SILVICULTURE TO RESTORE OAK WOODLANDS

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Abstract—Variability in historic fire regimes in eastern North America resulted in an array of oak savannas, woodlands and forests that were dominant vegetation types throughout the region. In the past century, once abundant woodlands have become scarce due to conversion to agriculture, or development of forest structure in the absence of fire. Restoration of oak woodlands is a primary goal for land management agencies and conservation organizations. Although oak woodlands can be restored with a long-term regimen of prescribed burning, a combination of prescribed burning, timber harvesting and forest thinning produces the desired structure and composition more efficiently. Sustaining oak woodlands requires an occasional longer fire-free period to allow for replacement of the overstory by recruitment of trees from the reserve of oak sprouts that have accumulated in the understory. Prescribed fire is useful for sustaining oak woodlands, but it must be used judiciously to minimize timber damage and decreases in value. Integrating fire in a silvicultural prescription that uses the shelterwood regeneration method to promote competitive oak reproduction has been successfully applied in the eastern US to sustain oak forests. Restoration of oak ecosystems is possible but requires innovative combinations of traditional practices, including prescribed burning.

INTRODUCTION

Restoring oak woodlands is increasingly a management priority among state and federal natural resource agencies and conservation organizations, for example, about one-third of the Mark Twain National Forest (438,000 acres) has woodland restoration as a primary management goal (MTNF 2005). Definitions of a woodland vary among the authorities but common characteristics include: overstory dominated by oak species with 30 to >80 percent crown cover and 30 to 80 ft^2 ac^{-1} in basal area, negligible midstory woody canopy layer, sparse and patchy woody understory, 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 (MDC 2010, Nelson 2010). Oak woodlands are natural communities that historically were prominent across the landscape in the Central Hardwood Region; for example, Hanberry and others (2014b) estimated that 65 percent of the Missouri Ozark Highlands was oak woodlands. Historically frequent fire created and maintained oak woodlands for thousands of years (Delcourt and Delcourt 1991, Guyette and others 2012). But today, woodlands have been diminished by succession to forests following fire suppression and conversion to agriculture land uses.

IMPORTANCE OF WOODLANDS

Woodlands are important natural communities and landscape components that need restoring. Before European settlement, woodlands added to the landscape diversity of natural communities that formed a variable complex matrix including prairie, savanna, woodland and forest throughout the Central Hardwood Region (Transeau 1935, Schroeder 1982, Anderson and others 1999, Batek and others 1999, Nigh and Schroeder 2002, Nelson 2010). The current Central Hardwood Regional landscape is less diverse in structure, complexity, function, composition and natural community type (Schulte and others 2007, Shifley and Thompson 2011, Shifley and others 2012, Hanberry and others 2012, 2014 a,c,d). Increasing ground flora diversity is associated with decreasing canopy cover along the structural gradient from forest to savanna (Taft and others 1995, Bowles and McBride 1998, Leach and Givnish 1999, Peterson and Reich 2008). Species diversity in invertebrates, small mammals, birds and herptofauna 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 and others 2001).

Wildlife species often prefer structural features of woodlands such as big brown bat (*Eptesicus fuscus*), eastern red bat (*Lasiurus borealis*), evening bat (*Nycticeius humeralis*), and tri-colored bat (*Perimyotis subflavus*), who preferred savanna and open-woodland habitats over closed canopy forests in the Missouri Ozarks (Starbuck and others 2014). Thompson and

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others (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. 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 and others (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 and others 2000, Brawn and others 2001, Brawn 2006, Grundel and Pavlovic 2007, Au and others 2008). Even bird species that are known to prefer mature, closed-canopied 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 and increasing biodiversity at all scales are considered key management strategies to address anticipated impacts due to climate changes (Janowiak and others 2011, Brandt and others 2014, Janowiak and others 2014). Restoration of savannas and woodlands would contribute to both of these mitigation strategies for the range of future climate scenarios predicted. Tree species common to Midwestern 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 and others 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 and others 2014). Restoration of 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 WOODLANDS

Soils and climate are suitable for tree growth in most places throughout the eastern United States. Therefore, in the absence of fire, 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 inches dbh) has more than doubled since the early 1800s (Hanberry and others 2012, 2014a,d) over two-thirds of the Missouri Ozark Highland region (ca. 15 million acres) (Hanberry and others 2014b). Available light in forests may range from as little as 5 percent of full sunlight on mesic to hydric, productive sites (Gardiner and Yeiser 2006, Parker and Dey 2008, Lhotka and Loewenstein 2009) to 20 percent on xeric sites (Sander 1979, Blizzard and others 2013), light levels too low to support populations of sun-loving grasses, sedges and forbs. Also, 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 below 20 percent, and the more shade tolerant oak species such as white oak (*Quercus alba*) will be most likely to persist, though its growth is inhibited by decreasing light levels. Forest development during the fire suppression era has led to several common situations challenging managers who desire to restore oak woodlands or regenerate oak: (1) oak advance reproduction is absent, or (2) it is present but small in size with low regeneration potential, and (3) ground flora characteristic of oak woodlands have been lost or greatly diminished, especially where sites have been impacted by overgrazing, soil erosion and invasive species.

The overriding goal in 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 to achieve “open” woodland 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 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 woodland restoration because of fire’s role in the historical ecology of woodlands. Many woodland indicator species are adapted to a regime of repeated fire, even requiring fire to stimulate germination, prepare suitable seed bed conditions, remove excessive litter, and retard woody species dominance, thus ensuring adequate light in the understory.

METHODS FOR WOODLAND RESTORATION

The Role of Fire

Initial thinking in 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. While 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 and others 2005, Hutchinson 2006, Waldrop and others 2008, Kinkead and others 2013). Low intensity fires are ineffective in significantly reducing overstory tree density or canopy cover. These fires are capable of reducing tree density for hardwoods less than about 4 to 6 inches dbh, depending on species (Dey and Hartman 2005, Arthur and others 2012), which may help achieve the structural targets for closed woodlands. But such fires only increase light levels from < 5 percent of full sunlight in the understory, typical of many forests, to 10 - 15 percent by removal of the midstory canopy (Lorimer and others 1994, Ostrom and Loewenstein 2006, Motsinger and others 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 using fire 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 (Marschall and others 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 the cost of managing other unmerchantable material, invasive species control, site preparation, or artificial regeneration of floral species. High intensity fires capable of killing overstory trees may have a role when restoring 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, it is a combination of timber harvesting, mechanical/ chemical thinning and prescribed burning that is the preferred alternative in oak woodland restoration.

Mechanical thinning or timber harvesting alone without fire have produced positive responses in desired species richness and coverage in woodland restoration, similar to what results after a single prescribed burning (Zenner and others. 2006, Hutchinson 2006, Waldrop and others. 2008, Kinkead and others. 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). 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. Therefore, it is the combination of mechanical thinning of the overstory with a cycle of prescribed burning that sustains ground flora recovery in woodlands. 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 and others 2006).

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 overtime. It is important to maintain a pool of larger oak advance reproduction for the day that the woodland overstory needs to be replaced. In many eastern oak forests, oak advance reproduction is commonly small seedlings that are < 12 inches tall and < 0.25 inches 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 and others 2013). Hence, alternatives to fire are needed to promote development of large oak advance reproduction. Timber harvesting to create a shelterwood overstory before initiating prescribed burning has been shown to benefit oak advance reproduction survival and growth (Brose and others 1999, Brose 2010).

ADAPTATION OF THE SHELTERWOOD METHOD

Developing Large Oak Advance Reproduction

Brose and others (2013) recommended using the shelterwood method to increase light for improved oak seedling survival and growth before initiating prescribed burning because larger oak seedlings (e.g., > 0.5 inches in basal diameter) have higher sprouting probabilities (Dey and Hartman 2005) and greater root reserves (Brose 2008) to support competitive growth rates. They suggested that burning may begin several years after the first harvest of a two-stage shelterwood system, or several years after the final overstory removal that releases the regeneration. Oak seedling growth can be promoted for several years by midstory removal and reducing overstory density by mechanical/chemical methods, that is, until competing vegetation begins to diminish available light to the oaks. 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. Keeping the intensity of the first fire low reduces the deleterious effects on smaller oak reproduction. Fuel loading may be high in areas where fire has been suppressed for 15 years or more (Stambaugh and others 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 inches 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 and others 2013). If oak advance reproduction is absent or sparse, then prescribed burning can be done immediately 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 promotes 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.

Managing Ground Flora

There is much flexibility in managing overstory density and prescribed fire regime to produce the desired ground flora composition and structure. Overstory density and vertical structure (number of canopy layers) largely determines 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 would be to set overstory density targets to provide light needed for the key indicator species that represent a high quality and healthy community, or needed for the predominant species or functional groups. Overstory crown cover must be less than 50 percent for many warm season (C4) grasses to be dominant in the community (Mayer and Khalyani 2011, Starver and others 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 and others 1999, Nelson 2010). For example, annual dormant season fires favor grasses, biennial and summer fires promote forbs, 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. A common concern in restoration is the presence of invasive species in or adjacent to the restoration site. Many invasive species such as smooth brome grass (*Bromus inermis*), musk thistle (*Carduus nutans*), sericia lespedeza (*Lespedeza cuneata*) and crown vetch (*Coronilla varia*) are adapted to fire and thrive in more open environments. Zouhar and others (2008) and DiTomaso and others (2006) provide good overviews of fire effects on and control of non-native invasive species.

GRAZING IN WOODLANDS

The inclusion of large ungulate grazers such as bison (*Bison bison*), elk (*Cervus canadensis*) and 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. This spatially and temporally dynamic interaction between grazers/browsers and fire at a landscape scale created a shifting mosaic and increased heterogeneity 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 and others. (2008). Most research in fire-grazer interactions and effects on ecosystems have been conducted in prairie ecosystems where Collins and others (1998) and Hartnett and others (1996) have observed that bison grazing on the dominant C4 grasses led to greater spatial heterogeneity in vegetation and increases in total species richness.

SETTING STRUCTURAL TARGETS IN WOODLANDS

Shelterwood overstory stocking levels that are prescribed to enhance oak regeneration in forests also fall within the range of desired woodland overstory stocking (MDC 2010, Nelson 2010) (fig. 1). For example, MTNF (2005) set desired woodland density in the

Missouri Ozarks from 30 to 80 ft^2/ac of basal area. Historically (early 1800s) in this same region, Hanberry and others (2014b) determined that average basal area and stocking in open woodlands were 61ft^2/ac and 41 percent, respectively; and averaged for closed woodlands 100 ft^2/ac and 64 percent, respectively, with much variation among ecological subsections. It is commonly recommended that overstory density be reduced to about B-level stocking (i.e., ca 60 percent) to promote oak regeneration (e.g., Brose and others 2008, Johnson and others 2009), which is within the range of historic stocking levels (30 to 75 percent according to Hanberry and others 2014b) in Missouri. Hence, shelterwood prescriptions for oak regeneration are also good starting points in developing prescriptions for woodland restoration. However, in 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 woodland management with the modification that the final shelterwood overstory would be retained for the long-term. Desired overstory density in woodlands is determined by considering wildlife habitat and biodiversity objectives, knowledge of reference stands and historic conditions, and the resource needs of ground flora. Stocking charts and their modifications have been developed to help managers implement woodland prescriptions and monitor restoration progress (Law and others 1994, Kabrick and others 2014) using basic structural metrics such as basal area, tree density, stocking and canopy crown cover (figs. 1 and 2). Relationships between structural metrics (e.g., crown cover and stocking) and understory light levels (Blizzard and others 2013) are indispensable for establishing structural thresholds and setting targets to ensure adequate light is available for oak regeneration and ground flora development (fig. 3).

WOODLAND MAINTENANCE

Once desired 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 250-400 years. Maintenance of woodland ecosystems requires frequent fire, the timing of which depends on sustaining the desired composition and structure. Fire is needed to

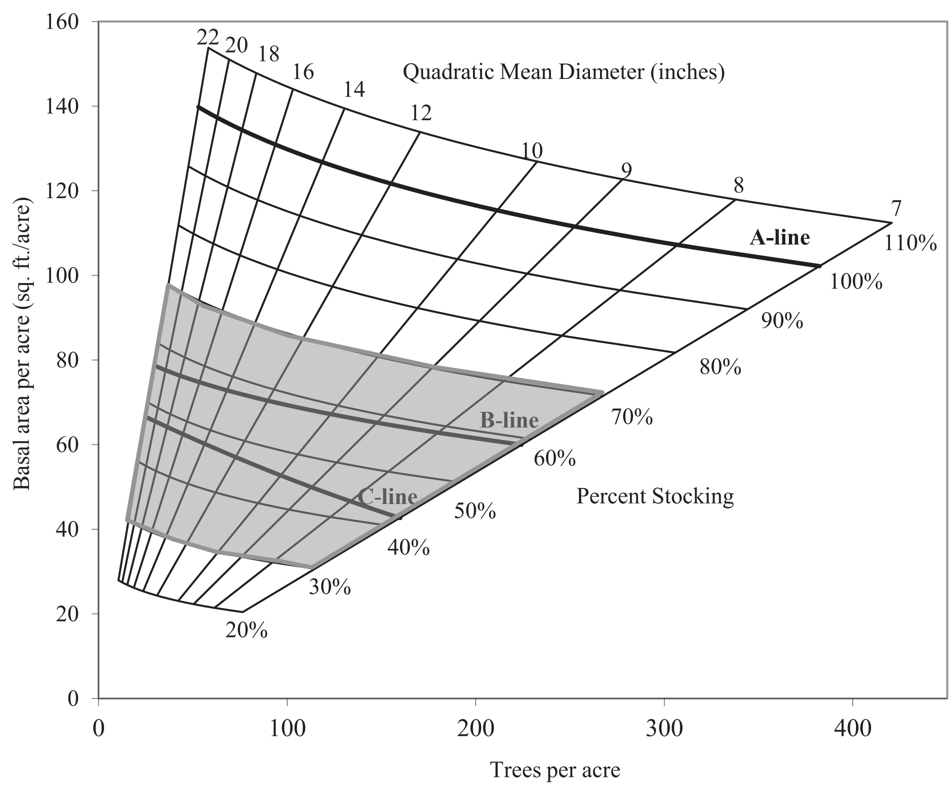

Figure 1—Stocking chart for upland *Quercus-Carya* in the Central Hardwoods Region (Gingrich 1967) modified for managing savanna and woodlands (Kabrick and others 2014). Stocking in woodlands is maintained between about 30% and 70% stocking. Closed woodlands have higher stocking (70%) compared to open woodlands (30 to 40%) and savannas (<30%). When regenerating closed woodlands, stocking is reduced to below B-level stocking.

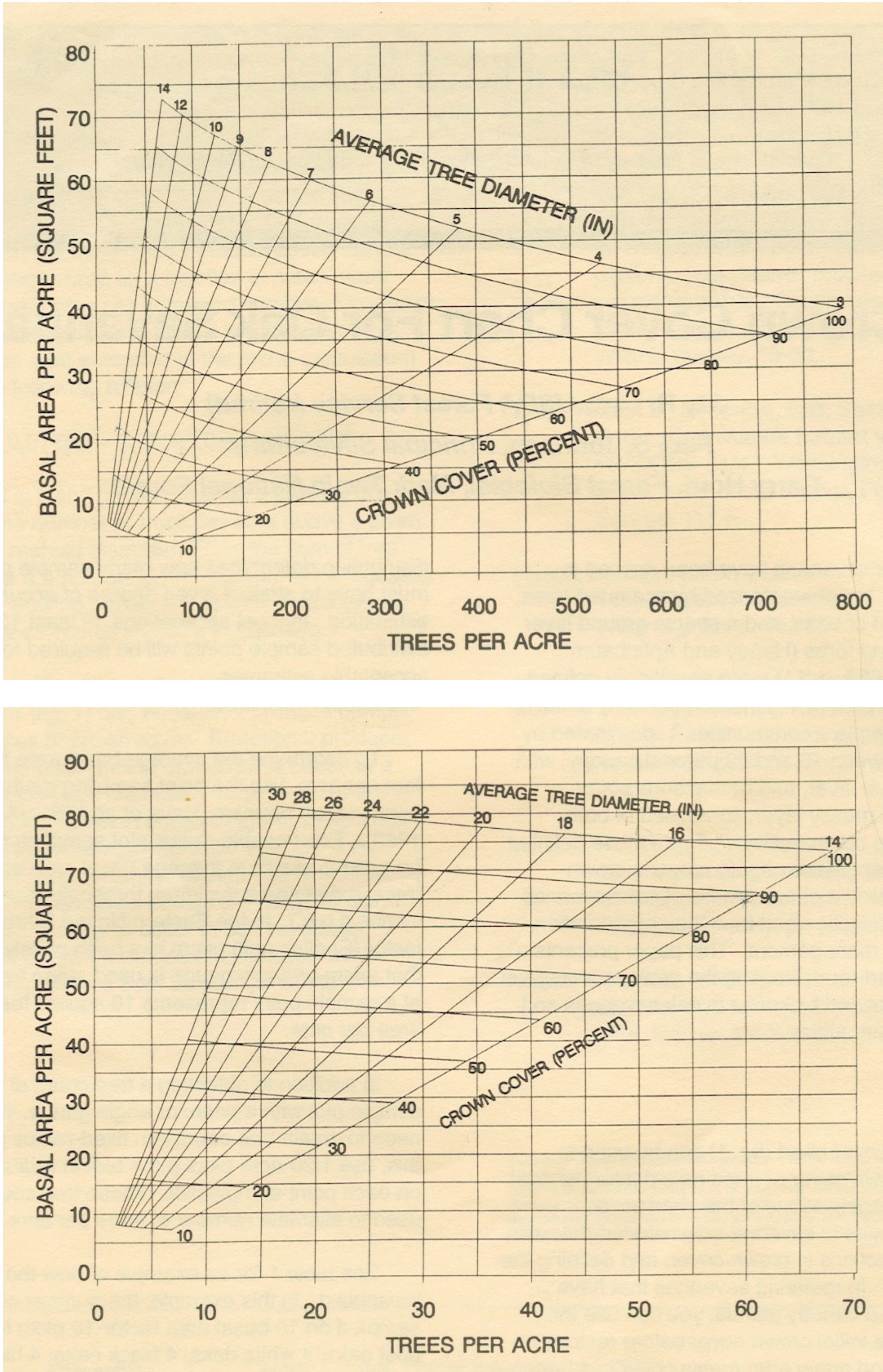

Figure 2—Estimation of crown cover percent in *Quercus-Carya* dominated savannas and open woodlands in the Central Hardwood Region based on Gingrich (1967) (from Law and others 1994, with permission).

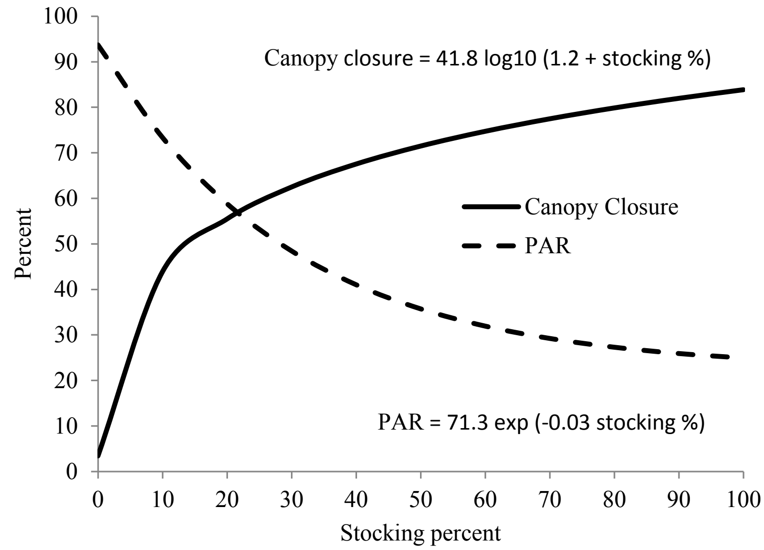

Figure 3—Relationships between stocking, canopy closure, and photosynthetically-active radiation (PAR) in *Quercus-Carya* stands that have been thinned from below in the Missouri Ozarks (adapted from Blizzard and others 2013).

both retard growth and dominance of woody species and to maintain floristic quality. 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 inches 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 feet base age 50) average 1.5 inches 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 inches 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 inches dbh in the same time (Dey and others 2008). Increasing overstory density reduces growth, especially for the more shade intolerant oaks, as little as 20 ft^2/ac 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 inches after 10 years growing under 62 ft^2/ac, 58 percent crown cover (Dey and others 2008).

If controlling hardwood regrowth were the only purpose for burning, fires would not have to be that frequent, i.e., every 10 to 20 years to retard hardwood dominance and canopy closure. However, Stambaugh and others (2006a) have shown that hardwood leaf litter reaches maximum depths in about 12 to 15 years in Ozark forests, and it takes only 4 years after a fire for leaf litter to recover to 75 percent 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 frequent than that depending on the ecology of the desired flora, for example, annual fires may be needed to sustain grass dominance.

REPLACING THE WOODLAND OVERSTORY

Eventually, there comes a time when woodland overstories need to be replaced and this necessitates the release of oak advance reproduction and its recruitment into the overstory. Fire must be withheld long enough for oak seedling sprouts to grow large enough that they can resist being topkilled when fire is returned to the woodland system. This may take 10 to 30 years depending on the myriad of factors that affect diameter growth in hardwoods (Arthur and others 2012, Kabrick and others 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 and others 2002, Guyette and others 2003, Guyette and Spetich 2003, Stambaugh and others 2006b). Variations of either even-aged or uneven-aged methods of regeneration can be used in woodlands depending on the size of individual woodland area, length of the woodland rotation, desire to maintain continuous mature tree cover, ability to manage intensively, and other factors. If for some reason, oak advance reproduction is not present for recruitment, then attention must be given to secure its establishment 10 to 20 years before the recruitment process begins. Artificial regeneration by planting seedlings or direct seeding of acorns may be necessary if the capacity of the overstory to produce acorns is insufficient. Supplementing natural oak advance reproduction through underplanting can shorten the time it takes to be ready for recruitment.

CONCLUSION

Open-structured oak woodlands were once prominent natural communities in eastern North America. They existed because of a long-history of frequent fire. 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 woodlands has become a focus of land managers. Restoration and maintenance of 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 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 woodlands will help to expand the distribution of rare natural communities, conserve native biodiversity, 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.

LITERATURE CITED

Anderson, R.C.; Fralish, J.L.; Baskin, J.M. 1999. Savannas, barrens, and rock outcrop plant communities of North America. Cambridge, UK: Cambridge University Press. 470 p.

Arthur, M.A.; Alexander, H.D.; Dey, D.C. [and others]. 2012. Refining the oak–fire hypothesis for management of oak-dominated forests of the Eastern United States. Journal of Forestry. 110: 257-266.

Au, L.; Andersen, D.E.; Davis, M. 2008. Patterns in bird community structure related to restoration of Minnesota dry oak savannas and across a prairie to oak woodland ecological gradient. Natural Areas Journal. 28: 330-341.

Batek, M.J.; Rebertus, A.J.; Schroeder, W.A. [and others]. 1999. Reconstruction of early nineteenth-century vegetation and fire regimes in the Missouri Ozarks. Journal of Biogeography. 26: 397-412.

Blizzard, E.M.; Kabrick, J.M.; Dey, D.C. [and others]. 2013. Light, canopy closure, and overstory retention in upland Ozark forests. In: Guldin, J.M., ed. Proceedings of the 15th biennial southern silvicultural research conference. e-Gen. Tech. Rep. SRS-GTR-175. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 73-79.

Bowles, M.L.; McBride, J.L. 1998. Vegetation composition, structure, and chronological change in a decadent Midwestern North America savanna remnant. Natural Areas Journal. 18: 14-27.

Brandt, L.; He, H.; Iverson, L. [and others]. 2014. Central Hardwoods ecosystem vulnerability assessment and synthesis: a report from the Central Hardwoods climate change response framework project. Gen. Tech. Rep. NRS-124. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station. 254 p.

Brawn, J.D. 2006. Effects of restoring oak savannas on bird communities and populations. Conservation Biology. 20: 460-469.

Brawn, J.D.; Robinson, S.K.; Thompson III, F.R. 2001. The role of disturbance in the ecology and conservation of birds. Annual Review of Ecology and Systematics. 32: 251-276.

Brose, P.H. 2008. Root development of acorn-origin oak seedlings in shelterwood stands on the Appalachian Plateau of northern Pennsylvania: 4-year results. Forest Ecology and Management. 255: 3374-3381.

Brose, P.H. 2010. Long-term effects of single prescribed fires on hardwood regeneration in oak shelterwood stands. Forest Ecology and Management. 260: 1516-1524.

Brose, P.H.; Van Lear, D.H.; Keyser, P.D. 1999. A shelterwood-burn technique for regenerating productive upland oak sites in the Piedmont region. Southern Journal of Applied Forestry. 16(3): 158-163.

Brose, P.H.; Dey, D.C.; Phillips, R.J.; Waldrop, T.A. 2013. A meta-analysis of the fire-oak literature: does prescribed burning promote oak reproduction in eastern North America? Forest Science. 59(3): 322-334.

Brose, P.H.; Gottschalk, K.W.; Horsley, S.B. [and others]. 2008. Prescribing regeneration treatments for mixed-oak forests in the Mid-Atlantic region. Gen. Tech. Rep. NRS-33. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station. 100 p.

Collins, S.L.; Knapp, A.K.; Briggs, J.M. [and others]. 1998. Modulation of diversity by grazing and mowing in native tallgrass prairie. Science. 280: 745-747.

Davis, M.A.; Peterson, D.W.; Reich, P.B. [and others]. 2000. Restoring savanna using fire: impact on the breeding bird community. Restoration Ecology. 8: 30-40.

Delcourt, P.A.; Delcourt, H.R. 1991. Quaternary paleoecology of the Lower Mississippi Valley. Engineering Geology. 45: 219-242.

Dey, D.C.; Hartman, G. 2005. Returning fire to Ozark Highland forest ecosystems: effects on advance regeneration. Forest Ecology and Management. 217: 37-53.

Dey, D.C.; Schweitzer, C.J. 2015. Timing fire to minimize damage in managing oak ecosystems. In: Holley, A.G.; Connor, K.F.; Haywood, J.D., eds. 2015. Proceedings of the 17th biennial southern silvicultural research conference. e-Gen. Tech. Rep. SRS-203. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 143-153

Dey, D.C.; Jensen, R.G.; Wallendorf, M.J. 2008. Single-tree selection reduces survival and growth of oak stump sprouts in the Missouri Ozark Highlands. In: Jacobs, D.F.; Michler, C.H., eds. 2008. Proceedings of the 16th central hardwood forest conference. Gen. Tech. Rep. NRS-P-24. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station: 26-37.

DiTomaso, J.M.; Brooks, M.L.; Allen, E.B. [and others]. 2006. Control of invasive weeds with prescribed burning. Weed Technology. 20(2): 535-548.

Fuhlendorf, S.D.; Engle, D.M.; Kerby, J.; Hamilton, R. 2008. Pyric herbivory: rewilding landscapes through the recoupling of fire and grazing. Conservation Biology. 23(3): 588-598.

Gardiner, E.S.; Yeiser, J.L. 2006. Underplanting cherrybark oak (*Quercus pagoda* Raf.) seedlings on a bottomland site in the southern United States. New Forests. 32: 105-119.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. Forest Science. 13: 38-53.

Green, J. 2008. Overstory density and its effect on regeneration abundance, understory height growth, and overstory canopy expansion in the Missouri Ozark Highlands. Columbia, MO: University of Missouri. 79 p. M.S. thesis.

Grundel, R; Pavlovic, N.B. 2007. Response of bird species densities to habitat structure and fire history along a Midwestern open-forest gradient. Condor. 109: 734-749.

Guyette, R.P.; Spetich, M.A. 2003. Fire history of oak–pine forests in the Lower Boston Mountains, Arkansas, USA. Forest Ecology and Management. 180: 463-474.

Guyette, R.P.; Dey, D.C.; Stambaugh, M.C. 2003. Fire and human history of a barren-forest mosaic in southern Indiana. The American Midland Naturalist. 149(1): 21-34.

Guyette, R.P.; Muzika, R.M.; Dey, D.C. 2002. Dynamics of an anthropogenic fire regime. Ecosystems. 5(5): 472-486.

Guyette, R.P.; Stambaugh, M.C.; Dey, D.; Muzika, R.M. 2012. Predicting fire frequency with chemistry and climate. Ecosystems. 15: 322- 335.

Haddad, N.M.; Tilman, D.; Haarstad, J. [and others]. 2001. Contrasting effects of plant richness and composition on insect communities: a field experiment. The American Naturalist. 158(1): 17-35.

Hanberry, B.B.; Dey, D.C.; He, H.S. 2012. Regime shifts and weakened environmental gradients in open oak and pine ecosystems. PLoS ONE 7 (7), e41337. doi:10.1371/journal.pone.0041337.

Hanberry, B.B.; Dey, D.C.; He, H.S. 2014a. The history of widespread decrease in oak dominance exemplified in a grassland-forest landscape. Science of the Total Environment. 476-477: 591-600.

Hanberry, B.B.; Jones-Farrand, D.T.; Kabrick, J.M. 2014b. Historical open forest ecosystems in the Missouri Ozarks: reconstruction and restoration targets. Ecological Restoration. 32(4): 407-416.

Hanberry, B.B.; Kabrick, J.M.; He, H.S. 2014c. Changing tree composition by life history strategy in a grassland-forest landscape. Ecosphere. 5(3):Article 34: 1-16. www.esajournals.org [Date accessed: May 10, 2015].

Hanberry, B.B.; Kabrick, J.M.; He, H.S. 2014d. Densification and state transition across the Missouri Ozarks landcape. Ecosystems. 17: 66-81.

Hartnett, D.C.; Hickman, K.R.; Fischer Walter, L.E. 1996. Effects of bison grazing, fire, and topography on floristic diversity in tallgrass prairie. Journal of Range Management. 49: 413-420.

Hunter, Jr., M.L.; Schmiegelow, F.K.A. 2011. Wildlife, forests and forestry. 2nd ed. New York: Prentice Hall. 259 p.

Huston, M.A. 1994. Biological diversity the coexistence of species on changing landscapes. Cambridge, UK: Cambridge University Press. 681 p.

Hutchinson, T.F. 2006. Fire and the herbaceous layer in eastern oak forests. In: Dickinson, M.B., ed. Fire in eastern oak forests: delivering science to land managers, proceedings of a conference; 2005 November 15-17; Columbus, OH. Gen. Tech. Rep. NRS-P-1. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station: 136-149.

Hutchinson, T.F.; Boerner, R.E.J.; Sutherland, S. [and others]. 2005. Prescribed fire effects on the herbaceous layer of mixed-oak forests. Canadian Journal of Forest Research. 35: 877-890.

Janowiak, M.K.; Swanston, C.W.; Nagel, L.M. [and others]. 2011. Silvicultural decisionmaking in an uncertain climate future: a workshop-based exploration of considerations, strategies, and approaches. Gen. Tech. Rep. NRS-81. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station. 14 p.

Janowiak, M.K.; Iverson, L.R.; Mladenoff, D.J. [and others]. 2014. Forest ecosystem vulnerability assessment and synthesis for northern Wisconsin and western Upper Michigan: a report from the Northwoods climate change response framework project. Gen. Tech. Rep. NRS-136. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station. 247 p.

Johnson, P.S. 1974. Survival and growth of northern red oak seedlings following a prescribed burn. Research Note NC-177. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 3 p.

Johnson, P.S.; Shifley, S.R.; Rogers, R. 2009. The ecology and silviculture of oaks. 2nd ed. New York: CABI Publishing. 580 p.

Kabrick, J.M.; Dey, D.C.; Kinkead, C.O. [and others]. 2014. Silvicultural considerations for managing fire-dependent oak woodland ecosystems. In: Groninger, J.W.; Holzmueller, E.J.; Nielsen, C.K.; Dey, D.C., eds. Proceedings of the 19th central hardwood forest conference. Gen. Tech. Rep. NRS-P-142. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station: 2-15.

King, D.I.; Schlossberg, S. 2014. Synthesis of the conservation value of the early-successional stage in forests of eastern North America. Forest Ecology and Management. 324: 186-195.

Kinkead, C.O.; Kabrick, J.M.; Stambaugh, M.C.; Grabner, K.W. 2013. Changes to oak woodland stand structure and ground flora composition caused by thinning and burning. In: Miller, G.W.; Schuler, T.M.; Gottschalk, K.W. [and others], eds. Proceedings of the 18th central hardwood forest conference. Gen. Tech. Rep. NRS-P-117. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station: 373-383.

Law, J.R.; Johnson, P.S.; Houf, G. 1994. A crown cover chart for oak savannas. Technical Brief TP-NC-2. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 4 p.

Leach, M.K.; Givnish, T.J. 1999. Gradients in the composition, structure, and diversity of remnant oak savannas in southern Wisconsin. Ecological Monographs. 69(3): 353-374.

Lhotka, J.M.; Loewenstein, E.F. 2009. Effect of midstory removal on understory light availability and the 2-year response of underplanted cherrybark oak seedlings. Southern Journal of Applied Forestry. 33(4): 171-177.

Lorimer, C.G.; Chapman, J.W.; Lambert, W.D. 1994. Tall understorey vegetation as a factor in the poor development of oak seedlings beneath mature stands. Journal of Ecology. 82: 227-237.

Marschall, J.M.; Guyette, R.P.; Stambaugh, M.C.; Stevenson, A.P. 2014. Fire damage effects on red oak timber product value. Forest Ecology and Management. 320: 182-189.

Mayer, A.L.; Khalyani, A.H. 2011. Grass trumps trees with fire. Science. 334: 188-189.

MDC. 2010. Missouri's forest resource assessment and strategy. Jefferson City, MO: Missouri Department of Conservation. 222 p.

Motsinger, J.R.; Kabrick, J.M.; Dey, D.C. [and others]. 2010. Effects of midstory and understory removal on the establishment and development of natural and artificial pin oak advance reproduction in bottomland forests. New Forests. 39: 195-213.

MTNF. 2005. 2005 Mark Twain National Forest Land and resource management plan. Rolla, MO: U.S. Department of Agriculture Forest Service, Mark Twain National Forest. 234 p.

Nelson, P.W. 2010. The terrestrial natural communities of Missouri. Jefferson City, MO: Missouri Natural Areas Committee. 550 p.

Nigh, T.A.; Schroeder, W.A. 2002. Atlas of Missouri ecoregions. Jefferson City, MO: Missouri Department of Conservation. 212 p.

Ostrom B.J.; Loewenstein, E.F. 2006. Light transmittance following midstory removal in a riparian hardwood forest. In: Connor, K.F.; ed. 2006. Proceedings of the 13th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-92. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 265-268.

Parker, W.C.; Dey, D.C. 2008. Influence of overstory density on ecophysiology of red oak (*Quercus rubra*) and sugar maple (*Acer saccharum*) seedlings in central Ontario shelterwoods. Tree Physiology. 28: 797-804.

Peterson, D.W.; Reich, P.B. 2008. Fire frequency and tree canopy structure influence plant species diversity in a forest-grassland ecotone. Plant Ecology. 194: 5-16.

Reidy, J.L.; Thompson III, F.R.; Kendrick, S.W. 2014. Breeding bird response to habitat and landscape factors across a gradient of savanna, woodland, and forest in the Missouri Ozarks. Forest Ecology and Management. 313: 34-46.

Sander, I.L. 1979. Regenerating oaks with the shelterwood system. In: Proceedings of 1979 J.S. Wright forest conference. West Lafayette, IN: Purdue University: 54-60.

Schroeder, W.A. 1982. Presettlement prairie of Missouri. Natural History Series No. 2. Jefferson City, MO: Missouri Department of Conservation. 38 p.

Schulte, L.A.; Mladenoff, D.J.; Crow, T.R. [and others]. 2007. Homogenization of northern U.S. Great Lakes forests due to land use. Landscape Ecology. 22: 1089-1103.

Shifley, S.R.; Smith, W.B. 1982. Diameter growth, survival, and volume estimates for Missouri trees. Research Note NC-292. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 7 p.

Shifley, S.R.; Thompson III, F.R. 2011. Chapter 6 spatial and temporal patterns in the amount of young forests and implications for biodiversity. In Greenberg, C.H.; Collins, B.S.; Thompson III, F.R., eds. Sustaining young forests communities ecology and management of early successional habitats in the Central Hardwood Region, USA. New York: Springer: 73-95.

Shifley, S.R.; Aguilar, F.X.; Song, N.; Stewart, S.I. [and others]. 2012. Forests of the northern United States. Gen. Tech. Rep. NRS-90. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station. 202 p.

Stambaugh, M.C.; Guyette, R.P.; Grabner, K.W.; Kolaks, J. 2006a. Understanding Ozark forest litter variability through a synthesis of accumulation rates and fire events. In: Andrews, P.L.; Butler, B.W., comps. 2006. Fuels management-how to measure success: conference proceedings. RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station: 321-332

Stambaugh, M.C.; Guyette, R.P.; McMurry, E.R.; Dey, D.C. 2006b. Fire history at the eastern Great Plains margin, Missouri River loess hills. Great Plains Research. 16: 149-159.

Starbuck, C.A.; Amelon, S.K.; Thompson III, F.R. 2014. Relationships between bat occupancy and habitat and landscape structure along a savanna, woodland, forest gradient in the Missouri Ozarks. Wildlife Society Bulletin. DOI: 10.1002/wsb.512. [Date accessed: unknown].

Starver, A.C.; Archibald, S.; Levin, S.A. 2011. The global extent and determinants of savanna and forest as alternative biome states. Science. 334: 230-232.

Taft, J.B.; Schwartz, M.W.; Philippe, L.R. 1995. Vegetation ecology of flatwoods on the Illinoian till plain. Journal of Vegetation Science. 6: 647-666.

Thompson III, F.R.; Reidy, J.L.; Kendrick, S.W.; Fitzgerald, J.A. 2012. Songbirds in managed and non-managed savannas and woodlands in the central hardwoods region. In: Dey, D.C.; Stambaugh, M.C.; Clark, S.L.; Schweitzer, C.J., eds. Proceedings of the 4th fire in eastern oak forests conference. Gen. Tech. Rep. NRS-P-102. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station: 159-169.

Transeau, E.N. 1935. The prairie peninsula. Ecology. 16(3): 423-437.

Waldrop, T.A.; Yaussy, D.A.; Phillips, R.J.; [and others]. 2008. Fuel reduction treatments affect stand structure of hardwood forests in western North Carolina and southern Ohio, USA. Forest Ecology and Management. 255: 3117-3129.

Zenner, E.K.; Kabrick, J.M.; Jensen, R.G.; [and others]. 2006. Responses of ground flora to a gradient of harvest intensity in the Missouri Ozarks. Forest Ecology and Management. 222: 326-334.

Zouhar, K.; Smith, J.K.; Sutherland, S. 2008. Effects of fire on nonnative invasive plants and invisibility of wildland ecosystems. In: Gen. Tech. Rep. RMRS-42, Vol.6, Ch.2. Ft. Collins, CO: U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station: 7-31.