continue to gain stature and eventually move into the overstory as openings develop. In some stand replacement fire regimens such as sand pine (*Pinus clausa*) in the south-eastern USA, this species dominates each of the four stages in succession until it forms the overstory (Wade et al., 2000). In others such as the boreal black spruce (*Picea mariana*), although the spruce becomes established right after the last fire, the stand is typically dominated by a shrub layer for several decades until the spruce finally outcompetes the shrubs and forms the overstory (Duchesne & Hawkes, 2000). Depending on their goals, managers might desire to encourage or discourage understory regeneration. Fire can exclude small woody plants, but can also increase growing space by exposing forest floor and killing fine roots of existing vegetation.

In the absence of disturbance, woody stems will grow out of the groundcover and form an understory. In forest stands, shrubs will be confined to the understory, while trees will continue to attain height, eventually forming a midstory. Pioneer species will drop out as stand development progresses and not return until after the next disturbance (Oliver & Larson, 1996).

On a spatial scale, fire is not a uniform disturbance agent, so the absence of fire typically results in a more homogeneous stand with decreased species richness and less variation in stand structure, which means that the plant community provides a desirable habitat to a reduced suite of fauna. For example, in longleaf pine forests, recurrent fire provides a mosaic of habitats including areas of open grassland, patches of forbs and briars that escaped the previous fire, the brushy edge along the burn perimeter, clumps of regeneration and high forest that wildlife such as the northern bobwhite quail need in order to thrive (Moser & Palmer, 1997). Prescribed fire is used during this stage for several reasons. It topkills competing vegetation, opens up growing space through occasional overstory mortality caused by hot spots, recycles nutrients and reduces fuel accumulation.

Often reintroducing fire into an ecosystem requires more than the just the fire itself (e.g. Moore

et al., 1999). For example, on 400 ha in Florida, a landowner instituted a sequence of herbicide application, overstory harvest and prescribed fire to reduce the overall density and the proportion of hardwoods in a mixed pine–hardwood stand. Previous attempts at managing species composition and density solely with fire were unsuccessful. Whether this preharvest state was in the understory reinitiation stage is debatable, but management accelerated the process by reducing the overstory basal area and releasing the growing space for the understory plants (wildlife food and herbaceous regeneration) (Moser & Jackson, 2005).

Mature forest (old-growth)

At some point overstory trees begin to die, often in an irregular fashion, from lightning, insects or disease. As this process continues, some midstory trees will grow into the overstory.

In the absence of disturbance, many ecosystems will pass through most of the stand development stages several times, each being dominated by a new suite of tree species. Depending on the type and periodicity of disturbance, the final structure and composition will vary. Species that depend on stand replacement fires for continued overstory dominance, such as sand pine (*P. clausa*) in Florida, rely on fire to restart the clock. According to Arno (2000), some species, such as Douglas fir (*Pseudotsuga menziesii*) in western North America, may require different fire regimens depending on climate or topography. The cooler, wetter, more northerly portions of the Pacific Coast Douglas fir type tend to be associated with stand replacement fire regimens, while mixed fire regimens are characteristic of this type in the southern part of its range. Interior Douglas fir stands in the Rocky Mountains are also associated with a mixed fire regimen except near timberline, where they are maintained by understory fires. Low-intensity fires, even when 100 years apart, result in stands with a significant Douglas fir component. If fire is excluded for many centuries, however, dense second growth stands of Douglas fir and western hemlock (*Tsuga heterophylla*) often stagnate and succumb to root rot. As fire is withheld over time, litter and down woody fuels as well as ladder fuels continue to accumulate, setting the stage for the catastrophic fires that these ecosystems are now experiencing.

As stated earlier, presettlement longleaf pine stands were probably maintained by a 2–10-year fire-return interval (Christensen, 1981; Frost, 1993). On some deep sands, the absence of fire did not result in significant compositional change from the longleaf pine forest (Abrahamson, 1984*a*, *b*; Christensen, 2000). On fertile and well-drained sites, however, fire exclusion will result in a southern mixed hardwood forest (Delcourt & Delcourt, 1977; Landers, 1991; Christensen, 2000). On sand ridges, the fire-return interval can dictate whether the future forest is longleaf pine (short interval) or sand pine scrub (long interval) (Christensen, 2000).

Many tree species, e.g. Douglas fir and western larch in the western USA and Canada, do not become fire tolerant until they grow out of the understory and their bark thickens. Where such species are part of the desired species mix on a site, prescribed fire should be withheld until this time. Although fire is used in the understory reinitiation stage to promote oak regeneration in the south-eastern USA, it also favors mature oaks because they have developed a thick bark by this time. In fact, fire during this stage is becoming an integral part of managing many mixed mesophytic hardwood stands (Brose and Van Lear, 1999).

Reintroducing fire in the mature stage of stand development is a long-term process. Where fire has not been excluded for long periods in southern pines such as longleaf, it is usually possible to conduct two or three winter burns, 2–3 years apart to reduce fuel loads, and then switch over to growing season burns to encourage the herbaceous groundcover (R. Phernetton, US Fish and Wildlife Service, pers. comm.). In contrast, where fire has been withheld for decades, allowing an unnaturally high accumulation of dead material on the forest floor as well as a fully stocked understory and midstory of hardwood brush and trees, the situation is much more volatile. Under dry conditions, a backing fire will consume too much of the forest floor, killing feeder roots, and thereby causing overstory pine mortality. In such stands, a headfire is necessary under cool, damp, windy conditions; the fire will have fairly high fireline intensity, but only the uppermost litter layer will be consumed. One has to make sure that the overstory is substantially above the midstory, so the hardwoods and needle drape do not act as a ladder to allow a lethal heat flux to kill overstory pines. This technique cannot be used in fire-starved southern pine plantations because the close proximity of pine crowns will facilitate crown fire development. The keys to success are a very steep duff moisture gradient and wind rather than season of year. A common mistake is to complete a successful reintroduction burn and then consume too large a duff increment in the second or third fire. It took decades of fire exclusion to create such an environment, so one should expect that it will also take decades to correct (Wade & Lunsford, 1988).

Summary

Every site has its own unique set of ecological conditions and deserves a unique management plan, including the appropriate role of fire. Yet there are certain conditions or trends that suggest that one should at least consider a limited set of options. Use of fire in the stand initiation stage establishes a new stand, although in short fire-return interval ecosystems characteristic of many pines, fire will again be needed in either stem exclusion or understory reinitiation, or both stages to control species composition. In fact, species composition seems to be one of the principal influences of fire throughout the life history of the stand. In some stages, such as the stem exclusion stage, fire can be an influence over density and spatial arrangement of trees, while in the old growth (mature) stage, fire can have a significant influence over the structure of the forest.

Examining a forest in light of the four stages of stand development, or any of a number of useful process models, aids forest managers in determining whether they are achieving their targets. Each type of forest policy—exclusion, prescription or reintroduction—has its own set of requirements and effects. Only when managers understand how fire can help to achieve management goals while adhering to basic ecological principles will they be able to incorporate it successfully.

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