SILVICULTURAL CONSIDERATIONS FOR MANAGING FIRE-DEPENDENT OAK WOODLAND ECOSYSTEMS

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Abstract.—Oak woodlands are characterized by open understories and dense ground flora composed of forbs, grasses, and sedges. They once were common in the western Central Hardwood Forest region and the prairie-forest transition zone where low-intensity fires occurred frequently. In the absence of fire, many of the woodland ecosystems throughout much of this region have succeeded to compositions and structures resembling those of mesophytic forests. Consequently, forest managers are increasingly interested in restoring the structure and composition of oak woodlands by thinning and prescribed burning. Presently, there are few guidelines based upon silvicultural principles for restoring and managing woodland ecosystems. However, many silvicultural concepts, principles, and methods used for managing forests can also be used for managing woodlands, but the application and timing of treatments may differ to meet the objectives of woodland management. In this paper, we summarize findings from a number of studies and offer guidelines for restoring and managing oak woodlands.

INTRODUCTION

Woodlands are natural communities characterized by open to nearly closed canopies of overstory trees, relatively sparse midstory and understory, and dense, species-rich ground flora. In contrast to forests, many of the dominant and codominant trees in the canopy of woodlands have large, spreading crowns (Nelson 2005, Nuzzo 1986, Taft 2009). Shrubs, saplings, and small trees may be present but generally are much less abundant than in a mature forest (Nelson 2005). The relatively open canopy and midstory of woodlands allows sunlight to reach the ground to support a species-rich layer of light-demanding plants dominated by forbs, sedges, and grasses that may be present but seldom are abundant in closed-canopy forests (Kinkead et al. 2013).

Woodlands were once common in the western Central Hardwood Forest region (CHFR) along the prairie-forest ecotone where low-intensity fires occurred periodically (Guyette et al. 2002, Johnson et al. 2009, Kinkead et al. 2013, Taft 2009). These fires largely were set by native people, and fire history studies indicate that before the 1930s the fire frequency was closely related to the population density (Guyette et al. 2002). Fire suppression policies beginning in the region in the 1930s greatly reduced the fire frequency, causing many of the woodland ecosystems throughout much of the CHFR to succeed to compositions and structures resembling those of mesophytic forests (Nowacki and Abrams 2008).

Managers are increasingly interested in restoring the structure and composition of oak (*Quercus* spp. L.) and oak-pine (*Pinus* L.) woodlands by thinning and applying prescribed burning (Dey and

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Hartman 2005, Fule´ et al. 2005, Glascow and Matlack 2007, Hutchinson et al. 2012, Peterson and Reich 2001). Despite the increasing interest, few guidelines based on silvicultural principles are available for restoring and managing woodlands. In this paper, we provide some guidelines for woodland management based upon the contemporary understanding of disturbances and site factors that influence woodland structure and species composition, important metrics for quantifying woodland structure, and silvicultural methods for managing and perpetuating woodlands.

WOODLAND COMPOSITION AND STRUCTURE

In the CHFR, oaks and hickories (*Carya* Nutt.) are the dominant hardwood tree species of woodlands and often occur in association with pines in the Ozark Highlands (Nelson 2005). Numerous ground flora species are considered woodland indicators, particularly graminoids, sedges, and species in the genera *Lespedeza* (Michx.), *Silphium* (L.), *Solidago* (L.), and *Symphyotrichum* (Nees) (Farrington 2010). Most of the woodland indicator species are herbaceous plants that produce flowers and seeds during the summer and are adapted to ecosystems where light penetration is relatively high. These species, often associated with prairie and savanna ecosystems, suggest that stand density has remained sufficiently low to allow sunlight to reach the ground vegetation (Taft 2009).

The Role of Fire

Fire history studies have documented that low-intensity ground fires occurred regularly before European settlement in the forests and woodlands of the CHFR (Guyette et al. 2002) and elsewhere in North America (Ryan et al. 2013). Throughout much of eastern North America and the CHFR, most of these fires were set by humans (Nowacki and Abrams 2008). Surface fires throughout the CHFR occurred frequently; the average fire-return interval ranged from 3 to 19 years but varied over space and time (Guyette et al. 2006). Fire scar data indicated that some locations burned every 2 to 3 years while nearby locations burned once every 20 years or longer because of differences in slope steepness, presence of streams, and occurrence of other features that acted as fire breaks (Guyette et al. 2006). At a single location, there is evidence that the fire-return interval changed over time with changes in the Native American population density (Guyette et al. 2002).

These frequent, low-intensity surface fires are thought to have played an important role in shaping the composition of woodlands (Nelson 2005, Nuzzo 1986, Packard 1993, Taft 2009). Oaks and hickories can persist in association with low-intensity fires because the cotyledons of oak and hickory seedlings remain belowground (Burns and Honkala 1990); if topkilled by fire, the cotyledons remain protected and provide some of the nourishment needed to resprout and remain in the stand. Oak seedlings also establish a large root system at the expense of early shoot growth (Johnson et al. 2009). This larger root system enables oak seedlings to resprout readily after being topkilled. In contrast, maples (*Acer* L.) are disfavored by fire; their cotyledons emerge aboveground and will perish if the seedling is topkilled by a surface fire (Burns and Honkala 1990). Maples also allocate more energy into shoot growth at the expense of root growth, leaving them more vulnerable to mortality following topkill (Burns and Honkala 1990). Grasses, sedges, forbs, and other herbaceous vegetation are also favored by fire compared to vines, shrubs, and other woody vegetation that lose much of their energy reserves if their aboveground tissue is consumed (Brose et al. 2013).

Fire was also thought to have played an important role in reducing stand density and altering forest structure (Nelson 2005, Taft 2009). Shrubs and other small-diameter trees are particularly susceptible to topkill by fire, and frequent, low-intensity fire is thought to have reduced the density of the midstory and understory layers. Surface fire also removes some or all of the leaf litter that can inhibit the germination of many species of grasses, sedges, and forbs. This wide variation in fire-return interval that has been documented to occur within a single location or region is thought to have greatly influenced woodland dynamics (Stambaugh et al. 2007). Frequent fires may have favored the establishment of oak or pine seedlings in woodlands but would prohibit their recruitment. Tree recruitment most likely occurred during fire-free periods (Stambaugh et al. 2007).

Other Disturbances

In addition to fire, disturbances such as severe winds, droughts, ice storms, insects, and diseases also periodically affected woodlands by reducing their density or by altering their species composition (Nelson 2005). As in forests, these disturbances historically contributed to regeneration and stand development patterns. Also, herbivore grazing undoubtedly affected historical woodland structure and composition (Nelson 2005). However, little information is available about how these disturbances shaped woodland character in the past.

Influence of Site Quality

Site quality also affects woodland composition and structure. Dry and nutrient-deficient sites support fewer plant species and lower shrub and understory densities than rich sites (Kabrick et al. 2008). The tree and shrub species that are adapted to these conditions produce litter that dries rapidly and decomposes slowly, allowing them to burn readily. The lower site quality causes trees and shrubs to grow more slowly so that their canopies remain open longer following disturbance (Johnson et al. 2009). Even in the absence of disturbances, the lower shrub and tree seedling and sapling densities allow many of the light-demanding woodland ground flora to persist in the understory (Kinkead 2013). Site classification systems are useful for identifying where site conditions favor the management of woodlands and for predicting how they will respond to management (Kabrick et al. 2008).

WOODLAND SILVICULTURE

Much like forests, woodlands must be managed to sustain their structure and biodiversity and to ensure desirable distribution of woody and herbaceous vegetation in the future (Nelson 2005). Where woodlands are left unmanaged, a dense midstory and understory eventually develops and the overall tree density and canopy cover increases. In addition to the increasing shade caused by the greater stand density and canopy closure, the absence of fire allows a thick layer of leaves to accumulate. Succession to a more shade-tolerant mix of vegetation may occur, particularly in woodlands of moderate to high site quality (Hutchinson et al. 2012). Generally, the intensity of management required to maintain woodland conditions increases with site quality (Nowacki and Abrams 2008). If woodlands are left unmanaged for long time periods, these successional changes may become extremely difficult to reverse due to losses of woodland sedges and grasses and to the additions of shrubs and woody plants that change the nature of the fuels and the response to fire (Nowacki and Abrams 2008).

Table 1.—Some reasons for thinning or burning in forests vs. woodlands

Forests	Woodlands
Thinning	Thinning
Improve stand quality	Reduce density and alter structure
Concentrate growth	Increase light reaching the ground
Utilize trees that will be lost to mortality	Provide growing space to ground flora
Reduce disease and infestation	Reduce disease and infestation
Burning	Burning
Favor desirable tree species during regeneration phase	Favor desirable ground flora species during tending phase
Reduce fuel loading during tending phase	Maintain suitable structure during the tending phase

Because most woodlands in the CHFR have not been managed for many years, a management priority is restoring woodland structure, composition, and function. Once the structure, composition, and function have been restored, it is necessary to plan for regenerating some of the trees in a woodland community. This need arises because some of the trees will succumb to competition-induced mortality as they mature, and others will die of old age or indirectly of injuries suffered through woodland management and other agents causing physiological stress and physical damage. In addition, many woodlands are also capable of producing saw logs, ties, and blocking material. The periodic harvest and sale of these timber products can be used to offset some of the management costs of the thinning and burning that are necessary during later stages. Although a comprehensive management system that includes a plan for regenerating trees is recommended for all woodland management regardless of objectives, this comprehensive plan becomes even more important where producing timber sustainably is an additional objective.

Important Silvicultural Tools, Metrics, and Principles

Many silvicultural concepts, principles, and methods used for managing forests can also be used for managing woodlands. However, the application and timing of treatments may differ to meet the objectives of woodland management (Table 1). Woodland management objectives emphasize conserving the native biodiversity and maintaining habitat rather than optimizing the production of the highest quality wood products. Therefore, treatments are applied at the appropriate frequencies to retain a small number of large trees in the overstory and reduce the number of trees and shrubs in the midstory and understory layers, consume some of the seedlings and leaf litter, and promote the diversity of forbs, sedges, and grasses in the ground layer.

Thinning and prescribed burning may be applied differently in woodlands managed for biodiversity than in forests managed for timber production. In forests, thinning operations are done to improve timber quality and to accelerate the growth of the remaining trees. Although thinning also accelerates the growth of the residual trees in woodlands, it is done primarily to alter stand structure and increase the amount of sunlight reaching the ground to favor light-demanding plant species. In forests, prescribed fire is also used but primarily as a regeneration tool to favor the accumulation of fire-adapted tree seedlings (Brose et al. 2013). Where timber quality is a concern, the application of prescribed fire is generally limited to a short time before or after a regeneration harvest to favor the desirable species. Fire is excluded from the stand during later tending operations to prevent damage to future timber trees (Brose et al. 2013). In woodlands, prescribed fire is used as a tending tool to periodically reduce seedling and sapling density, remove leaf litter, and maintain ground layer species composition.

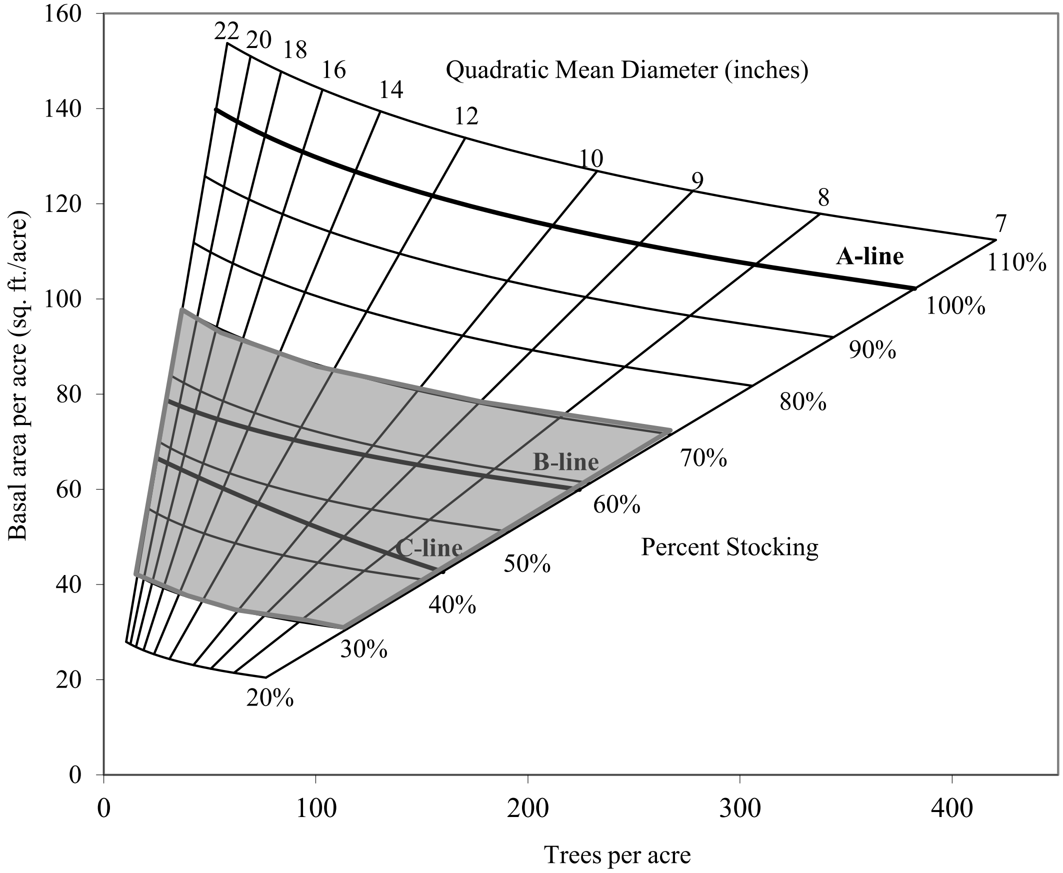

Figure 1.—Stocking chart (Gingrich 1967) for oaks and hickories where the quadratic mean diameter at breast height is >7 inches. Tending operations in woodlands keep the stocking between 30 and 70 percent stocking with closed-canopy woodlands maintained near the B line and open-canopy woodlands maintained below the B line. At stocking levels less than 30 percent, the structure begins to resemble that of a savanna. However, for regenerating forests and woodlands, stocking is reduced below the B line.

Because prescribed burning and thinning are so important to woodland management, drip torches, chainsaws, and herbicides are all important tools for managing contemporary woodlands. However, one of the most important but often neglected tools for managing woodlands is a stocking chart (Fig. 1) (Gingrich 1967). Stocking is an important measure of density related to canopy cover and growing space occupancy (Johnson et al. 2009). Reducing stand density decreases the crown closure and increases the amount of sunlight reaching the ground. Equations are available for estimating canopy closure or light levels as a function of stocking (Blizzard et al. 2013).

Two critical stocking levels are important for managing either forests or woodlands (Fig. 1). The first is the A level, which identifies the average maximum number of trees of a given diameter that can occupy the growing space (Gingrich 1967). The second is the B level, which identifies the average minimum number of trees of a given diameter that can occupy all of the growing space (Gingrich 1967). The B level is an important and biologically meaningful reference because reducing stocking to below the B level ensures that canopy gaps will occur (Johnson et al. 2009). For tending forests, stocking is generally reduced by thinning to the B level and allowing the forest to grow back to the A level (i.e., where full stocking is maintained); for regenerating forests, stocking is reduced to below the B level to allocate growing space to a new cohort of trees. For managing woodlands, stocking is generally maintained at a lower level than for forests. For tending operations in closed-canopy woodlands, stocking levels should be maintained at slightly above or slightly below the B level;

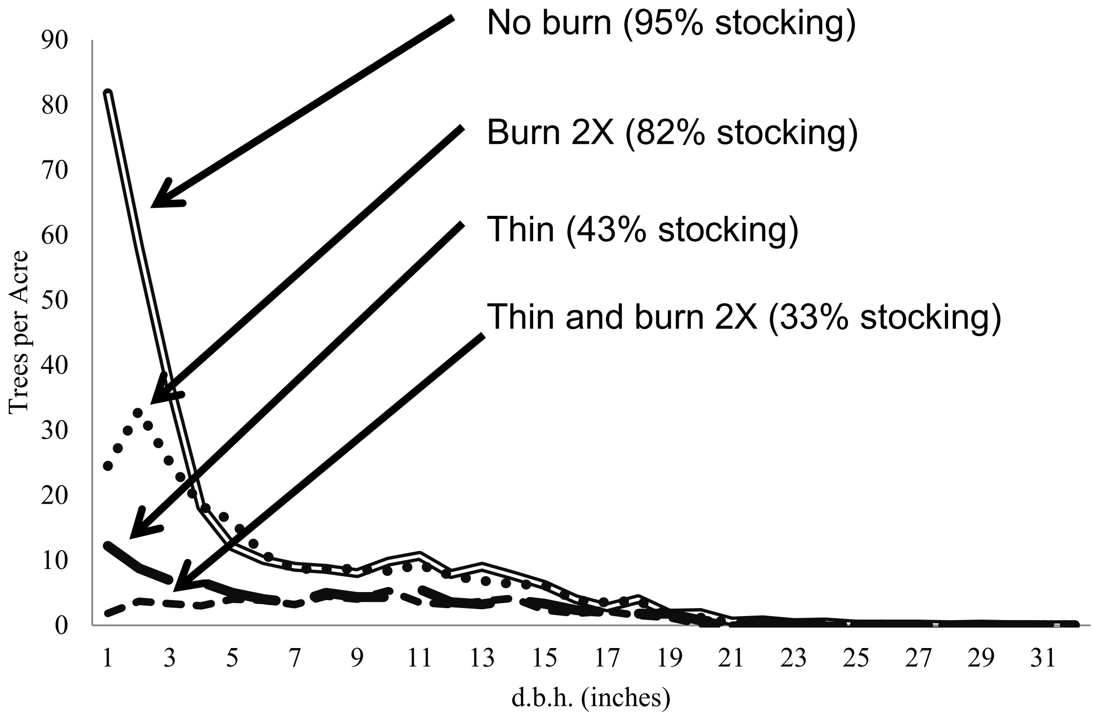

Figure 2.—Diameter distributions coupled with estimated stocking are useful for evaluating the effects of burning and thinning treatments on woodland structure. Greater reductions in stand density can be achieved by thinning or thinning and prescribed burning than by prescribed burning alone. In this example, two prescribed fires were applied 2 years apart (adapted from Kinkead et al. 2013).

for open-canopied woodlands, stocking levels should be maintained below the B level. Although arbitrary, woodland stocking levels during tending operations would remain above 30 percent, the point at which the density would resemble that of a savanna. Much as for forests, woodland regeneration requires stocking to be reduced below the B level.

Stocking estimates can be used along with diameter distributions for assessing the effects of woodland management treatments. For example, in fully stocked stands, two prescribed fires applied 2 years apart will reduce the stem density by 40 percent but will reduce the stocking by only about 15 to 25 percent (Kinkead et al. 2013) by reducing the number of small-diameter stems (Fig. 2). This difference is because trees <5 inches d.b.h. are much more susceptible to topkill or mortality than are larger trees (Dey and Hartman 2005). Greater reductions in stocking require the removal of large trees. For more substantial changes to the stocking, mechanical thinning is needed.

Reducing the stocking only temporarily decreases the growing space occupancy and the canopy cover (Johnson et al. 2009). In the absence of disturbance, stocking increases to the A level over time as the residual trees become larger and new trees become established. During this time the canopy closes and light levels decrease. From the B level, stocking increases on average about 1.5 percent per year but may range from 1 percent per year on low quality sites to 3 percent per year on high quality sites (Dale and Hilt 1989). Consequently, the frequency of thinnings may need to increase as site quality increases to maintain target stocking levels. In woodlands where low stocking is desirable, periodic thinning may be needed, particularly if the stand comprises trees that are too large to be thinned by prescribed fire (Hutchinson et al. 2012).

Table 2.—Historical and contemporary density and diameter of trees > 5 inches d.b.h. of selected Missouri Ecological Sections and Land Type Associates derived from witness tree data from the General Land Office (GLO) and Forest Inventory and Analysis (FIA) databases [a,b]

Ecological Section and Land Type Association	Trees per acre		D.b.h. (inches)		Stocking (%)	
	GLO	FIA	GLO	FIA	GLO	FIA
OZ7 Oak Woodland Plains and Hills	50	146	13	9	37	59
OZ7 Oak Woodland/Forest Hills	63	151	13	9	48	60
OZ7 Oak-Pine Hills	66	153	13	9	48	57
OZ7 Pine-Oak Woodland Plains	63	158	13	9	46	57
OZ7 Rugged Hills and Forest Breaks	53	140	13	9	43	53
OZ8 Oak Woodland Plains and Hills	77	138	12	9	48	59
OZ8 Oak Woodland/Forest Hills	57	136	13	10	45	63
OZ8 Oak-Pine Hills	130	138	13	10	99	60
OZ8 Pine-Oak Woodland Plains	65	148	14	9	49	60
OZ9 Oak-Pine Hills	75	138	15	9	59	55
OZ9 Pine-Oak Woodland Plains	63	146	15	9	54	60
OZ9 Rugged Hills and Forest Breaks	111	128	14	9	86	56

[a]Values are averages adapted from Hanberry et al. 2014.
[b]In Missouri, General Land Office Surveys were conducted between 1815 and 1850.

Reducing the stocking to below the B level also stimulates the production and development of seedlings, seedling sprouts, and stump sprouts (Larsen et al. 1997). Unless this is desired for regenerating the stand, the high density of sprouts and seedlings may shade the desirable woodland grasses, forbs, and sedges. Under low residual overstory stocking, prescribed fire or some other method of sprout control may need to be applied more frequently than where residual overstory stocking levels remain above the B level, particularly on high quality sites where reproduction establishes more rapidly (Kabrick et al. 2008).

Understanding stocking is also important for interpreting information about the structure of presettlement forests and woodlands. Witness tree data from the General Land Office survey records have been used for identifying restoration target densities for woodlands throughout the CHFR and generally show that there were fewer trees >5 inches d.b.h. per acre than in contemporary forests and woodlands (Table 2, Hanberry et al. 2014). Based on this evidence, many have concluded that forests today have a much greater density than historically and that reducing stand density is a priority for woodland restoration. However, trees at the time of the land surveys were also 1.4 times larger in diameter, and when accounted for using a metric such as stocking, it becomes apparent that even though some woodlands historically had low stocking, many other woodlands and forests had high stocking and at levels comparable to the >5 inch d.b.h. trees in contemporary woodlands and forests (Hanberry et al. 2014). This suggests that the high level of ground flora diversity generally occurring in many woodlands may be due to something other than low overstory stocking such as the removal of leaf litter and the understory vegetation by fire (Kinkead 2013).

Silvicultural Systems

A silvicultural system is a comprehensive plan for regenerating and tending a stand of trees (Nyland 1996). Presently, there are no well-defined silvicultural systems that include a planned series of treatments for regenerating and tending woodlands. Nonetheless, many relevant silvicultural methods are potentially applicable to woodlands as discussed below.

Most of the regeneration methods used in forest management can be applied to woodlands. For example, trees in woodlands can be regenerated with even-age methods including with clearcuts (Roach and Gingrich 1968), the seed tree method where pines are dominant (Nyland 1996), or the shelterwood method (Brose et al. 1999), each with reserves and tended with thinning and prescribed burning. They also can be regenerated with uneven-age methods including with group selection with reserves (Johnson et al. 2009) and tended with thinning and burning. Retaining reserve trees making up 10 to 30 percent stocking is preferable for regenerating woodlands. The reserve trees are retained in the stand to provide habitat for wildlife and partial shade to reduce the density of regeneration that develops after harvesting. Without the reserve trees, the high density of reproduction that develops will eventually shade the woodland ground flora, substantially reducing its cover. If possible, the reserves should be the large-diameter, full-crowned legacy trees that contribute to woodland character.

During the regeneration phase in woodlands, prescribed fire should be excluded until a portion of the reproduction cohort is sufficiently large to escape being topkilled by fire's reintroduction. Here it is important to recognize that in mature woodlands there will only be about 30 to 40 canopy dominant or codominant trees per acre. Thus, managing trees in woodlands is analogous to the silvicultural practice of crop-tree management in which a small number of trees are selected at an early age as the crop trees and are carefully cultured while the vast majority of trees in the stand are left unmanaged. In woodland management, the non-crop trees are subject to removal arbitrarily by burning or deliberately by mechanical thinning.

According to Arthur et al. (2012), the fire-free interval in oak systems should be from 10 to 30 years to allow a sufficient number of trees—30 to 40 per acre—to become large enough to not be topkilled by fire (>6 inches d.b.h.) so that they can recruit into the overstory. If producing marketable timber is also an objective, the fire-free interval may need to be 30 years or longer to allow a critical number of trees to become large enough to not be severely damaged by prescribed fire. These trees are to be treated as the future timber crop so that they can eventually be harvested to offset some of the costs of implementing woodland management treatments. For example, it is reasonable to assume that as trees approach saw log size they become less vulnerable to large losses in value caused by fire scarring of their bark because the damaged outer portion of the saw logs cut from these trees will be removed with the slab wood during milling operations (Marschall et al., in press). If it is assumed that 10 inches d.b.h. is the minimum size threshold for minimizing fire value loss, data from long-term studies of clearcuts conducted on the Sinkin Experimental Forest indicate that more than 20 trees per acre exceed this threshold by age 35 and more than 40 trees per acre exceed this threshold if the stands are thinned at age 20 (Table 3). After the regeneration phase, care must be practiced when reintroducing prescribed burning to prevent mortality of the desired trees or to minimize damage to the future timber crop.

Table 3.—Number of oaks greater than 6 or 10 inches d.b.h. in clearcuts that were not thinned or thinned with a rule-based thinning method to 60 percent stocking in the Missouri Ozarks[a]

	Trees per acre >6 inches d.b.h.		Trees per acre >10 inches d.b.h.	
Stand age (years)	Not thinned	Thinned to B level at age 20	Not thinned	Thinned to B level at age 20
15	14	--	0	--
20	58	--	0	--
25	130	128	1	4
30	189	168	6	17
35	214	185	26	42

[a]Unpublished data from the Sinkin Experimental Forest.

A 30-year period without prescribed fire may be longer than may have occurred in the pre-European CHFR (Guyette et al. 2006). However, this extended fire-free period is only required if reducing value losses of a future timber crop is a management objective. For woodlands where producing marketable timber for offsetting the costs of woodland management is not an objective, the fire-free period may be a short as 10 years in the CHFR to ensure sufficient recruitment (Arthur et al. 2012).

Reducing the stocking to about 10 to 30 percent during the regeneration phase is important for ensuring that the reproduction cohort can recruit rapidly. Maintaining greater residual stocking levels will substantially reduce the growth rate of the new cohort of trees, increasing the duration of the fire-free interval needed for allowing sufficient numbers of trees to grow larger than the threshold diameters identified above. Reducing the stocking to below 10 percent would increase the growth rate of the new cohort but would leave few large trees in the stand for habitat and for refuge for the ground flora.

Because of uncertainly in fire behavior, silvicultural practices using area regulation are better suited for managing woodlands (Fig. 3). With area regulation, specific stands or land units of the woodland are selected for regeneration or tending. For those selected for regeneration, prescribed fire can be excluded from stands or land units with fire lines, roads, or natural fire breaks to protect the seedlings and allow for recruitment. After a sufficient number of trees have recruited and are no longer in danger of being topkilled or severely damaged, fire can be reintroduced along with other tending methods. Unless the fire-free interval is longer than 10 years, it may be exceptionally difficult to manage woodlands using single-tree selection because this method requires the continuous establishment and recruitment of seedlings and small trees that are vulnerable to topkill by fire.
In general, the fire-free interval will need to increase as residual stocking increases, because higher stocking will slow the growth of the regeneration cohort, lengthening the time it takes for desirable regeneration to recruit into size classes less vulnerable to fire damage or topkill.

Longer rotations may be used in woodlands than in forests. Rotations of 100 years are commonly used in hardwood forest management for optimizing the sustained production of timber. However, a longer rotation can be used for managing long-lived species where timber production is not a primary objective. For example, in the Ouachita National Forest, rotations for shortleaf pine-bluestem woodlands were extended from 70 to 120 years for red cockaded woodpecker (*Picoides borealis*) recovery or 160 years for old-growth restoration (Hedrick et al. 2007). Extending the rotation means that woodlands can remain in the tending phase longer where they can be maintained with prescribed fire for more of the rotation.

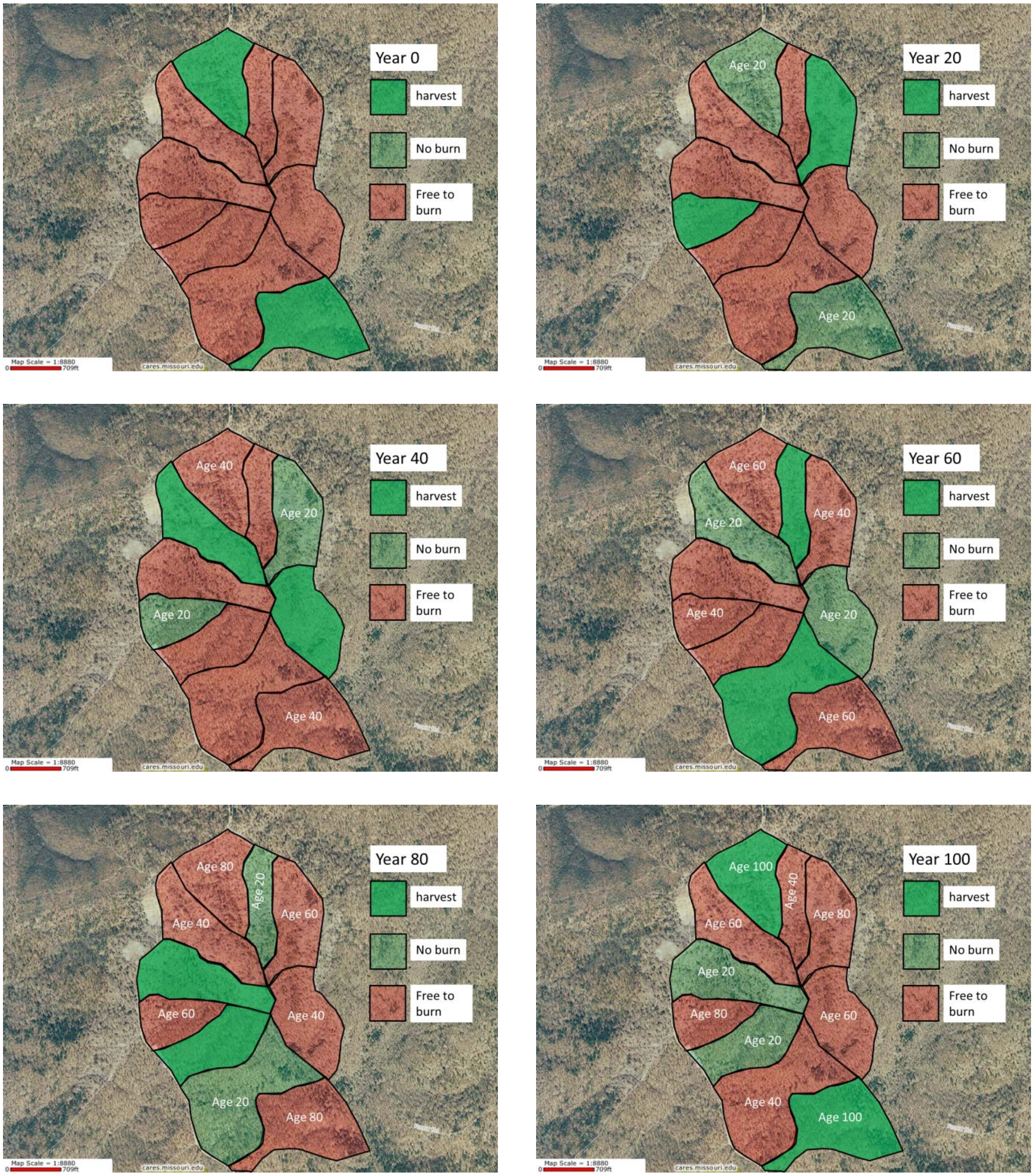

Figure 3.—Area regulation can be used to manage a mosaic of structural states and age classes across an administrative compartment or large woodland tract. In this example, a 200-acre area representing an administrative compartment is subdivided into 10 equal sized fire management units. The boundaries follow old skid trails to facilitate timber removal and fire line maintenance; fire lines elsewhere can be created and maintained with a blower. Regeneration harvests that can include clearcutting with reserves, seed tree method with reserves, or irregular shelterwoods occur in selected fire management units totaling 20 percent of the compartment land area during each 20-year re-entry. Fire is excluded from the regenerated areas for at least 30 years to allow for recruitment and to minimize fire damage to a future timber crop. Other configurations can be generated by changing the rotation age, the re-entry period, and the assumptions about the duration of the fire-free period required for recruitment.

SUMMARY AND CONCLUSIONS

Much like forests, woodlands in the CHFR must be managed to sustain their structure and biodiversity and to ensure desirable distribution of woody and herbaceous vegetation in the future. Many of the tending and regeneration methods used for managing forests can be adapted for managing woodlands although there may be differences in the timing and purpose of treatments. The concept of stocking is useful for managing woodland density and tracking woodland response to management treatments. It generally is easier to use area-regulation methods such as those applied in even-age systems or with the group selection method in uneven-age systems rather than methods using structure control such as in single-tree selection. With area-regulation methods, a stand or management unit can be divided into two phases: the tending phase and the regeneration phase. During the tending phase, prescribed fire can be applied with or without mechanical thinning methods to achieve desirable structure and composition. During the regeneration phase, fire can be excluded from the stand or management unit until a critical number of trees in the regeneration cohort are sufficiently large to escape either topkill or damage so that they can recruit into the overstory.

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LITERATURE CITED

Arthur, M.A.; Alexander, H.D.; Dey, D.C.; Schweitzer, C.J.; Loftis, D.L. 2012. **Refining the oak–fire hypothesis for management of oak-dominated forests of the eastern United States.** Journal of Forestry. 110: 257-266.

Blizzard, E.M.; Kabrick, J.M.; Dey, D.C.; Larsen, D.R; Pallardy, S.G.; Gwaze, D.P. 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. Gen. Tech. Rep. SRS-174. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 73-79.

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

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. 23: 158-163.

Burns, R.M.; Honkala, B.H., tech. coords. 1990. **Silvics of North America: 2. Hardwoods.** Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture, Forest Service. 877 p.

Dale, M.E.; Hilt, D.E. 1989. **Stocking chart for upland central hardwoods.** In: Clark, F.S., tech ed.; Hutchinson, J.G., ed. Central hardwood notes. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. Note 5.02.

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

Farrington, S. 2010. **Common indicator plants of Missouri upland woodlands.** Jefferson City, MO: Missouri Department of Conservation. 16 p.

Fule´, P.Z.; Laughlin, D.C.; Covington, W.W. 2005. **Pine-oak forest dynamics five years after ecological restoration treatments, Arizona, USA.** Forest Ecology and Management. 218: 129-145.

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

Glasgow, L.S.; Matlack, G.R. 2007. **Prescribed burning and understory composition in a temperate deciduous forest, Ohio, USA.** Forest Ecology and Management. 238: 54-64.

Guyette, R.P.; Dey, D.C.; Stambaugh, M.C.; Muzika, R.M. 2006. **Fire scars reveal variability and dynamics of eastern fire regimes.** In: Dickinson, M.B., ed. Fire in eastern oak forests: delivering science to land managers; proceedings of a conference. Gen. Tech. Rep. NRS-P-1. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 20-39.

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

Hanberry, B.B.; Kabrick, J.M.; He, H. 2014. **Densification and state transition across the Missouri Ozarks landscape.** Ecosystems. 66-81.

Hedrick, L.D.; Bukenhofer, G.A.; Montague, W.G.; Pell, W.F.; Guldin, J.M. 2007. **Shortleaf pine-bluestem restoration in the Ouachita National Forest.** In: Kabrick, J.M.; Dey, D.C.; Gwaze, D., eds. Shortleaf pine restoration and ecology in the Ozarks: proceedings of a symposium. Gen. Tech. Rep. NRS-P-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 206-213.

Hutchinson, T.F.; Yaussy, D.A.; Long, R.P.; Rebbeck, J.; Sutherland, E.K. 2012**. Long-term (13-year) effects of repeated prescribed fires on stand structure and tree regeneration in mixed-oak forests**. Forest Ecology and Management. 286: 87-100.

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

Kabrick, J.M.; Zenner, E.K.; Dey, D.C.; Gwaze, D.; Jensen, R.G. 2008. **Using ecological land types to examine landscape-scale oak regeneration dynamics.** Forest Ecology and Management. 255: 3051-3062.

Kinkead, C.O. 2013. **Thinning and burning in oak woodlands.** Columbia, MO: University of Missouri. 125 p. M.S. thesis.

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.; Brooks, J.R.; Grushecky, S.T.; Spong, B.D.; Rentch, J.S., eds. Proceedings, 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.

Larsen, D. R.; Metzger, M.A.; Johnson, P.S. 1997. **Oak regeneration and overstory density in the Missouri Ozarks.** Canadian Journal of Forest Research. 27: 869-875.

Marschall, J.M.; Guyette, R.P.; Stambaugh, M.C.; Stevenson, A.P. [In press]. **Fire damage effects on red oak timber product values.** Forest Ecology and Management.

Nelson, P.W. 2005. **The terrestrial natural communities of Missouri.** Jefferson City, MO: Missouri Natural Areas Committee. 550 p.

Nowacki, G.J.; M.D. Abrams 2008. **The demise of fire and 'mesophication' of forests in the eastern United States.** BioScience. 58: 123-138.

Nuzzo, V.A. 1986. **Extent and status of Midwest oak savanna: pre-settlement and 1985.** Natural Areas Journal. 6(2): 6-36.

Nyland, R.D. 1996. **Silviculture: concepts and applications.** Boston: McGraw Hill. 633 p.

Packard, S. 1993. **Restoring oak ecosystems.** Restoration and Management Notes. 11: 5-16.

Peterson, D.W.; Reich, P.B. 2001. **Prescribed fire in oak savanna: fire frequency effects on stand structure and dynamics.** Journal of Applied Ecology. 11: 914-92.

Ryan, K.C.; Knapp, E.E.; Varner, J.M. 2013. **Prescribed fire in North American forests and woodlands**: **history, current practice, and challenges.** Frontiers in Ecology and the Environment. 11: e15-e24.

Roach, B.A.; Gingrich, S.F. 1968. **Even-aged silviculture for upland central hardwoods.** Agric. Handb. 355. Washington, DC: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 39 p.

Stambaugh, M.C.; Guyette, R.P.; Dey, D.C. 2007. **What fire frequency is appropriate for shortleaf pine regeneration and survival?** In: Kabrick, J.M.; Dey, D.C.; Gwaze, D., eds. Shortleaf pine restoration and ecology in the Ozarks: proceedings of a symposium. Gen. Tech. Rep. NRS-P-15. Newtown, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 121-128.

Taft, J.B. 1997. **Savanna and open-woodland communities.** In: Schwartz, M.W., ed. Conservation in highly fragmented landscapes. New York: Chapman and Hall: 24-54.

Taft, J.B. 2009. **Effects of overstory stand density and fire on ground layer vegetation in oak woodland and savanna habitats.** In: Hutchinson, T. F., ed. Proceedings of the 3rd fire in eastern oak forests conference. Gen. Tech. Rep. NRS-P-46. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 21-39.