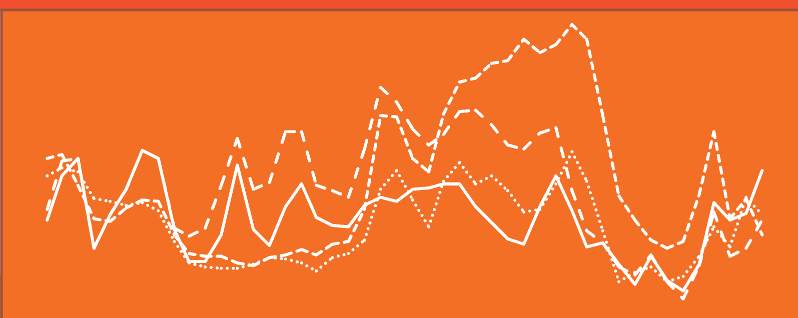
United States Department of Agriculture

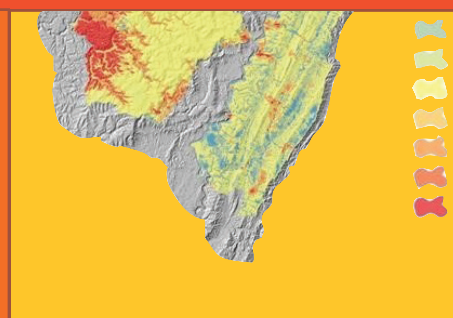
Oak Symposium: Sustaining Oak Forests in the 21st Century through Science-based Management

October 24-26, 2017

Knoxville Hilton Hotel

Knoxville, TN





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Papers published in these proceedings were submitted by authors in electronic media. Some editing was done to ensure a consistent format. Authors are responsible for content and accuracy of their individual papers and the quality of illustrative materials.

Photos

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Abstract

The 2017 Oak Symposium was convened in Knoxville, TN, to share knowledge on state-of-the-art management and research to improve sustainability of the upland oak resource in the Eastern United States. The symposium featured 33 invited speakers, an audience discussion period, a field trip, and 21 offered posters. Speakers addressed topics including the history of silviculture, fire, and research; current status of the oak resource; emerging economic markets; forest health; silviculture for climate change; artificial regeneration; wildlife habitat management; approaches to secure natural advanced oak regeneration; prescribed burning to promote oak regeneration; and management of woodland habitat. Presenters represented various organizations from non-governmental organizations, Federal agencies, State agencies, universities, and industry.

Keywords: Climate change, economic markets, oak woodlands, prescribed fire, regeneration, silviculture, wildlife.

Preface

Significant progress has been made in research and oak management since the mid-20th century, but knowledge of prescriptions to regenerate, sustain, and conserve oak forests is still lacking. The first comprehensive meeting on oak silviculture and management was held in 1971 in Morgantown, WV; it addressed problems with securing oak regeneration, multiple use management, and wood products and utilization [White, D.E. and Roach, B.A. (co-chairmen), Oak Symposium Proceedings. Northeastern Forest Experiment Station, USDA Forest Service]. In 1979, a regional meeting was held at Purdue University that concentrated primarily on the oak regeneration problem [Holt, H.A. and Fisher, B.C. (editors), John S. Wright Forestry Conference: Regenerating Oaks in Upland Hardwood Forests. Purdue Research Foundation]. A meeting was held in 1992 in Knoxville, TN [Loftis, D.L. and McGee, C.E. (editors), Oak Regeneration: Serious Problems, Practical Recommendations. Southeastern Forest Experiment Station, USDA Forest Service, General Technical Report SE-84] that synthesized knowledge and approaches to problems and opportunities associated with regenerating oak. The most recent symposium was held in 2002 in Fayetteville, AR [Spetich, M.A. (editor), Upland Oak Ecology Symposium: History, Current Conditions, and Sustainability. Southern Research Station, USDA Forest Service, General Technical Report SRS-73] that addressed silviculture to regenerate oak, oak decline, wildlife ecology, and forest health. The 2017 Oak Symposium was developed to continue these technology transfer efforts and to share knowledge on state-of-the-art management and research to improve sustainability of the upland oak resource in the Eastern United States. The symposium was hosted by The University of Tennessee (UT), Department of Forestry, Wildlife, and Fisheries, and featured 33 invited speakers, an audience discussion period, and a poster session. Topics addressed included emerging economic markets, silviculture for climate change, artificial regeneration, wildlife habitat management, approaches to secure natural advanced oak regeneration, and prescribed burning to promote oak and to create woodland habitat. A field trip was offered that showcased collaborative research between the UT Forest Resources AgResearch and Education Center, the UT Department of Forestry, Wildlife, and Fisheries, and the USDA Forest Service, Southern Research Station.

Acknowledgments

The committee would like to thank personnel with the Department of Forestry, Wildlife, and Fisheries at The University of Tennessee and the Departmental staff for assistance with hosting this event and coordinating the field trip: Keith Belli, Department Head; David Buckley, Professor; Josh Granger, Post-doctoral Research Associate; John Johnson, Research Specialist III; Scott Schlarbaum, Professor; Ami Sharp, Research Associate II; Alison Shimer, Graduate Student; and Miriam Wright, Administrative Specialist. Sandra Baker and Monica Schwalbach, Secretary and Assistant Station Director, respectively, with the Southern Research Station, USDA Forest Service, provided valuable support with navigating meetings management for the Forest Service. Kevin Hoyt and Martin Schubert, Director and Cumberland Forest Manager, respectively, with The University of Tennessee's Forest Resources AgResearch and Education Center, provided logistical support for the field trip. We would like the thank the staff with the Knoxville Hilton, particularly Dustin Gibson and Tracy O'Connor, and the UT Conference Center, particularly Jessica Swett, for their assistance in registration, meeting arrangements, lodging, and logistics. Nancy Bastin, Office Automation Clerk, Southern Research Station, USDA Forest Service, provided invaluable assistance in editing and formatting papers for the proceedings. We would like to thank the sponsors, field trip hosts, and moderators listed below for their contributions to this meeting.

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The Department of Forestry, Wildlife, and Fisheries, The University of Tennessee (fwf.tennessee.edu)

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The Forestland Group (forestlandgroup.com)

The Kentucky-Tennessee Society of American Foresters (ktsaf.org)

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Appalachian Hardwood Manufacturers, Inc. (appalachianhardwood.org)

Tennessee Wildlife Resources Agency (tnwildlife.org)

Mountain Lakes Chapter, Alabama Division, Society of American Foresters

Field Trip Hosts

(Thursday, October 26)

The University of Tennessee: David Buckley, Professor; Josh Granger, Post-doctoral Research Associate; and Scott Schlarbaum, Professor.

Forest Resources AgResearch and Education Center: Kevin Hoyt and Martin Schubert, Director and Cumberland Forest Manager, respectively.

Southern Research Station, USDA Forest Service: Stacy L. Clark, Research Forester.

Moderators

Tuesday, October 24

General Session morning: Stacy L. Clark, Research Forester, Southern Research Station, USDA Forest Service

General Session afternoon: Callie J. Schweitzer, Research Forester, Southern Research Station, USDA Forest Service

Concurrent **Session 1, Adaptive Silviculture for Climate Change**: Sunshine Brosi, Associate Professor, Department of Biology, Frostburg State University

Concurrent **Session 2, Shelterwood Methods for Oak Regeneration**: Ken Smith, Professor and Assistant Dean, Integrated Program in the Environment, The University of the South

Wednesday, October 25

General Session morning: Thomas Schuler, Project Leader, Northern Research Station, USDA Forest Service

Concurrent **Session 3, Prescribed Fire in Oak Forests**: Brian Izbicki, Master's Student, Department of Forestry, Mississippi State University

Concurrent **Session 4, Artificial Regeneration**: David Buckley, Professor, Department of Forestry, Wildlife, and Fisheries, The University of Tennessee

Concurrent **Session 5, Wood Products and Economic Markets**: Matt Bumgardner, Research Forest Products Technologist, Northern Research Station, USDA Forest Service

Concurrent **Session 6, Silviculture to Restore Oak Woodlands**: Daniel C. Dey, Project Leader and Research Forester, Northern Research Station, USDA Forest Service

Concurrent **Session 7, Stand Improvement**: Josh Granger, Post-doctoral Research Associate, Department of Forestry, Wildlife, and Fisheries, The University of Tennessee

Concurrent **Session 8, Early Successional Wildlife Habitat**: Emily Hockman, Ph.D. candidate, Department of Forestry, Wildlife, and Fisheries, The University of Tennessee

SILVICULTURE TO RESTORE OAK WOODLANDS AND SAVANNAS

Daniel C. Dey, Benjamin O. Knapp, and Michael C. Stambaugh

Abstract—We present a perspective on how to approach developing silvicultural prescriptions for restoring oak woodlands and savannas. A large degree of success depends on selecting appropriate sites for restoration. We discuss historical landscape ecology, fire history, detecting legacies of woodland/savanna structure, and models of historical vegetation surveys. Ultimately, site selection for restoration is determined by integrated management goals and objectives. We discuss silvicultural practices for restoration including prescribed burning and thinning by mechanical or chemical methods or timber harvesting. We provide an overview of fire effects on vegetation and stress how the timing and sequencing of the various practices can be used flexibly depending on site restrictions, initial vegetation condition, and threats such as invasive species. We review various fire regime attributes that managers can control in moving the vegetation toward the desired future condition. We conclude by giving a perspective on developing the restoration prescription using a holistic, integrated resource management approach.

INTRODUCTION

Oak savannas and woodlands were once significantly more prominent on eastern landscapes in the United States and Canada. Since European settlement, their loss has decreased landscape diversity and resilience, and diminished our ability to conserve and sustain native biodiversity and promote ecosystem/landscape productivity and health. We lack silvicultural strategies, prescriptions, and tools to restore these natural communities. However, we have a strong foundation in hardwood forest silviculture that we may draw upon to develop plans for restoring oak woodlands and savannas. In addition, a strong understanding of oak woodland and savanna ecology forms the critical basis for developing the silviculture needed to manage these systems. This paper discusses silviculture strategies, practices, and tools for restoration of oak natural communities including (1) positioning restoration on the landscape, (2) developing the silvicultural prescription—available practices, and (3) the restoration prescription—setting the quantitative targets.

POSITIONING RESTORATION ON THE LANDSCAPE

Landform, Topography, and Soils

Landscape patterns of oak forests, woodlands, and savannas and prairies resulted, in part, directly from the physical characteristics of landform, geology, soils, and topography, and indirectly by the effect of the landscape on disturbance regimes (Anderson and others 1999, Batek and others 1999, Nigh and Schroeder 2002, Stambaugh and Guyette 2008). Important environmental and physical site variables that influence species distribution and natural community type can be identified through landscape modeling with spatially explicit historic vegetation information (e.g., Bolliger and others 2004; Hanberry and others 2012, 2014a, 2014b, 2014c). For example, oak species that are typical of woodlands and savannas were more likely to occur on increasingly xeric sites as defined by variables such as elevation, slope, parent material, wetness index, and solar radiation in the Missouri Ozarks according to Hanberry and others (2012), who modeled species occurrence and community tree structure using General Land Office (GLO) witness tree survey data. Managers can also use vegetation and ecological classifications developed by ecologists who have reconstructed or modelled the location and extent of historic vegetation types for States and physiographic regions (e.g., Anderson and others 1999, Curtis 1959, Nigh and Schroeder 2002, Schroeder 1982).

Tree density and canopy cover may be limited on sites that are seasonally flooded (e.g., oak flatwoods) and droughty where (1) soils are shallow in depth, or where rooting volume is limited by the presence of claypans and fragipans, (2) soils are coarse textured and extremely well-drained such as those derived from sandstones,

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and (3) soils have high rock content that limits water holding capacity and increases internal drainage. All of these soil-site features may restrict the development of forests and promote woodland and savanna communities as defined by Nelson (2010). Collectively, these site characteristics often increase the likelihood of droughts that limit tree development and fires that can create oak woodlands and savannas. Certain oak species such as post oak (*Quercus stellata*), white oak (*Q. alba*), bur oak (*Q. macrocarpa*), and chinkapin oak (*Q. muehlenbergii*) were dominant overstory trees in these systems and on these sites because of their adaptations to fire and drought, ability to resist wood decay, and longevity (Abrams 1990, Bahari and others 1985). Given a set of physical site characteristics, the nature of the fire regime would then determine the outcome, i.e., whether oak forests, woodlands, or savannas formed.

Topography/landform influences various attributes of a fire regime including fire frequency and size (fig. 1). Frequent fires—sometimes annual fires—were characteristic of the once extensive prairies in the Eastern United States (Anderson 2006, Transeau 1935). In the past, prairies occurred most often on level to gently rolling terrain (e.g., <4 percent slope) where fires could spread rapidly and extensively. As topography becomes more dissected, topographic roughness increases, and fire frequency and size decrease (Guyette and others 2006, Stambaugh and Guyette 2008). Prairies transition into savannas as the topography becomes gently rolling and headwater drainage ways begin to form. Steeply dissected topography creates landscapes that have more natural barriers to fire spread such as waterways and protected mesic north-to-east slopes, which either physically oppose the advance of fire,

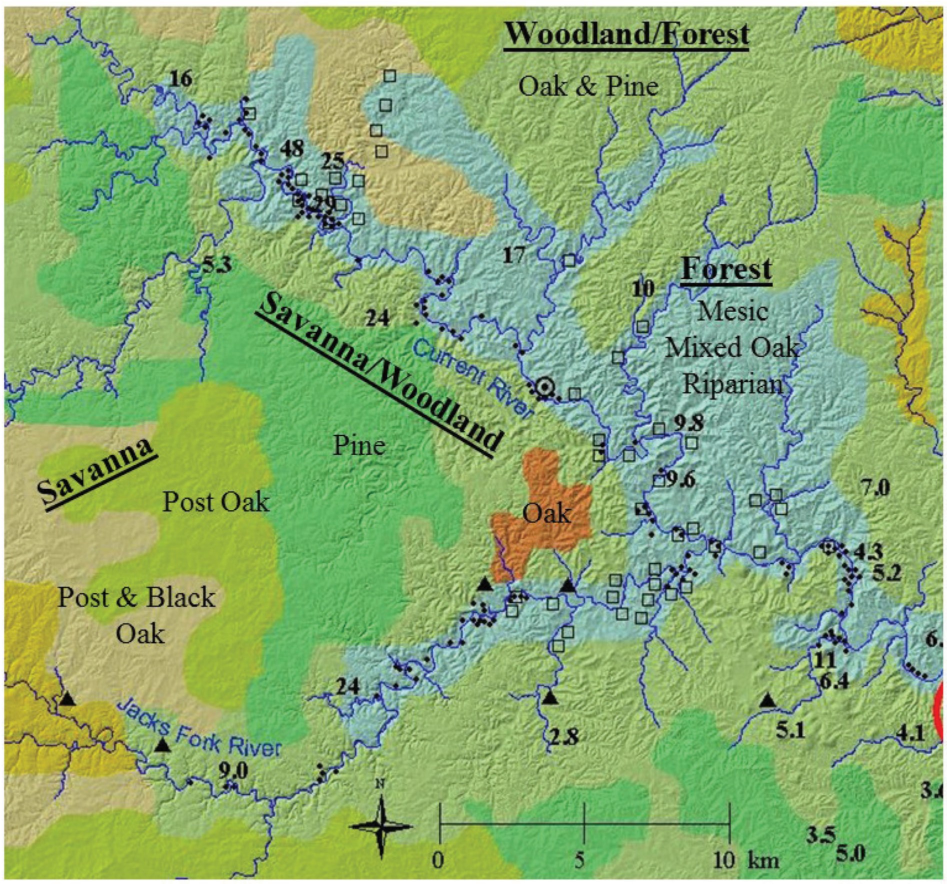

Figure 1—Topography had a strong influence on fire frequency and size before the fire suppression era. In plains and relatively flat terrain, fires were more frequent and larger in size resulting in prairie, or oak-pine savanna and open woodlands. In more severely dissected terrain, fire frequency and size were reduced due to the increase in natural fire breaks in the form of streams and north-east aspects that were less conducive to burning. Oak-pine woodlands were a dominant type on moderately dissected terrain. On the leeward side of major waterways, fires burned relatively infrequently, and mesic forests were able to develop. This example from the upper Current River watershed in the Missouri Ozarks illustrates the interaction of fire and topography that resulted in distinct, spatially explicit patterns in tree composition and structure (based on Batek and others 1999).

or modify fire weather, fuel dynamics (e.g., continuity, loading and moisture), and site hydrology to restrict fire spread. Although fires can burn rapidly and more intensely up exposed, xeric, south-west slopes, the rate of fire spread—especially that of low-intensity backfires—is reduced on north-east slopes due to cooler and moister conditions, increased fuel moisture, changes in fuel loading and flammability, and increased tree density among other factors. With less frequent fire on protected and mesic sites, trees increase in dominance and density, and forests develop complex vertical structure with the formation of a midstory canopy and shrub/tree understory while the more flammable grasses and heliotrophic forbs are greatly diminished. Litter from the more shade-tolerant trees and shrubs has relatively low flammability; forms a compact, flat fuel structure; and decomposes quickly. These conditions act to reduce the probability of fire ignition, the fire intensity, and the rate of spread. This mesophication that occurs in the absence of fire, or in areas of infrequent fire, creates a positive feedback that promotes succession and forest development toward more fire-resistant conditions (Nowacki and Abrams 2008). In heavily dissected terrain, oak woodlands prevailed and true forests formed on mesic aspects and lower toe-slope positions, and on the leeward side of major natural fire barriers such as rivers and lakes.

Historic Legacies in Vegetation Composition and Structure

Stand structure and characteristics of individual trees may indicate previous savanna or woodland conditions. The presence of large “wolf” trees with low and wide spreading crowns and large lateral branches indicates that previously the trees had grown in the open in low-density savannas or open woodlands. Sometimes these trees are also surrounded by dense thickets of smaller diameter saplings or pole-sized trees that invaded the savanna or woodland following fire suppression. Oaks often dominate the initial recruitment of trees in savannas and woodlands during an extended fire-free period following a long-term history of frequent fire (Stambaugh and others 2014). Encroachment of mesophytic tree species such as red maple requires longer periods of fire suppression (Fei and Steiner 2007, Johnson and others 2009, Nowacki and Abrams 2008). Final confirmation of natural community location on the landscape may be gained by a study of historic photos or journals that provide anecdotal information on local natural community types and composition and insights on fire history and land use practices to better understand vegetation change since European settlement.

Remnant ground flora may indicate more open woodland and savanna conditions once occurred in the past. Many public and non-profit conservation organizations have published lists of indicator plant species for natural communities that can be used to identify sites that once were savanna or woodland, and still have the potential to respond well to silvicultural restoration practices (e.g., Bader 2001, Farrington 2010, Packard and Mutel 1997). Floristic inventory of the candidate restoration area can reveal the presence and coverage of desired indicator species, which indicates the site’s potential to respond well naturally to the reintroduction of fire and reduction of tree density. Ecological indices developed by plant ecologists such as floristic quality index and coefficient of conservatism can be used to identify those sites that have the capacity to recover through natural regeneration of the ground flora following restoration practices (Swink and Wilhelm 1994, Taft and others 1997), and to anticipate ahead of time the need for supplemental artificial regeneration of desired ground flora to meet management objectives on degraded sites. Knowledge of land use history is useful for considering how degraded sites may be. Severely degraded sites are those that were cultivated annually or overgrazed, and allowed to erode severely. They are of low floristic quality having lost native seed bank and remnant vegetation, and are dominated by weedy, invasive exotic or native-generalist species. Historical photos or local journals provide anecdotal insights on historical conditions and land uses.

Knowledge of Local Fire History

Knowledge of local fire history can provide insight on the occurrence of savannas, woodlands, and forests. Site-specific fire histories are increasingly being developed throughout eastern North America (e.g., Brose and others 2013a; Guyette and Spetich 2003; Guyette and others 2003; Hoss and others 2008; Stambaugh and others 2006a, 2011). A landscape model predicting historic fire frequency for the continental United States has been produced by Guyette and others (2012) and is a useful guide for areas that lack local fire history data. Annual and biennial fire regimes are more closely associated with prairies and savannas (Anderson and others 1999, Anderson 2006, Nelson 2010). Less frequent mean fire return intervals favor woodland (>5 years) and forest (>10 years) development. Fire histories provide a wealth of information on past fire regimes such as variation in fire occurrence at a given site, which is equally important as average fire frequency. Infrequent but extended fire-free periods of from 10 to 30 years are needed to permit recruitment of tree saplings into the overstory to replace the overstory (Arthur and others 2012, Dey 2014). Infrequent high-severity fires are capable of killing much of the overstory and provide regeneration and recruitment opportunities, or fundamentally change oak natural communities from one type to another. Variation in fire seasonality results in higher plant diversity in the long term. Frequent fire regimes that lack variability in fire-free periods trend toward producing savanna or prairie communities

because they suppress tree recruitment into the overstory and as overstory tree mortality occurs then stand density decreases.

Management Goals and Objectives

Forestry organizations, agencies, and industries usually develop a hierarchy of plans and prescriptions to guide management at the forest level (e.g., MTNF 2005, OSFNF 2005), project level (e.g., MTNF 2015), and stand level (e.g., Wisconsin DNR 2013). They often use a synthesis of the above mentioned criteria in setting forest, management unit, and stand goals and objectives. However, selection of areas and sites for oak woodland and savanna restoration also considers the character of modern-day landscapes, priority needs for wildlife habitat, landscape and stand resilience goals, forest health risks and threats, rural community sustainability, and demands for goods and services from the public. Hence, sites may be designated for restoration regardless of historic patterns, disturbances, and processes.

DEVELOPING THE SILVICULTURAL PRESCRIPTION – AVAILABLE PRACTICES

In the absence of fire, savannas and woodlands become forests, and many landscapes have come to be dominated by mature forests of similar composition. Forests today have two to three times more trees than former woodlands and savannas did in the early 1800s (e.g., Hanberry and others 2012, 2014b, 2014c). The most common starting condition in areas designated for savanna or woodland restoration is the mature forest state. In mature oak forests in Eastern North America there is an absence or lack of large oak advance reproduction, and the ground flora is sparse, being dominated by woody species and shade-tolerant forbs, with low diversity. Light levels in the understory are extremely low, often inhibiting survival and growth of all but the most shade-tolerant species (Dey 2014). This forest condition provides habitat that favors wildlife species associated with complex forest structure.

In the absence of an invasive species problem (see below for further discussion), an initial silvicultural objective is to reduce stand density. This can be achieved in a number of ways using timber harvesting, prescribed fire, mechanical cutting and girdling, or herbicide application, or a combination of these practices. There are several sources that can be used to set a reasonable range in stand structure metrics that define desired future conditions at intermediate stages in restoration, or endpoint conditions that represent the beginning of the maintenance phase in sustainable natural community management. In some areas, models of historic natural communities at specified historic times can be used to guide setting of quantitative ranges in tree density, size, stocking, and canopy cover (e.g., table 1). Alternatively, matrices can be developed by experts based on ecological principles and knowledge that define key attributes of the range of natural communities (e.g., table 2).

Prescribed Fire Effects on Vegetation

Since fire was instrumental in creating and sustaining oak savannas and woodlands historically, it is natural to think about reintroducing fire by prescribed burning to begin restoration. Prescribed fire is often conducted in winter and spring seasons, when it burns with low intensity and severity. These types of fires are capable of killing or topkilling hardwood stems that are <4–6 inches diameter at breast height (dbh) and thereby begin the process of reducing stand density (Arthur and others 2012, Dey and others 2017). The midstory canopy in mature forests can be diminished or eliminated by one or more low-intensity dormant season fires (fig. 2) (Dey and Hartman 2005; Fan and Dey 2014; Hutchinson and others 2005a; Knapp and others 2015, 2017). Removal of the hardwood midstory canopy increases light levels to about 15 percent of full sunlight depending on the composition of the overstory, i.e., northern hardwood vs. oak vs. pine, with light levels being highest under pine overstories (Lockhart and others 2000, Lorimer and others 1994, Motsinger and others 2010, Ostrom

Table 1—Setting structural targets for oak woodlands and savannas using historical conditions[a] in the Missouri Ozarks

Natural community[b]	Density *trees per acre*		Dbh *in*	Basal area *ft^2/ac*		Stocking *percent*		Canopy cover *percent*	
	avg	range	avg	avg	range	avg	range	avg	range
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

[a] Estimates are based on models of witness trees from General Land Office surveys done in the early 1800s.
[b] Natural communities were defined as: savanna—10 to 30% stocking, 20 to 40 tpa; open woodland—30 to 55% stocking, 40 to 71 tpa; closed woodland—55 to 75% stocking, 71 to 101 tpa; forest—≥75% stocking, ≥101 tpa (based on Hanberry and others 2014b).

Table 2—Quantitative attributes defining desired conditions for natural community types on the Mark Twain National Forest, Missouri Ozarks (MTNF 2005)

	Overstory trees		Shrubs	Ground cover layer	
Natural community types	Tree canopy *percent*	Basal area ft^2/ac	Shrub layer *percent*	Ground organic layer	Ground cover *percent*
Prairie	<10	NA	<10	Scattered grasses, sedges, and forbs	90–100
Savanna	20–40	40–60	50	Scattered grasses, sedges, and forbs; 60–80% leaf litter cover	30–50
Open woodland	40–70	40–70	20–40	Scattered grasses, sedges, and forbs; 30–50% leaf litter cover	30–40
Closed woodland	70–90	80–100	5–10	Scattered sparse grasses, sedges, and forbs; 100% leaf litter cover	20–30
Upland forest	90–100	80–100	50% in 2-acre openings/wind gaps; <5 % elsewhere	Moderately deep leaf litter; sparse ground cover	<30
Bottomland forest	90–100	90–100	Multi-layered; uneven-age; few gaps	Deep leaf litter; ephemeral herbs	50–70
Fen	<10	NA	Variable	Shallow marly to deep muck	90–100
All glade types	<20	NA	<40	Sparse to dense thatch of grasses; mineral soil sometimes exposed	30–90 grasses dominant

Figure 2—Low-intensity prescribed fires done in the spring (March to April) are effective in eliminating or significantly reducing density of the hardwood midstory in mature oak forests in the Missouri Ozarks (A). Annual fires (B) or periodic fires (every 2–3 years) (C) over 10 years can topkill saplings that form the midstory and inhibit redevelopment of the midstory by causing mortality of understory stems and repeated topkilling of survivors. Overstory density is relatively unaffected by these burning regimes, and growth of hardwood sprouts is reduced by shade of the closed-overstory canopy. (photographs courtesy of Daniel C. Dey, USDA Forest Service)

and Loewenstein 2006). This improves environmental conditions for oak regeneration development and increases ground flora diversity and coverage, but further increases in light levels are often needed to achieve desired future conditions in both tree regeneration and ground flora (Dey 2014, Hutchinson 2006, Kinkead and others 2017). However, an incremental approach and deliberate progress toward the final desired condition may be prudent when transitioning from a forest condition with aggressive competing tree species such as yellow-poplar (*Liriodendron tulipifera* L.), sweet birch (*Betula lenta* L.), and aspen (*Populus* spp.), or disturbance-adapted invasive species. Low-intensity fires have little effect on overstory mortality (Fan and Dey 2014, Fry 2008, Horney and others 2002, Hutchinson and others 2005a).

Oak reproduction is generally favored over other hardwood species in a regime of frequent fire (Brose and others 2013b). Oak seedling and sapling sprouts can grow and increase root mass with adequate light under a regime of frequent fires, i.e., every 2 to 5 years (Brose 2008, Brose and others 2013a, Dey and Parker 1997, Rebbeck and others 2011). However, young and small-diameter oaks are vulnerable to mortality when subjected to low-intensity, dormant season prescribed burns (Johnson 1974). Survival of oak advance reproduction is relatively high (80 to 90 percent) after only one fire regardless of species, but mortality among oak species varies with repeated fires, and scarlet oak is one of the most fire-sensitive species (Dey and Hartman 2005). Differential mortality rates between oak and its competitors in a frequent fire regime give oak a competitive advantage over time (Brose and others 2013b, Dey and Hartman 2005).

Acorns are recalcitrant seed and must maintain high moisture content to remain viable (Korstian 1927). Seed lying on the forest floor or mixed in litter is vulnerable to desiccation over the winter, especially in regions without permanent snow cover. Some leaf cover (e.g., 1 to 2 inches) helps to maintain moisture content in acorns located beneath the litter and in contact with mineral soil, but deep litter (>2 inches) can reduce germination and seedling establishment (Barrett 1931). Prescribed fire is an effective tool for reducing leaf litter depth but must be applied periodically (e.g., <4 years) to consume additional litter input and maintain optimal litter depth (Barrett 1931, Stambaugh and others 2006b). Fire conducted before acorn drop and in forests with little to no oak advance reproduction can reduce leaf litter, midstory density, understory height structure, and canopy coverage, and begin to manage competitor seed in the forest seed bank (Schuler and others 2010). Repeated fire is important in controlling seed bank and young germinants of competing or undesirable species (Schuler and others 2010). Once a good acorn crop is on the ground, fire should be delayed until oak seedlings are well-established (e.g., for 2 to 3 years) because fire can kill 70 percent or more of the acorn crop (Auchmoody and Smith 1993, Greenberg and others 2012). Sufficient light in the understory promotes oak seedling development and shortens the time that fire should be avoided to minimize mortality in small oak advance reproduction.

In addition to using fire to restore and maintain the woody structure of savanna ecosystems, the restoration of fire as a disturbance that shapes the ground flora community is important. Fire may increase ground flora diversity and promote its development by breaking chemical or thermal seed dormancy, thus increasing germination in some species (Hutchinson 2006). Fire may improve establishment of herbaceous plants by reducing thick litter layers that act as a physical barrier to seedling establishment by inhibiting roots from reaching mineral soil, or emerging shoots growing beneath litter from reaching the light of day. Litter removal elevates soil temperature that promotes germination and early seedling growth. Fire releases nutrients when litter is consumed, which promotes plant growth. It also increases available light for herbaceous plants by top killing woody trees, shrubs, and vines. Fire frequency, season, intensity and other attributes of the fire regime can be set by the manager, and various combinations of these attributes can dramatically direct plant dominance and community succession.

The use of prescribed fire alone in mature forests generally increases herbaceous species coverage, richness, and diversity, but improvements are small in magnitude due to the shade from a closed-canopy overstory (Lettow and others 2014; Ralston and Cook 2013; Taft 2003, 2005). These improvements in the ground flora are also ephemeral unless burning is repeated to control the sprouting and regrowth of trees and shrubs in the understory (Abrahamson and Abrahamson 1996, Bowles and others 2007, Glasgow and Matlack 2007, Kuddes-Fischer and Arthur 2002, Vander Yacht and others 2017). It may take 20 to 40 years of annual burning to eliminate most of the understory woody species (Knapp and others 2015, Waldrop and others 1992). Each woody and herbaceous species is unique, but some generalities in how functional groups of plants respond to changes in the fire regime are worth noting. Annual fires increase grass dominance, and biennial fires promote forb species richness and cover, especially in open environments such as prairies, savannas, and open woodlands (Anderson and others 1999, Burton and others 2010, Haywood and others 2001, Nelson 2010, Peterson and others 2007). Fires separated by 3 to 5 years or longer favor trees, shrubs, and vines (Briggs and others 2002, Burton and others 2010, Haywood 2009, Peterson and others 2007). Ground flora diversity is relatively lower in prairies where tallgrasses can dominate or in forests where woody species are the major competitors than in savannas and open woodlands where there is the greatest heterogeneity in environmental conditions that support high plant diversity (Haywood 2009, Peterson and others 2007, Peterson and Reich 2008, Towne and Kemp 2003).

Controlling the season of burning can help promote specific plant functional groups. Burning in the spring (March to April) favors warm season grasses and forbs; may promote flowering and biomass production of late summer flowering species; and diminishes survival, growth, and vigor of cool season grasses and forbs (Copeland and others 2002, Glen-Lewin and others 1990, Howe 1994, Peterson and Reich 2008, Taft 2003, Towne and Kemp 2003). Promoting the dominance of warm season grasses may actually decrease total plant diversity due to the ability of warm season grasses to suppress all subdominant vegetation (Biondini and others 1989, Copeland and others 2002). Compared to winter or spring fires, summer burns (mid-July to early August) can increase cool season grass and forb diversity, cover, and density; reduce to a greater extent woody trees, shrubs, and vines; and increase perennials that are able to flower before the summer burn (Haywood and others 2001, Haywood

2009, Howe 1994, Nelson 2010, Waldrop and others 1992). Summer burns done during a time when warm season grasses are actively growing can reduce their dominance, thus releasing subdominant vegetation and increasing total species richness (Biondini and others 1989). The outcomes of fall (September to October) fires are somewhat inconsistent but show a tendency to decrease cool season exotic grasses; reduce woody cover; increase perennial forb cover; and either increase or have no effect on warm and cool season grasses and forbs (Biodini and others 1989, Bowles and others 2007, Copeland and others 2002, Howe 1994, Towne and Kemp 2003, Weir and Scasta 2017). Dormant season (December to February) fires have the least impact on herbaceous or woody species, even when repeated for decades (Haywood 2009, Hutchinson 2006, Waldrop and others 1992, Weir and Scasta 2017). Consistency in application of prescribed fire tends to create homogeneity in the vegetation community. Therefore it can be beneficial to vary the frequency, intensity and season of burning to sustain plant species diversity and provide a variety of habitats for wildlife, insects, pollinators, and other taxa (Hiers and others 2000, Howe 1994, Nelson 2010, Peterson and Reich 2008). An important factor that governs the initial response of ground flora to burning is the abundance of propagules in the seed and bud bank. These may be diminished on sites degraded from decades of agricultural land use or from years under heavy forest shade and deep litter (Ralston and Cook 2013). Restoration of severely degraded sites may require artificial regeneration of the ground flora by seeding and planting (e.g., Packard and Mutel 1997).

Prescribed Fire, Woody Structure, and Ground Flora Interactions

Heavy tree canopy cover is a major limiting factor contributing to low diversity and productivity of ground flora (i.e., grasses, forbs, and legumes) (Peterson and Reich 2008, Ratajczak and others 2012, Vander Yacht and others 2017, Zenner and others 2006). Application of low-intensity dormant season fires is effective at creating closed-woodland structure (Hutchinson and others 2005a, Knapp and others 2017, Waldrop and others 1992), but other practices are needed to create open-woodland and savanna structure and promote their ground flora. Increasing fire intensity to produce moderate to high-severity fires is generally not the preferred method for reducing overstory density. Thinning by herbicide or mechanical methods or harvesting using a modified shelterwood system is preferred for managing stand density, regulating tree density in time and space, controlling species composition, and receiving income from timber sales. The shelterwood system is flexible to accommodate incremental adjustments to tree density and stocking, can be used to achieve a wide range of final desired tree density and stocking, and can be applied as an irregular or uniform pattern to create heterogeneity in structure. The application of the shelterwood method in restoration of woodlands and savannas differs from the traditional forestry application in that the final shelterwood is retained for the long term in restoration, and is removed once adequate desirable regeneration is secured when timber goals are a priority. The details of how tree structure and fire are managed depend largely on desired future conditions of the ground flora, and the prescription is modified by initial stand conditions, physical environment, site quality, presence of invasive species, initial floristic composition and structure, and the physiology and ecology of key indicator native flora.

Thinning the overstory to reduce its density (i.e., removing larger diameter trees that are resistant to fire treatments) often increases herbaceous richness and coverage by increasing light levels at the forest floor (Hutchinson 2006, Kinkead and others 2017, Waldrop and others 2008, Zenner and others 2006). Retaining a moderate-density overstory may benefit cool season grasses, sedges, and shade-tolerant forbs, but any tree cover inhibits warm season prairie grasses and forbs that thrive best in the open (Peterson and others 2007). The increasing species richness and coverage in the ground flora are accelerated when stand basal area is held <60 square feet per acre, which is below B-level stocking (i.e., where growing space is unoccupied by trees and thus available to ground flora in treeless openings) (fig. 3) (Vander Yacht and others 2017). However, these gains in ground flora restoration are ephemeral, because an abundance of woody sprouts can rapidly form a dense midstory that shades out the ground flora once again. Thinning or harvesting trees in a way that leaves a variable-density overstory maximizes heterogeneity and increases diversity (Peterson and others 2007, Peterson and Reich 2008, Vander Yacht and others 2017). Thinning alone is no surrogate for fire when it comes to other ecosystem processes and functions such as nutrient cycling, litter dynamics, plant regeneration and competition, and community development (Hutchinson 2006, Phillips and Waldrop 2008). Restoration of a healthy, productive, diverse ground flora community can be accelerated by thinning the overstory from below and implementing prescribed burning, which provides substantial increases in cover, species richness, diversity, and plant productivity compared to burning or thinning alone. Repeated burning is effective in preventing the dominance of sprouting trees and shrubs after harvesting (Hutchinson and others 2005b, Kinkead and others 2017, Lettow and others 2014, Waldrop and others 2008).

There are treatments that can precede harvesting or be done in conjunction with harvesting to reduce density, limit dominance of tree and shrub sprouts, or control an invasive species problem. Reducing the regeneration potential of undesirable competing vegetation before

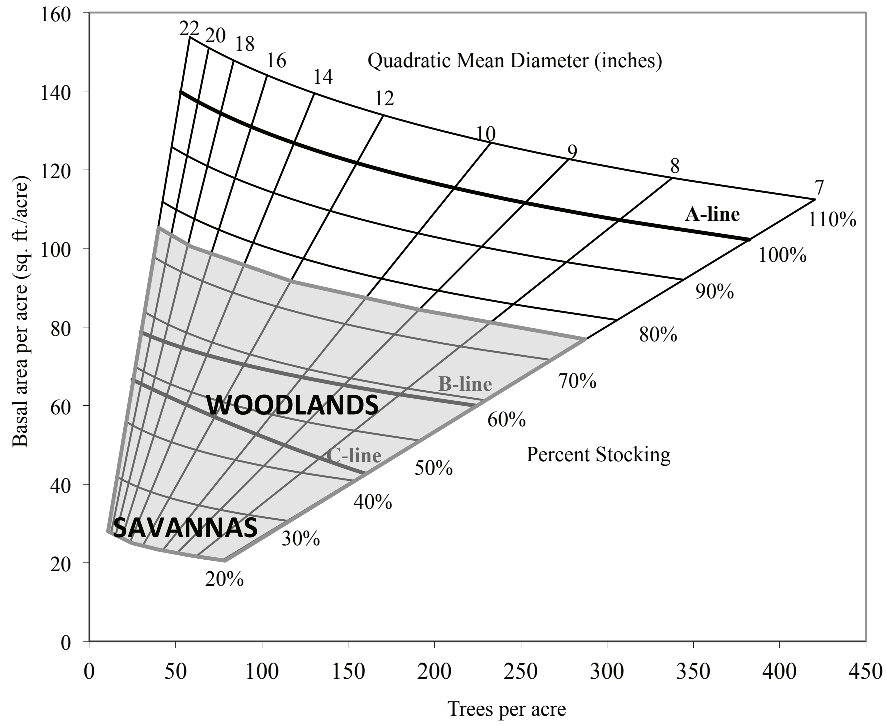

Figure 3—Stocking (Gingrich 1967) for woodlands and savannas (shaded area). Stocking in woodlands is maintained between 30 and 75 percent. Closed woodlands are maintained above the B-line, and open woodlands are maintained between 30 percent stocking and the B-line. Savannas are maintained at stocking levels <30 percent. For regenerating woodlands, stocking is reduced below 30 percent stocking. Stocking in savannas is low enough to permit recruitment anytime there is a sufficiently long fire-free period (based on Hanberry and others 2014b).

thinning or harvesting the overstory takes advantage of overstory shade to reduce response and vigor of undesirable vegetation. Combinations of fire, herbicide, and mechanical practices (e.g., cutting, scarification, and mastication) can be used to minimize the response of undesirable vegetation after overstory harvest. Maintaining higher levels of overstory canopy cover (e.g., >70 percent) or density (e.g., >60 square feet per acre) can suppress the growth of woody sprouts or invasive species in the understory through shading (Dey and Hartman 2005, Kinkead and others 2017), but this would also delay the restoration of savanna ground flora, which requires more sunlight. In the end, rapid reduction of the overstory to meet long-term structure objectives for woodlands and savannas promotes the greatest response in ground flora (Zenner and others 2006). A chart has been developed that is useful for managing stand density to produce desired crown cover in upland oak savannas depending on overstory tree size and density (Law and others 1994). Models have been developed that are useful for estimating available light in the understory from overstory crown cover, density, basal area, or stocking for upland oak-hickory forests in the Missouri Ozarks (Blizzard and others 2013, Dey and others 2017). These can be used to manage stand density to provide light levels necessary to promote desirable ground flora.

Nonnative invasive species (NNIS) are increasingly a threat to oak management and restoration (Kurtz 2013, Miller and others 2013, Oswalt and Oswalt 2011). No longer are they merely a problem in urban areas; they are rapidly expanding into rural forest lands. Many of the more common and problematic NNIS prosper in open environments and are adapted to fire. Thus, prescriptions to sustain or restore oak forests, woodlands, and savannas that use regeneration methods such as the group selection, clearcut, shelterwood, or seed tree in combination with prescribed burning can potentially promote the rapid colonization and invasion by NNIS (Phillips and others 2013, Rebbeck 2012).

Fire can promote NNIS colonization and spread, or it can be a useful method for control, depending on the timing and severity of fire and the phenology, physiology, mode of reproduction, and ecology of the invading NNIS (DiTomaso and others 2006, Huebner 2006, Miller and others 2013, Rebbeck 2012, Zouhar and others 2008).

Nonnative invasive species often have traits that help them prosper in a post-fire environment. The ability to self-pollinate allows them to reproduce in low-density or sparse populations. Some species are prolific seed producers, and seed can be dispersed by the wind or birds, or both, which maximizes the number of seeds disseminated for opportunistic colonization of ephemerally favorable sites. The seed of some NNIS can remain viable in the seed bank for years or decades. Thus, seed can accumulate to densities far exceeding those of annual crops and remain ready for release by a future disturbance. Chemically or thermally induced seed dormancy ensures that germination is likely to occur after a fire when the post-fire environment is favorable for establishment and early growth. Reproductive structures such as rhizomes, caudices, bulbs, corms, and root crown buds are commonly buried in mineral soil or located under moist duff and, hence, protected from fire injury. Thus, after a fire, NNIS are immediately onsite and capable of rapid vegetative growth when resources are most available. Rapid early growth is characteristic of many NNIS as they are adapted to high-light environments following moderate- to high-severity disturbances. This promotes early dominance and acquisition of resources for development toward maturity and completion of their life cycle.

Monitoring for early detection of NNIS is key to controlling invasive populations when they are still small. Aggressive eradication at this stage is necessary to avoid the development of an expensive problem that can thwart other management goals. Nonnative invasive species monitoring and control are essential elements of contemporary sustainable management programs. A prudent approach to NNIS control is to deal with threats before initiating major disturbances such as overstory harvesting that may accelerate expansion and dominance of the NNIS. Early treatment of existing NNIS in and around a management unit takes advantage of overstory shade that can help limit the response of shade-intolerant NNIS. Complications arise when considering NNIS control treatment impacts on desired native flora, because an important control strategy is to promote the establishment and dominance of native species, thereby increasing the competitive pressure on NNIS.

Fire can be used alone or in combination with other practices to control some NNIS. The timing and severity of fires are key to controlling NNIS and determine the fate of native species as well. The easiest NNIS to control are annuals that produce seed after the fire season, whose seed is readily exposed directly to fire's flames and does not persist in the seed bank. Late spring to early summer fires are most likely to control NNIS annuals that set seed later in the summer. Biennial and perennial NNIS are more difficult to control. Severe fires are needed to kill reproductive structures in organic or mineral soil layers. Few NNIS are controlled with a single fire. It takes consecutive, repeated fires to stop seed production by killing existing individuals and to eliminate plants that arise from the seed bank or from vegetative structures, which often are stimulated by the initial fire. Scheduling fires several years apart only allows NNIS to add seed to the seed bank, or build energy reserves in belowground structures.

Burning followed by herbicide application can be an effective control method (DiTomaso and others 2006). The fire kills current vegetation, stimulates germination, converts large plants into small, concentrated sprout clumps through topkill and sprouting, and removes debris that facilitates herbicide application. Herbicides can be effective at killing plants that sprout prolifically from large underground bud banks and stored energy reserves. The succulent growth of seedling sprouts and germinants readily absorbs herbicides, increasing their efficacy. Fire effects on native species must also be considered in planning prescribed fire regimes to ensure they are not adversely impacted and that their response to fire is vigorous. Dominance of native species after fire can help to suppress NNIS establishment or recovery.

THE RESTORATION PRESCRIPTION – SETTING THE QUANTITATIVE TARGETS

There are several elements that guide the development of silvicultural prescriptions for restoration. Vegetation compositional and structural targets are good for defining forests, woodlands, and savannas. Both woody and ground flora are important because they play an essential role in the development of the natural community, its functioning, and its diversity potential, and production of ecological, economic, and social goods and services. Vegetation composition and structure are good for setting quantitative intermediate and final end targets in the silvicultural prescription that aid in selection and sequencing of practices to transform the initial state into the desired future condition (Dey and Schweitzer 2014). The initial vegetation structure and composition determine the initial stages and activities that are needed to achieve the desired future condition. The divergence of the initial state from the desired future state influences the extent of the restoration period. Site productivity influences the rate of change in vegetation, and hence, the scope of practices, their timing, and the investment in energy (both financial and all other resources and capital, including the human) needed to manage for the desired composition and structure in vegetation. Invasive species, troublesome herbivores, and insect and disease threats are modifiers in the prescription process.

Compositional and structural targets can be quantified using: (1) analysis and modeling of historical vegetation surveys, (2) inventory of high quality modern examples, (3) ecophysiology requirements of the desired indicator and competing species, and (4) wildlife habitat objectives. Ground flora targets are formed from a list of natural community indicator species and quantified through the use of conservation goals to increase diversity, coverage, floristic quality index, and coefficient of conservatism. The structure (vertical and horizontal) of vegetation can be quantified using common metrics derived from field surveys and inventories and models that define the relationship among the suite of structural variables that influence the environment, physical resources, and competitive dynamics. Modes of reproduction of desired species and their key competitors influence the choice of silvicultural practices and their sequencing. Threats from invasive plant species require special consideration in the prescription process. Developing a successful silvicultural prescription for restoration requires a holistic approach that integrates the key components in a dynamic system over the entire period that starts with the initial condition and ends with the final desired future condition, and entry into the sustainable, maintenance phase of management.

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