

silviculture

Silviculture to Restore Oak Savannas and Woodlands

Daniel C. Dey, John M. Kabrick, and Callie J. Schweitzer

Variability in historic fire regimes in eastern North America resulted in an array of oak natural communities that were dominant across the region. In the past century, savannas and woodlands have become scarce because of conversion to agriculture or development of forest structure in the absence of fire. Their restoration is a primary goal for public agencies and conservation organizations. Although they can be restored with a long-term regimen of prescribed burning, a combination of fire, timber harvesting, and forest thinning produces the desired structure and composition more efficiently. Prescribed fire is useful for sustaining oak savannas and woodlands, but it must be used judiciously to minimize timber damage and decreases in value. Integrating fire within a modified shelterwood approach promotes competitive oak reproduction and is flexible enough to produce savannas or woodlands. Sustaining these communities requires the replacement of the overstory during periods of no fire.

Keywords: restoration, silviculture, oak ecology, woodland, savanna

Natural communities dominated by oak species such as savannas and woodlands are recognized as some of the most endangered worldwide (Noss et al. 1995, Hoekstra et al. 2005, Noss 2013), and sustaining oak forests is a persistent and global conservation issue (Dey 2014). Restoring oak savannas and woodlands and other natural communities is increasingly a management priority in the United States, collectively affecting millions of acres throughout the eastern region (e.g., Mark Twain National Forest 2005, Ozark-St. Francis National Forests 2005, Eastern Tallgrass Prairie and Big Rivers Landscape Scale Conservation Cooperative 2014). Definitions of savannas and woodlands vary among the authorities, but common characteristics include the following: overstory dominated by oak species with 10–30% crown cover ($<30 \text{ ft}^2 \text{ ac}^{-1}$) in savannas and 30–80% crown cover ($30\text{--}80 \text{ ft}^2 \text{ ac}^{-1}$ in

basal area) in woodlands. Both community types have a negligible midstory woody canopy layer, sparse and patchy woody understorey, and diverse ground flora dominated by grasses, forbs, and sedges that is highly variable in composition and structure, depending on site conditions and overstory canopy cover (Missouri Department of Conservation 2010, Nelson 2010). Oak savannas and woodlands are natural communities that historically were prominent across the landscape in the eastern United States, especially in the forest-prairie transition region that stretched from the Great Lakes and surrounding Canadian Provinces to eastern Texas (McPherson 1997, Anderson et al. 1999, Hanberry et al. 2014b). In the United States, Noss (2013) reminded us of the once expansive southern grasslands, many of which were oak and pine savannas and woodlands. Historically, frequent fire created and maintained oak savannas and

woodlands for thousands of years (Delcourt and Delcourt 1991, Guyette et al. 2012). Fire interacted with topography to create a mosaic of natural communities with prairies blanketing the plains, savannas bounding the prairies on gently rolling topography, and woodlands and forests covering the rougher and dissected hill country (e.g., Batek et al. 1999). Today, these natural communities have been diminished by succession to forests after fire suppression and conversion to agriculture land uses. Savannas occur only in small relicts and for all purposes are missing from the modern landscape, $<1\%$ of their original extent (Nuzzo 1986).

Importance of Savannas and Woodlands

Savannas and woodlands are important natural communities and landscape components that need restoring. Before European settlement, savannas and woodlands added to the landscape diversity of natural communities that formed a variable complex matrix including prairie, savanna, woodland, and forest throughout the eastern United States (Transeau 1935, Anderson et al. 1999, Noss 2013). The current eastern United States landscape is less diverse in structure, complexity, function, composition, and natural community type (Schulte et al. 2007, Shifley and Thompson 2011, Hanberry et al. 2012, 2014a, 2014c, 2014d). Increasing ground flora diversity is associated with decreasing

Received December 28, 2015; accepted March 31, 2016; published online May 19, 2016.

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tree canopy cover along the structural gradient from forest to savanna (Taft et al. 1995, Bowles and McBride 1998, Leach and Givnish 1999, Peterson and Reich 2008). Species diversity in invertebrates, small mammals, birds, and herpetofauna is often higher with increasing plant species richness and heterogeneity in vegetation structure, which is highest in savanna communities (Huston 1994, Leach and Givnish 1999, Haddad et al. 2001).

Wildlife species often prefer the structural features of savannas and open woodlands. The big brown bat (*Eptesicus fuscus*), eastern red bat (*Lasiurus borealis*), evening bat (*Nycticeius humeralis*), and tricolored bat (*Perimyotis subflavus*) preferred savanna and open woodland habitats over closed canopy forests in the Missouri Ozarks (Starbuck et al. 2014). Likewise, Thompson et al. (2012) observed that restored savannas and woodlands in the Ozark Highlands provided habitat for a diverse mix of grassland and canopy nesting bird species that are of high conservation concern. The blue-winged warbler (*Vermivora cyanoptera*), eastern towhee (*Pipilo erythrophthalmus*), eastern wood-pewee (*Contopus virens*), field sparrow (*Spizella pusilla*), prairie warbler (*Dendroica discolor*), and summer tanager (*Piranga rubra*) were more abundant in savannas and woodlands than in closed canopy forests. Reidy et al. (2014) found that large-scale savanna and woodland restoration in the Missouri Ozarks provided additional habitat for woodland generalists and early successional species, some of which are of conservation concern. In the managed restorations, most of the focal bird species they studied responded positively to a history of fire over the past 20 years. In this largely forested landscape, fire increased the diversity of habitats available to songbirds, with corresponding increases in bird species richness, diversity, and density. Others have demonstrated the importance of having savannas and woodlands on the landscape for the conservation of rare and declining bird species that rely on disturbance and early successional habitats (Davis et al. 2000, Brawn et al. 2001, Brawn 2006, Grundel and Pavlovic 2007, Au et al. 2008). Even bird species that are known to prefer mature, closed canopy interior forests benefit from early successional habitat in the nearby landscape because juvenile birds forage for food and use the habitat as a refuge from predators (King and Schlossberg 2014).

Managing for disturbance-adapted ecosystems, increasing biodiversity at various scales, promoting drought-tolerant species, and maintaining low tree densities are considered key management strategies to address anticipated impacts due to climate changes (Janowiak et al. 2011, 2014, Brandt et al. 2014). Restoration of savannas and woodlands would embody these mitigation strategies for the range of future climate scenarios predicted. Many of these approaches for managing ecosystem resistance and resilience are reasoned conjectures and not universally tested hypotheses. For example, D'Amato et al. (2013) reported that thinning red pine (*Pinus resinosa*) forests to low density only increased drought resistance in the short term, as open-grown large trees in low-density stands have greater hydraulic constraints and increased water demand that make them more vulnerable in drought years. Tree species common to eastern United States savannas and woodlands such as post oak (*Quercus stellata*), blackjack oak (*Quercus marilandica*), and bur oak (*Quercus macrocarpa*) are expected to be favored by predicted changes in temperature and precipitation, modifications in their seasonal patterns, and frequency of extreme weather events (Brandt et al. 2014). Communities such as these, with high species richness, are considered more resilient to climate change, are better able to recover from disturbance such as drought, are less vulnerable to environmental stress and biotic threats, and are less susceptible to high-severity wildfires (Brandt et al. 2014). Restoration of savannas and woodlands would increase biodiversity at the community and landscape scales by increasing the diversity of habitats (vertical

and horizontal structure), local environmental conditions, and spatial heterogeneity in patch size and distribution (Hunter and Schmiegelow 2011).

State of Modern Savannas and Woodlands

Soils and climate are suitable for tree growth in most places throughout the eastern United States. Therefore, in the absence of fire, savannas and woodlands become forests by increasing in tree density and developing a midstory tree canopy layer and by transitioning of the ground flora to a less diverse community that is dominated by shade-tolerant forbs and woody species (e.g., Nelson 2010). For example, tree density (trees ≥ 5 in. dbh) has more than doubled since the early 1800s (Hanberry et al. 2012, 2014a, 2014d) over two-thirds of the Missouri Ozark Highland Region (~15 million acres) (Hanberry et al. 2014b). Available light in forests may range from as little as 5% of full sunlight on mesic to hydric, productive sites (Gardiner and Yeiser 2006, Parker and Dey 2008, Lhotka and Loewenstein 2009) to 20% on xeric sites (Sander 1979, Blizzard et al. 2013), light levels too low to support populations of sun-loving grasses, sedges, and forbs. Furthermore, it is less likely that individual oak seedlings will accumulate from successive acorn crops to develop into large advance reproduction when understory light levels are $<20\%$, and the more shade-tolerant oak species such as white oak (*Quercus alba*) will be most likely to persist, although its growth is inhibited by decreasing light levels. Forest development during the fire suppression era has led to two

Management and Policy Implications

Restoring oak savannas and woodlands is an increasingly common management goal for public agencies and conservation organizations, especially in the midwestern and southern regions of the United States. For decades, fire suppression has brought many benefits, but it has had also some negative ecological consequences including loss of biological diversity, abundance and quality of wildlife habitat, and ecosystem and landscape resilience. Oak savannas and woodlands are fire dependent. Our challenge as natural resource managers is not only to relearn fire use but also to discover how to combine it with other silvicultural practices to efficiently and effectively restore oak savannas and woodlands, which are some of our rarest ecosystems. Managers who use prescribed fire to restore oak savannas and woodlands are pioneering and defining silvicultural systems that are novel and innovative. While research begins to establish long-term studies on the ecology and silviculture of oak restoration, guidelines are needed now. This article synthesizes a large body of existing research to produce much needed guidance to forest managers and planners and provides for the first time quantitative structural metrics that define these systems and the range of variation within which they function properly.

common situations challenging managers who desire to restore oak savannas and woodlands or regenerate oak: oak advance reproduction is absent or it is present but small in size with low regeneration potential; and ground flora characteristic of oak savannas and woodlands have been lost or greatly diminished, especially where sites have been impacted by overgrazing, soil erosion, and invasive species.

Assessing the potential for restoration of savannas and woodlands is an important first step in directing limited resources and funds to priority areas. Many public and nonprofit conservation organizations have published lists of indicator plant species for savanna and woodland communities that can be used to identify sites that have the potential to respond well to silvicultural practices (e.g., Packard and Mutel 1997, Bader 2001, Farrington 2010). Managers can also use vegetation and ecological classifications by ecologists who have documented the location and extent of historic vegetation types for states and physiographic regions (e.g., Curtis 1959, Anderson et al. 1999, Faber-Langendoen 2001) and have described the strong associations between natural communities and soil type, geology, topography, hydrology, and other environmental variables that influence plant distribution (e.g., Nigh and Schroeder 2002, Hanberry et al. 2012, 2014a, 2014b, 2014c, 2014d). Ecological indices developed by plant ecologists such as the floristic quality index and coefficient of conservatism can be used to inventory sites and identify those that have the capacity to recover through natural regeneration of the ground flora following restoration practices (Swink and Wilhelm 1994, Taft et al. 1997).

Ecology and Silviculture of Savanna and Woodland Restoration

Restoring and sustaining oak savannas and woodlands require active and purposeful management. Because there has been a widespread increase in tree density in the past 150 years (e.g., Hanberry et al. 2014 a, 2014b, 2014d), the overriding goal in savanna and woodland restoration is to reduce tree density and canopy cover by removing any midstory stratum and possibly a portion of the overstory. Removal of the midstory creates “closed” woodland structure, but overstory tree density must be reduced also to achieve “open” woodland or savanna

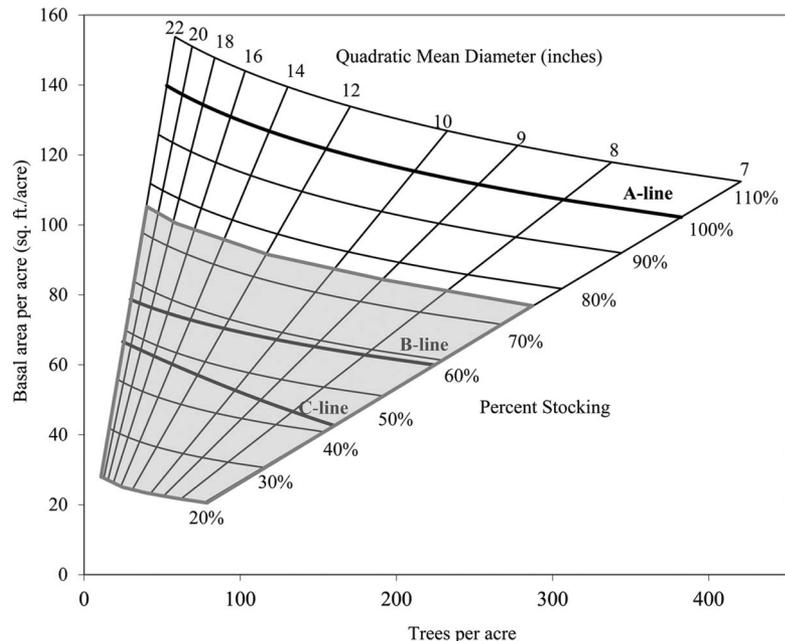


Figure 1. Stocking (Gingrich 1967) for woodlands and savannas (shaded area). Stocking in woodlands is maintained between 30 and 75%. Closed woodlands are maintained above the B-line, and open woodlands are maintained between 30% stocking and the B-line. Savannas are maintained at stocking levels less than 30%. For regenerating woodlands, stocking is reduced below 30%. Stocking in savannas is low enough to permit recruitment anytime there is a sufficiently long fire-free period.

structure and light levels to support heliophilic ground flora species (Nelson 2010). The degree of overstory removal is often driven by desired ground flora composition and wildlife habitat considerations. Reducing tree density achieves several objectives in savanna and woodland restoration by creating desirable woody structure and by increasing available light in the understory to stimulate ground flora recovery. Prescribed burning has been the method of choice for savanna and woodland restoration because of fire’s role in the historical ecology of these natural communities. Many savanna and woodland indicator species are adapted to a regime of repeated fire, even requiring fire to stimulate germination, prepare suitable seedbed conditions, remove excessive litter, and retard woody species dominance, thus ensuring adequate light in the understory.

Silviculture prescriptions for restoring savannas and woodlands lay out the sequence and timing of management treatments to begin moving existing vegetation composition and structure to the desired future condition. Silviculture prescriptions are more effectively implemented when they have quantitative targets for composition and structure at key intermediate stages in restoration as well as the final mature state that is to be sustained for the long term. This

facilitates early detection through monitoring of aberrant responses of vegetation to planned treatments or unexpected perturbations that lead to unwanted outcomes and permits correction by adaptive management.

Setting Structural Targets in Savannas and Woodlands

Structural and compositional targets can be derived from analyses of historical surveys such as the General Land Office (GLO) surveys, which represent snapshots in time of historic vegetation before it was completely obliterated by human history (Dey and Schweitzer 2014). For example, Hanberry et al. (2012, 2014a, 2014b, 2014c, 2014d) provided quantitative metrics of structure (percent crown cover, stocking, tree size, basal area, and density) for natural communities in Missouri present in the early 1800s based on spatially explicit modeling of GLO witness tree data and a multitude of environmental variables related to vegetation distribution and dominance (Figures 1 and 2; Table 1). Desired future conditions can also be quantified by inventory of modern examples of successfully restored savannas and woodlands or by consideration of the ecophysiological needs of the suite of desired species in the understory of savannas

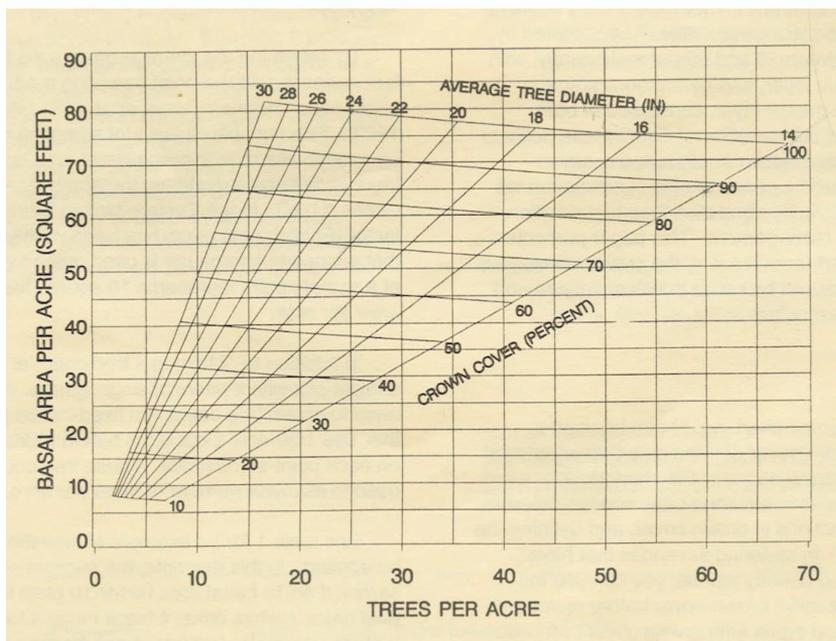
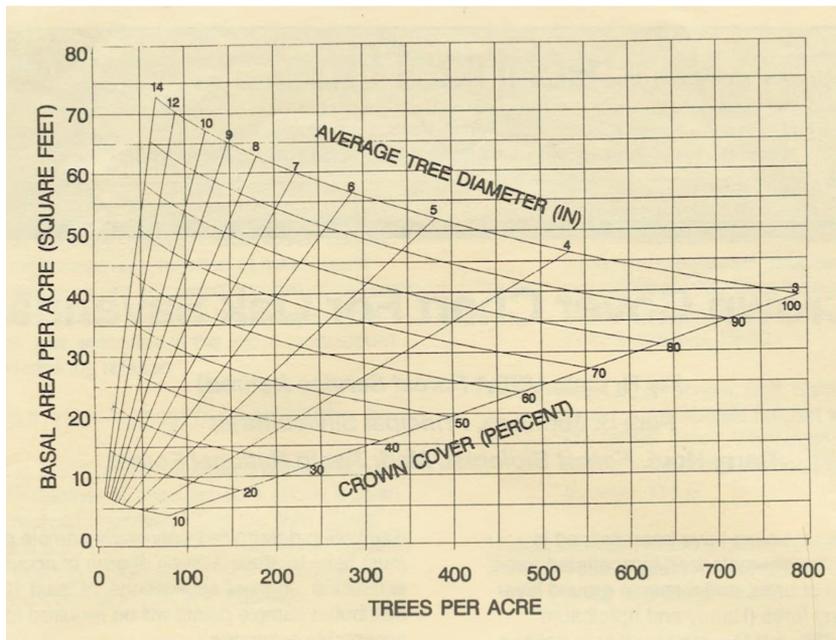


Figure 2. Estimation of crown cover percentage in *Quercus-Carya*-dominated savannas and open woodlands in the Central Hardwood Region based on Gingrich (1967). Estimates of crown cover are based on the maximum crown area for open-grown trees. Estimates of crown cover are slightly higher than what may be observed in the field because they do not account for within crown canopy gaps that permit light to penetrate to the ground. (Reprinted with permission from Law et al. 1994.)

and woodlands. Knowing critical physiological thresholds for survival, growth, and reproduction for desired tree reproduction and key indicator species in the ground flora can be linked to managing woody structure to ensure that resources are adequate to sustain diverse and viable populations. Woody structure can be related to environmental variables such as light (Figure 3), which has a strong influence on ground flora composi-

tion, abundance, biomass, and reproductive capacity, both asexual and sexual.

Overstory stocking levels that are prescribed to enhance oak regeneration in forests also fall within the range of desired savanna and woodland overstory stocking (Missouri Department of Conservation 2010, Nelson 2010) (Figure 1). For example, the Mark Twain National Forest (Mark Twain National Forest 2005) set desired

woodland density in the Missouri Ozarks from 30 to 80 $\text{ft}^2 \text{ac}^{-1}$ of basal area. Historically (early 1800s) in this same region, Hanberry et al. (2014b) estimated that average basal area and stocking in open woodlands were 61 $\text{ft}^2 \text{ac}^{-1}$ and 41%, respectively, and for closed woodlands were 100 $\text{ft}^2 \text{ac}^{-1}$ and 64%, respectively, with much variation among ecological subsections. It is commonly recommended that overstory density be reduced to about B-level stocking (i.e., $\sim 60\%$) to promote oak regeneration (e.g., Brose et al. 2008, Johnson et al. 2009), which is within the range of historic stocking levels for savannas and woodlands (30–75% according to Hanberry et al. 2014b) in Missouri. Hence, shelterwood prescriptions for oak regeneration are also good starting points for developing prescriptions for woodland restoration. However, in savanna and woodland restoration, the final overstory removal harvest would not be done, and the overstory would be retained over the long run until it needed to be replaced due to senescence, increasing mortality, and loss of acorn production. Two- and three-stage shelterwood approaches are appropriate for savanna and woodland management with the modification that the final shelterwood overstory would be retained for the long term. Functioning oak savannas and woodlands are inherent accumulators of large oak advance reproduction under a regime of periodic burning that allows for sprouting, recovery of shoot growth, and increased root biomass between consecutive prescribed fires. Knapp et al. (2015) found that burning every 4 years for >60 years in the Missouri Ozarks significantly increased oak seedling sprouts compared with annual burning and the control treatment (no burning).

Desired overstory density is determined by natural community type with consideration of wildlife habitat and biodiversity objectives and the resource needs of ground flora. Stocking charts and their modifications have been developed to help managers implement savanna and woodland prescriptions and monitor restoration progress using basic structural metrics such as basal area, tree density, stocking, and canopy crown cover (Figures 1 and 2) (Law et al. 1994, Kabrick et al. 2014). Relationships between structural metrics (e.g., crown cover and stocking) and understory light levels (Figure 3) (Blizzard et al. 2013) are indispensable for establishing structural thresholds and setting targets to ensure that adequate light is available for oak regeneration and ground flora

Table 1. Estimates of historic structure for natural communities in the Missouri Ozark Region based on models of a suite of environmental variables and GLO survey data on witness trees.

Natural community	Density		Avg dbh (in.)	Basal area		Stocking		Canopy cover	
	Avg	Range		Avg	Range	Avg	Range	Avg	Range
	. . (trees/ac) (ft ² /ac) (%)			
Savanna	33	23–44	14	35	22–44	25	16–30	51	38–60
Open woodland	54	34–87	13	61	39–87	41	30–55	66	50–80
Closed woodland	81	53–100	14	100	78–126	64	55–75	81	74–87

GLO survey data were from Hanberry et al. (2014b). The average (Avg) values of density, tree size, basal area, and percent stocking and canopy cover can be used to develop quantitative metrics for desired future conditions in oak savanna and woodland restoration. Ranges in values quantify the range in natural variation found in specific natural communities.

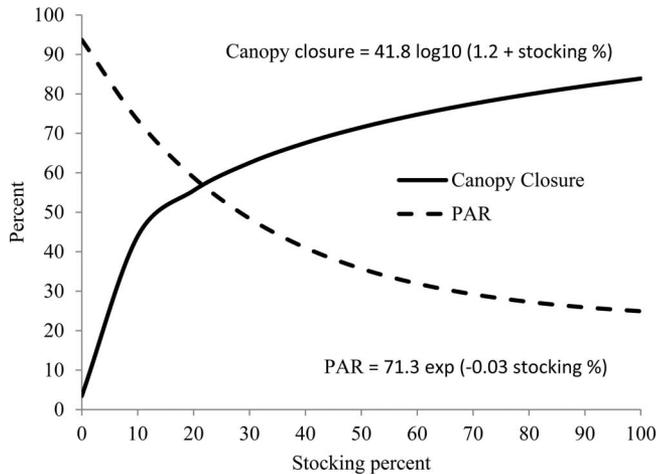


Figure 3. Relationships between stocking, canopy closure, and photosynthetically active radiation (PAR) in *Quercus-Carya* stands that have been thinned from below in the Missouri Ozarks. (Adapted from Blizzard et al. 2013.)

development (Figure 3). Stocking charts and crown cover charts can be used to assess current structure and quantify silvicultural objectives for managing structure throughout the developmental life cycle of a savanna or woodland.

The Role of Fire

The initial thinking in savanna and woodland restoration was that “If we just started burning again, all would be well.” However, early experiences with low-intensity prescribed fires conducted in the dormant season were less than gratifying. Whereas a single application of low-intensity dormant season fire has been shown to slightly improve species richness and percent cover of woodland indicator species, significant increases in the coverage of desired woodland ground flora required reduction of overstory density by mechanical cutting in conjunction with low-intensity burning (Hutchinson et al. 2005, Hutchinson 2006, Waldrop et al. 2008, Kinkead et al. 2013). Low-intensity fires are ineffective for significantly reducing overstory tree density or

canopy cover. These fires are capable of reducing tree density for hardwoods less than about 4–6 in. dbh, depending on species (Dey and Hartman 2005, Arthur et al. 2012), which may help achieve the structural targets for closed woodlands. But such fires only increase light levels from <5% of full sunlight in the understory, typical of many forests, to 10–15% by removal of the midstory canopy (Lorimer et al. 1994, Ostrom and Loewenstein 2006, Motsinger et al. 2010). This is insufficient to promote the proliferation of many species that demand moderate to full sunlight conditions. More intense fires are needed to thin the overstory, but fire is an imprecise tool for managing the overstory, especially on small tracts.

Mechanical and Chemical Thinning

There is less control over what trees are removed when fire is used than if thinning is done by mechanical or chemical methods. It is more difficult to achieve desired stand stocking targets and to control spatial arrangements of trees by prescribed burning.

Increasing fire intensity sufficient to kill large trees also increases the probability of injuring the lower boles of surviving trees, which makes them more vulnerable to fungal infection and wood decay over time, and of increasing mortality in increasingly larger advance reproduction of desirable species (Brose et al. 2013, Marschall et al. 2014, Dey and Schweitzer 2015). Therefore, using commercial harvesting and mechanical/chemical thinning of unmerchantable trees that are too large for low- to moderate-intensity fires to control is often preferred for meeting desired future stocking conditions. Income from commercial harvesting can help pay for managing other restoration activities such as removal of unmerchantable material, invasive species control, site preparation, or artificial regeneration of floral species. In addition, fire-injured overstory trees may not fully realize their potential longevity due to advanced decay in the lower tree bole that structurally weakens them and increases their risk to stem breakage from wind and ice storms. Among the oak species, there are differences in susceptibility to fire damage and decay development; larger diameter trees in the white oak group, in general, are better able to protect against fire injury than trees in the red oak group (Dey and Schweitzer 2015). White oak species also have more decay-resistant heartwood than red oak species, and they are more effective at compartmentalizing cambial injury and spread of decay fungi.

However, high-intensity fires capable of killing overstory trees may have a role in restoration of large landscapes where timber is noncommercial due to insufficient volume, quality, or accessibility. Such fires may occur on those portions of the landscape that may support that fire behavior while maintaining public safety. In many applications though, a combination of timber harvesting, mechanical/chemical thinning, and prescribed burning is the preferred alternative in oak savanna and woodland restoration.

The sequencing of timber harvesting or mechanical/chemical thinning and commencement of prescribed burning to reduce stand density can be managed to allow small oak advance reproduction to persist and accumulate as large reproduction over time. It is important to maintain a pool of larger oak advance reproduction for the day that the savanna or woodland overstory needs to be replaced. In many eastern oak forests, oak advance reproduction consists commonly of

small seedlings that are <12 in. tall and <0.25 in. in basal diameter. Small oak seedlings have higher probabilities of mortality from prescribed burning than larger oak seedlings and seedling sprouts (Johnson 1974, Dey and Hartman 2005, Brose et al. 2013). Hence, alternatives to fire are needed to promote development of large oak advance reproduction in the early stages of restoration that begins with a mature oak forest. Timber harvesting to create a shelterwood overstory before initiating prescribed burning has been shown to benefit oak advance reproduction survival and growth (Brose et al. 1999, Brose 2010).

Developing Large Oak Advance Reproduction

Brose et al. (2013) recommended using the shelterwood method to increase light for improved oak seedling survival and growth before initiation of prescribed burning because larger oak seedlings (e.g., >0.25 in. in basal diameter) have higher sprouting probabilities (Dey and Hartman 2005) and greater root reserves (Brose 2008) to support competitive growth rates. Brose et al. (2013) suggested that burning may begin several years after the first harvest of a two-stage shelterwood system that substantially reduces overstory density (e.g., >50% of initial basal area in mature, fully stocked forests), or several years after the final overstory removal that releases the regeneration. Burning before release by shelterwood harvesting causes high mortality in the typically small oak advance reproduction (e.g., 6 in. tall and <0.25 in. in basal diameter) that have low root reserves growing in the low light of mature forests. After the first shelterwood entry that eliminates the midstory and reduces overstory stocking by mechanical/chemical methods, oak seedling growth can be promoted for several years. However, competing vegetation begins to diminish available light to the oaks within several years. At that point, a second harvest to bring final overstory density to desired levels or the initiation of prescribed burning will be needed to release oak advance reproduction. If oak seedlings are generally small at the time of the first prescribed burn, then keeping the intensity low reduces oak seedling mortality. Otherwise, higher fire intensity (>2 foot flame lengths) and burning in the growing season provides the most benefit to relative oak dominance over competitors.

Fuel loading may be high in areas where fire has been suppressed for 15 years or more

(Stambaugh et al. 2006a) or where there have been increases in fuels from silvicultural activity; in these situations, controlling fire behavior to keep intensity low can avoid undesirable effects on oak reproduction or overstory trees. Later, when oak reproduction is large enough (e.g., >0.5 in. basal diameter) and oak competitors are leafing out in the late spring, moderate- to higher-intensity fires may give oak an added competitive advantage (Brose et al. 2013). Overstory trees can be retained in the savanna or woodland through their seed-bearing years and beyond. Large oak advance reproduction is well adapted to persist in the open overstory under a regime of fire every 3–10 years. Prescribed fire will topkill the larger oak advance reproduction, but it will sprout and continue to build a root system during the fire-free intervals with sufficient light levels typical of savannas and woodlands.

If oak advance reproduction is absent or sparse, then prescribed burning can be done to reduce deep leaf litter, decrease midstory canopy, begin controlling understory woody vegetation, release nutrients, stimulate germination of seeds that have chemical or thermal dormancy, increase soil temperature, and increase light, all of which promote ground flora development (Hutchinson 2006). But once a good acorn crop is on the ground, fire should be delayed until large oak seedlings are developed through a modified shelterwood regeneration method approach because fire causes high levels of mortality in acorns and small oak seedlings (Johnson 1974, Auchmoody and Smith 1993).

Managing Native Ground Flora and Invasive Species

There is much flexibility in managing overstory density and a prescribed fire regime to produce the desired ground flora composition and structure. Overstory density and vertical structure (number of canopy layers) largely determine the amount of light reaching the ground flora. The overstory density can be managed to suppress shade-intolerant undesirable species, but this must be balanced with the physiological needs for light of the desired flora. Since there may be 300 or more species in the understory, with a range of different light requirements for good growth and reproduction, a reasonable approach is to set overstory density targets to provide the light needed for the key indicator species that represent a high quality and healthy commu-

nity or needed for the predominant species or functional groups. For example, overstory crown cover must be less than 50% for many warm season (C_4) grasses to be dominant in the community (Mayer and Khalyani 2011, Starver et al. 2011). Heterogeneity in the spatial arrangement of trees can create variation in understory light conditions that can accommodate the needs of more species than if the overstory were uniformly dispersed. Fire frequency and seasonality strongly influence the dominance of plant functional groups (Anderson et al. 1999, Nelson 2010). For example, annual dormant season fires favor grasses, biennial and summer fires promote forbs, and periodic dormant season fires favor woody species. Varying the frequency, intensity, and seasonality of fire may provide for greater plant diversity in the long term.

Mechanical thinning or timber harvesting alone without fire has produced positive responses in desired species richness and coverage in woodland restoration, similar to what results after a single prescribed burn (Hutchinson 2006, Zenner et al. 2006, Kinkead et al. 2013). However, these gains in diversity are ephemeral as an abundance of woody sprouts grow rapidly to form canopy closure and shade out the ground flora, especially if residual overstory density is moderate to low (B-level stocking or greater). Maintenance of a closed canopy in the overstory can retard the regrowth of hardwood and shrub sprouts (Dey and Hartman 2005), but it also inhibits ground flora production because of low levels of available light (Lettow et al. 2014). Therefore, the combination of mechanical thinning of the overstory with a cycle of prescribed burning sustains ground flora recovery in savannas and woodlands (Hutchinson et al. 2005, Waldrop et al. 2008, Kinkead et al. 2013). Lettow et al. (2014) observed that thinning and burning significantly increased the richness and abundance of flowering forbs compared with burning alone or doing nothing in an oak savanna restoration in southern Michigan. Herbicides can be used effectively to kill woody stems when applied by stem injection or basal bark application before timber harvesting or prescribed burning or when applied as a foliar spray to woody sprouts that form after topkill resulting from mechanical cutting or prescribed burning (DiTomaso et al. 2006). Reducing the density of woody stems that have high sprouting capacity (seedlings and saplings of most species) with herbicides before the overstory is

thinned helps to reduce dense stands of hardwood and shrub sprouts from forming.

The settlement of Europeans in North America over the past 400 years has increasingly promoted the introduction of alien plant and animal species that have become invasive in natural communities. Nonnative invasive plant species (NNIS) such as smooth brome grass (*Bromus inermis*), Canada thistle (*Cirsium arvense*), musk thistle (*Carduus nutans*), sericea lespedeza (*Lespedeza cuneata*), autumn olive (*Elaeagnus umbellata*), multiflora rose (*Rosa multiflora*), teasel (*Dipsacus* spp.), crown vetch (*Coronilla varia*), white sweetclover (*Melilotus alba*), yellow sweetclover (*Melilotus officinalis*), spotted knapweed (*Centaurea biebersteinii*), European buckthorn (*Rhamnus cathartica*), and Japanese honeysuckle (*Lonicera japonica*) thrive in open environments and have certain adaptations to fire and other disturbances that make them hard to control when oak savannas and woodlands are being restored. Therefore, it is often prudent to spend time controlling NNIS in and around the restoration area before using fire, disturbing the forest floor, and increasing resources by reducing tree density. Effective methods for controlling many of the common NNIS in savannas and woodlands including prescribed fire, herbicides, and mechanical treatments, and combinations thereof have been reported by Grace et al. (2001), Zouhar et al. (2008), DiTomaso et al. (2006) and others. Complete eradication of NNIS is impractical, so monitoring and controlling spot invasions when they occur is part of the maintenance and sustaining management of savannas and woodlands.

Grazers and Browsers in Savannas and Woodlands

The inclusion of large ungulate grazers such as bison (*Bison bison*) and elk (*Cervus canadensis*) and browsers such as white-tailed deer (*Odocoileus virginianus*) can modify plant response under a given overstory density and fire regime. By their grazing, they place selective pressure on the more palatable species and reduce fine fuel loading, lessening the occurrence and intensity of the next fire. Freshly burned areas attract large ungulates because of the abundance of nutritious, highly palatable and available forage and browse plants. This spatially and temporally dynamic interaction between grazers/browsers and fire at a landscape scale created a shifting mosaic and increased het-

erogeneity of habitats in the past that supported relatively high biodiversity in flora and fauna. The fire-grazer interaction has been termed pyric herbivory (fire-driven grazing) by Fuhlendorf et al. (2008). Most research in fire-grazer interactions and effects on ecosystems has been conducted in prairie ecosystems where Collins et al. (1998) and Hartnett et al. (1996) have observed that bison grazing on the dominant C_4 grasses led to greater spatial heterogeneity in vegetation and increases in total species richness. Harrington and Kathol (2009) evaluated the ability of cattle in a rotational grazing system to control shrub density in restoring oak savannas in southwestern Wisconsin. They found that fire was more effective overall in controlling unwanted shrubs, but cattle were more effective in controlling some species such as *Rubus* spp. They concluded that grazing cattle may be a good additional tool to supplement fire in managing shrubs in savanna restoration, but they were not a replacement for fire.

Savanna and Woodland Maintenance

Once desired savanna or woodland structure and composition have been achieved, management changes from a restoration approach to one of maintenance of the desired condition. The period of maintenance management may persist for 100 years or more, depending on the longevity of the overstory trees. Oaks can be long-lived; i.e., red oaks may live to 150–200 years and white oaks from 250 to 400 years. Maintenance of savanna and woodland ecosystems requires frequent fire, the timing of which depends on sustaining the desired composition and structure. Fire is needed to retard growth and dominance of woody species, to control invasive species, and to maintain floristic quality. The frequency of fire to control woody stems depends on the growth rates of seedlings and sprouts. Low-intensity fires can readily topkill hardwoods up to about 4 in. dbh. Growth rates of hardwoods depend on reproductive origin (true seedling or sprout from well-established root system), species, site quality, and overstory density. For example, dominant white oak saplings growing in the open on sites of medium site index in Missouri (e.g., 63 ft, base age 50) average 1.5 in. of diameter growth in 10 years (Shifley and Smith 1982). Hence, it would take more than 20 years for stems to grow large enough to have increased chances

of surviving a low-intensity fire intact. Oak stump sprouts have higher initial growth rates than other forms of oak reproduction. For example, white oak stump sprouts can grow to 2.2 in. dbh after 10 years of growing in the open on average sites in the Missouri Ozarks, whereas scarlet oak stump sprouts can average 3.1 in. dbh in the same time (Dey et al. 2008b). Increasing overstory density reduces growth, especially for the more shade-intolerant oaks: as little as 20 ft² ac⁻¹ of basal area can significantly reduce height growth in black and scarlet oak (Green 2008), and diameters of oak stump sprouts averaged only 0.4 in. after 10 years growing under 62 ft² ac⁻¹, 58% crown cover (Dey et al. 2008b).

If controlling hardwood regrowth were the only purpose for burning, fires would not have to be that frequent, i.e., every 10–20 years to retard hardwood dominance and canopy closure. However, Stambaugh et al. (2006a) have shown that hardwood leaf litter reaches maximum depths in about 12–15 years in Ozark forests, and it takes only 4 years after a fire for leaf litter to recover to 75% of preburn levels. More frequent fires are needed to keep leaf litter from reducing ground flora abundance and diversity. And finally, fires may need to be even more frequently than that, depending on the ecology of the desired flora; e.g., annual fires may be needed to sustain grass dominance.

Replacing the Savanna and Woodland Overstory

Eventually, there comes a time when savanna or woodland overstories need to be replaced, and this necessitates the release of oak advance reproduction and its recruitment into the overstory. Overstory replacement may be triggered by the impending natural mortality of overstory trees, which varies by species. Oak decline may cause mortality before the inherent longevity is reached, e.g., at age 80–120 years. If oak advance reproduction is lacking, then oak regeneration and recruitment activities should begin 10–30 years before acorn production potential declines in overstory trees to establish seedlings using natural processes. Large, old oak trees have low sprouting potential and will not contribute to the pool of oak reproduction, which is why the emphasis is on acorn production and the development of large oak advance reproduction to replace the overstory (Johnson et al. 2009). Artificial regeneration by planting

seedlings or direct seeding of acorns (Dey et al. 2008a, 2012) may be necessary if the capacity of the overstory to produce acorns is low and advance reproduction is insufficient. Supplementing natural oak advance reproduction through underplanting can shorten the time it takes to be ready for recruitment. The best approach is to have an adequate pool of large oak advance reproduction at all times to buffer against unexpected losses of overstory trees due to fire, weather, insects, or diseases.

Fire must be withheld long enough for oak seedling sprouts to grow large enough in height and diameter that they can resist being topkilled when fire is returned to the woodland system. This may take 10–30 years, depending on the myriad of factors that affect growth in hardwoods (Arthur et al. 2012, Kabrick et al. 2014). Fire-free periods of this length have been commonly observed in the historic period since the mid-1600s in many fire history studies in eastern hardwoods (e.g., Guyette et al. 2002, 2003, Guyette and Spetich 2003, Stambaugh et al. 2006b). Variations of either even-aged or uneven-aged methods of regeneration can be used in savannas and woodlands, depending on the size of the management area, rotation period, desire to maintain continuous mature tree cover, ability to manage intensively, and other factors. For example, the overstory on 0.5% of a savanna area needs to be replaced each year on a 200-year rotation. Thus, on a 200-acre parcel, 1 acre of overstory trees needs to be replaced each year or about 20 trees per acre where the savanna trees average 14 in. dbh. Overstory recruitment can be done on an entire acre or by replacement of 20 individual trees scattered over the management area. Certainly logistical considerations and management ability will guide the process of how overstory replacement is implemented. In addition, overstory replacement need not take place every year but can be accumulated for 10–20 years so that 10–20 acres can be replaced at once to make operations more feasible and economical.

Conclusion

Open-structured oak savannas and woodlands were once prominent natural communities in eastern North America. They existed because of a long history of frequent fire and grazing/browsing by large ungulates. Their distribution changed over time with changing climates and human populations and cultures. With the advent

of fire suppression, these communities succeeded to closed forests. Today, they are rare throughout the East. Restoration of oak savannas and woodlands has become a focus of land managers. Restoration and maintenance of savanna and woodlands requires active management. Reintroducing fire is fundamental to restoration, but other silvicultural practices are needed to efficiently manage vegetation composition and structure and achieve desired future conditions. Management efforts to restore oak savannas and woodlands often precede research, provide early tests of innovative treatment combinations, and help to identify key research questions. Monitoring to inform adaptive management is an important source of knowledge and a critical part of the learning process. Restoring oak savannas and woodlands will help to expand the distribution of rare natural communities, conserve native biodiversity, and create a more diverse landscape, provide habitat for wildlife species of concern and should increase our options for responding to uncertain futures due to increasing human population, climate change, and invasive species.

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