

WHAT DO WE KNOW ABOUT OAKS? KEYSTONES OF OAK SILVICULTURE

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INTRODUCTION

A wealth of information about the silviculture, management, and utilization of oaks (*Quercus* spp.) is available in many research papers and symposia. The first symposium dedicated to oaks was held at West Virginia University in 1971 (Northeastern Forest Experiment Station 1971) in response to five oak presentations given at the Division of Silviculture session at the Society of American Foresters (SAF) Annual Meeting in Philadelphia, PA in October 1968 (Northeastern Forest Experiment Station 1970) when SAF attendees expressed an interest in a more comprehensive conference on oak silviculture. Three other oak symposia have been held since: in 1979 at Purdue University as part of the John S. Wright Forestry Conference focusing on regeneration (Holt and Fischer 1979), in 1992 at The University of Tennessee also focusing on oak regeneration (Loftis and McGee 1993), and in 2002 in Fayetteville, AR focusing on upland oak ecology (Spetich 2004). The 19 Biennial Southern Silvicultural Research Conferences and the 20 Central Hardwood Forest Conferences have a majority of their hardwood research presentations centering on oak. There are many other various regional symposia, conferences, and compendiums on oaks (e.g., Brose and others 2008, Ffolliott and others 1992, Johnson 1985, USDA Forest Service 1980). Peer-reviewed journal articles are also abundant concerning oak regeneration, growth and development, management alternatives, and utilization. However, even with the plethora of materials and resources available about oaks, many questions remain. This fifth Oak Symposium (present conference) returning to The University of Tennessee (2017) provides a framework of what is known about the biology and management of upland oaks and the concerns that research should continue to address within present

contexts of oak ecology and ecosystems, forest health, economics, climate change, wildlife habitat, and prescribed burning.

This review of oak silviculture is a compendium of my own research as well as reflections of conversations with other researchers and forest practitioners alike. My Extension position has allowed me to observe on-the-ground practices, markets, and costs associated with hardwood (oak) silviculture and management as well as values and attitudes of private forest owners and stand prescriptions implemented on public lands. Associations with several mentors, including Dr. John Hodges at Mississippi State University; Drs. C.E. (Gene) McGee, Glendon Smalley, and David Loftis at the Southern and Southeastern Forest Experiment Stations (now merged into the Southern Research Station); and Dr. Ed Buckner at the University of Tennessee, as well as many silviculturists at universities across the country, have greatly influenced my knowledge and perspectives of oak ecosystems.

Past and present research about oak species is summarized, and what is known and not known and the opportunities or priorities for future research and management to successfully manage oak development and environments from regeneration through harvest are discussed in this review.

WORKING WITH OAKS IS PARADOXICAL

According to Oxford Dictionaries (2017), paradox is defined as “a statement or proposition which, despite sound (or apparently sound) reasoning from acceptable premises, leads to a conclusion that seems logically unacceptable or self-contradictory.” Various practitioners, landowners, and researchers for a period of years have noted the numerous paradoxes that arise when working with oaks. Although these statements (and their numerical estimates) about oaks and the oak resource cannot be attributed to any one person or literature reference as the original source, these

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assertions have a degree of truth associated with them as well as aggravation in addressing some of the difficulties related to oak management. Working with oaks can be both exhilarating and exasperating!

1. More money is spent each year controlling or eradicating oak where it is unwanted than is spent on oak silviculture.
2. Although oak is widely distributed and of great abundance, a major research problem is the difficulty associated with replacing existing oak stands with future oak stands.
3. High-quality oaks command high prices. Yet, for a high proportion of typical oak stands, there is not a market for abundant low-quality or low-grade oaks.
4. Oaks are widely perceived to be long-lived, but more than 99 percent of the natural oak population dies before it is 5 years old.
5. Oaks vary in their ecological requirements and their productive potential, yet little is known on how to predict the quality or quantity of mast crops. Many silvicultural recommendations made to favor wildlife may actually reduce acorn production potential.
6. The best growth and yield models and volume tables for upland oaks are still those in the Schnur (1937) publication.
7. Hundreds of thousands of oaks are planted each year, but few attain maturity, become merchantable for wood products, or bear acorns.
8. Timber buyers reduce their stumpage offers by 20 percent or more if there are indications of burning in hardwood stands. Meanwhile, veneer buyers, as a rule, will not buy stumpage from stands with evidence of burning.
9. Production of high-grade hardwood timber was not present in quantity until wildfire control programs were implemented in the 1940s and 1950s.
10. Typically, 20 percent of the hardwood species produce 90 percent of the hardwood revenue and within such trees, 90 percent of the value is in the butt (first) log.

Oak practitioners from the science, management, and economic spectrums contend with a range of frustrations about this popular taxon. The paradox of managing oaks begins with their biology. Potential solutions to oak management and regeneration will stem from further understanding of oak biology, especially as compared to other associated species.

SPECIES-SITE RELATIONSHIPS

Unlike many forests that are composed of few species, oak forests are composed of many species, both oak and non-oak. For oak species, the myriad of different species that each grows with and the variety of sites where each occurs (xeric, mesic, hydric, and transitions)

make regeneration and growth of oaks extremely complex and variable. Different oak species regenerate and grow at different rates on different sites. Therefore, silviculture should focus on the requirements of each oak species rather than the broad oak genus. The specificity in the management and culture of oak species goes well beyond the two subgenera: *Erythrobalanus* (red oaks) and *Leucobalanus* (white oaks). Typically each species within each subgenus will respond differently to silvicultural treatments based on the biology/ecology of the species and the site conditions.

These highly variable species-site relationships concerning oak regeneration and management are much more pronounced in Tennessee, the area where I work, than most Eastern States. The landscapes range from the Blue Ridge Mountains in the east to the Mississippi Alluvial Plain in the west (fig. 1). The Forest Service research installations that perform or have performed oak research applicable to Tennessee are many, usually keyed to different physiographic areas. Oak response to practices that may be applicable or suitable for one physiographic region such as the Western Highland Rim is quite different than at higher elevations that are less dissected like the Cumberland Plateau or more dissected such as the Blue Ridge Mountains.

Although the native ranges of white oak (*Q. alba*) and northern red oak (*Q. rubra*) are quite ubiquitous on the landscape covering all States east of the Mississippi River and States that border the western edge of the river (Burns and Honkala 1990), the sites, vegetation, disturbance histories, and climates are quite variable resulting in different oak growth responses. With the widespread occurrence of oak in the Eastern United States, management is often keyed to the least common denominator or a mentality where similar prescriptions will yield similar results. However, the diverse landscape that oaks occupy usually results in much greater unpredictability and inconsistencies based on the wide combinations of biotic and abiotic factors. Often site evaluation is either not performed or misinterpreted yielding unfortunate outcomes. Site evaluation is becoming a lost art, particularly with the wide variability of oak species, each with distinctive environmental settings and constraints. The challenge is to determine oak response to these environmental gradients (Arthur and others 2012).

Oaks, with their conservative growth strategy, regenerate well on lower quality, drier, more xeric upland sites where they do not compete with faster-growing species. Root growth is emphasized during the seedling stage which may be a survival mechanism on more xeric sites, but conversely on more mesic sites, height growth is diminished allowing faster growing competitor species to overwhelm the oak (Dickson and others 1990, Rebbeck and others 2011). However, between these two site



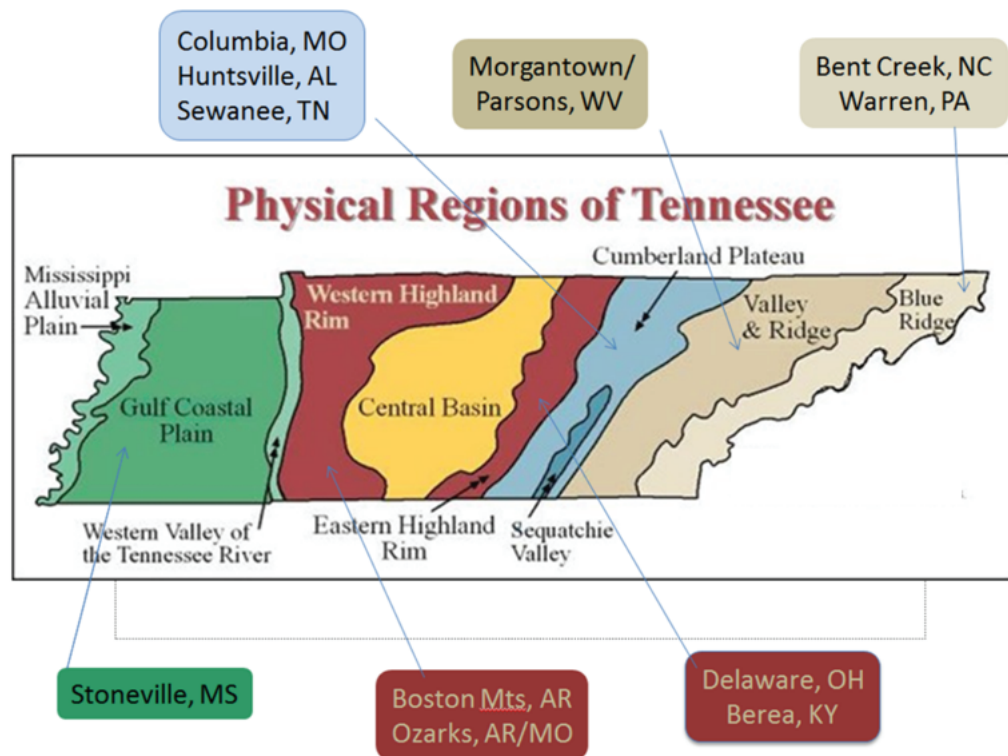


Figure 1—Physical regions of Tennessee and past and present U.S. Department of Agriculture Forest Service locations responsible for research associated with those regions (maps adapted from Miller 1974).

extremes, both oak and competitor species can co-exist (estimated site index between 65 to 75 feet for oak at 50 years). On these “average” sites, the growth of oaks is enhanced somewhat from the xeric sites and the growth of faster growing competitor species is reduced. If oaks are desired, sites should be chosen that encourage the biological requirements of oaks as opposed to the competing species (Hodges and Gardiner 1993).

Site productivity is difficult to judge on many eastern hardwood sites. Stands have been disturbed repeatedly through indiscriminant cutting, burning, and grazing as well as natural disturbances such as climatic events resulting in stands that are poorly stocked with an undesirable species mix and trees that are defective with poor form and stem injuries. Desirable growing stock is not present or poorly represented with erratic degrees of stocking, structure, and age. The trees in the stand are not representative of growth potential and previous communities and thus are not good candidates for a direct measure of site index or site productivity. In lieu of direct estimations of site productivity, landforms or landtypes have been incorporated as spatial synthesizers integrating physiography (geographic setting, geology, and topography), soil, and climate to potential vegetation in indirectly assessing site productivity (Baker and Broadfoot 1979, McNab and others 2007, Smalley 1986). Ultimately, species grow where they can compete successfully and tolerate

local conditions, not necessarily where they grow best. Matching species, sites, and environmental gradients is instrumental for hardwood (and oak) management with the wide array of sites and species present. Sites are also dynamic and change based on pedogenesis, vegetation succession, and disturbances through processes such as deposition, erosion, drainage alterations, and climate variability which impact species-site relationships.

NATURAL REGENERATION

The majority of oak research has been investigations into some aspect of oak natural regeneration. However, a few steadfast standards are apparent. Oaks can regenerate from seed, sprouts, and advance reproduction (seedling in place). Typically, new oak germinants shunt energy into root growth and are outcompeted by existing competitor species. Oak sprouts, although fast growing with their existing root system, are too few in number to establish a viable oak stand. Advance reproduction is more effective in regenerating oak since a root system is already established and leaves and shoots are more developed.

Pioneering studies by Sander (1972, Sander and others 1976) suggest that advance reproduction of oak with sufficient numbers and size (generally ≥ 4 feet tall) is necessary to successfully regenerate oak. This advance oak reproduction should be present before the harvest

cut. Otherwise, shade-tolerant species such as maple (*Acer* spp.) and beech (*Fagus* spp.) that are present in the understory and midstory and intolerant species from seed such as yellow-poplar (*Liriodendron tulipifera*) and cherry (*Prunus* spp.) will outgrow and supplant small oak reproduction (<2 feet tall) or germinating acorns. Typically, oaks with their intermediate light tolerance are favored in partial light conditions and on drier, xeric sites, whereas tolerant species are more abundant with more limited light or closed canopies on mesic sites and decline on xeric sites. Intolerants prefer open canopies and greater sunlight on mesic sites (Hodges and Gardiner 1993).

The number of large oak seedlings recommended to be present at harvest depends on management objectives for the number of mature oaks desired in the future stand. The common guideline of 100 to 200 large oak seedlings as advance reproduction per acre (Stringer 2016) is sufficient to have 40 to 60 mature oaks per acre at maturity (Clatterbuck and Hodges 1988). These general recommendations should be taken into consideration with existing stand and environmental conditions that vary widely within the oak range. Modifications to these guidelines should be considered based on differences in site productivity, management goals for species composition and stand structure, abundance of competing species, and external influences such as herbivory (Dey 2014).

Unfortunately, many stands suitable for harvest have not been disturbed or managed for many years resulting in closed canopies and dense midstories and understories of shade-tolerant species. These environmental conditions restrain establishment and development of advance oak reproduction which has intermediate light tolerance. The harvest of these oak-dominated stands without adequate oak advance reproduction usually shifts future composition to non-oak species. Hodges (1989) states “the answer to the question of how to ensure adequate oak regeneration . . . is not the development of some radically new method of cutting, but recognition that all cutting operations in the stand, from the very first, should have as some of their objectives creation of an environment, largely light conditions, favorable for oak regeneration . . . and furthermore . . . ensure that cuttings occur frequently enough to maintain growth of oak regeneration.” However, the scarcity of markets for small-diameter trees in many hardwood areas has inhibited thinnings and other intermediate treatments that can promote advance reproduction. With the absence of these operations and other disturbances such as fire, grazing, weather-related occurrences, and insect and disease infestations, closed canopies are prevalent for extended time periods prohibiting advance oak reproduction.

The key to establishing and developing advance oak reproduction for natural regeneration is in the regulation of sunlight reaching the forest floor. Too much or too little light can deter advance reproduction promoting other species rather than oak. Many studies have agreed that 20 to 30 percent of full sunlight is necessary for developing competitive oak seedlings (Dillaway and Stringer 2006, Gardiner and Hodges 1998, Gottschalk 1994, Lhotka and Lowenstein 2009, Lorimer and others 1994, Phares 1971). These light levels can be attained through several practices that have been or continue to be studied: shelterwood, midstory removal, expanding gap, and variable overstory retention as well as opening sizes.

The shelterwood regeneration method favors species with intermediate light tolerance such as oaks. However, there is a fine line in practice to promote oak species as discussed previously. Too much light or too little light will promote species other than oaks. The shelterwood method for oak regeneration is primarily used to encourage the development of large seedlings from existing smaller ones, so that they will be able to successfully compete with other vegetation when the overstory is removed (Loftis 1990a, 1990b). A caveat with the shelterwood method is that advance oak reproduction must be present and cultured to a larger size by regulating the amount of light. If advance oak reproduction is not present, the method should not be implemented until advanced reproduction is present, usually following a bumper seed year, and environmental conditions are favorable for acorn germination. The environmental conditions for germination (primarily moisture and seedbed receptivity) and good acorn crops that exceed predation do not occur regularly such that establishment of advance reproduction may take several to many years (Burns and Honkala 1990, Dey 2014).

Partial or diffuse light levels that are beneficial to oak advance reproduction and discourage other vegetation can be achieved through midstory removal. This practice is often used in stands that have a dense midstory layer composed of tolerant species. Removal of the midstory layer allows more penetration of diffused sunlight through the canopy, increasing the amount of light for the oak seedlings. Midstory removal is commonly practiced with shelterwoods and small openings (0.5 to 1 acre) to develop greater size of small existing oak advance reproduction (Loftis 1990b, Stringer 2006).

Likewise, light conditions that promote greater size of oak reproduction can be implemented through varying the size of openings (light received within the opening) and edge effects of openings, often referred to as expanding gap or *femelschlag* (Kern and others 2017, Lhotka and Stringer 2013). Midstory control is used



in conjunction with varying opening sizes to increase light penetration within and on the edge of the opening. Different opening sizes provide different light intensities and durations supporting different suites of species, parallel to species light tolerances. Small, individual tree openings support tolerant species, large openings support intolerant species, and intermediate openings favor more intermediate species (Lhotka 2013). The edge of the opening receives light from the opening. With midstory removal within the opening and from the edge outward (expanding gap), additional light is available (Craig and others 2014). Although research into expanding gap and various gap and opening sizes are in their infancy, investigations evaluating these partial light concepts to favor oaks are continuing in efforts to provide more definitive management guidelines for regenerating oak in partial light matrices.

Even when oak regeneration is ample, oaks have a difficult time emerging into the overstory. The “oak bottleneck” occurs when mature oaks and oak seedlings are numerous in the overstory and understory, respectively, but oak saplings are scarce in the midstory such that there is little potential of oak ingrowth into the overstory (Dey 2014, Signell and others 2005). Nowacki and Abrams (2008) suggested that long-term forest mesophication due to fire suppression may be promoting more vigorous, fire-tolerant species rather than oak. However, the same bottleneck is also occurring on moist sites without a burning history in absence of disturbances. Research is beginning to investigate the bottleneck problem. Crop tree release (Miller and others 2007) at an early stage of development before or at canopy closure may be one solution.

In summary, advance oak reproduction of adequate size and number is necessary for regeneration. Oaks regenerate well on average to poor productivity sites (sub-mesic to xeric) where competition from faster growing species is less. On the better sites, the issue is that even though oak advanced regeneration of sufficient size and number is present, faster growing species tend to supplant and overwhelm oaks (bottleneck effect) before they reach the overstory. Regulation of the sunlight is necessary to promote oaks and discourage other vegetation. Regeneration of oak must be planned several years before the harvest cut for advanced reproduction of oak to develop and become a component of the next stand. Stands should be entered and disturbed more frequently to create light conditions for growth and development of advance regeneration. Typically these measures can be attained on lands that are continually managed, but do not occur on unmanaged lands where disturbances are infrequent and closed canopies are maintained for an indefinite period. Natural regeneration of oak is a process and not an event. Merely harvesting an oak stand without

oak advance regeneration will yield a future stand of non-oaks. Advance regeneration should be established and cultured to larger sizes. With this process, oak regeneration can also be interpreted as disturbance-dependent to allow for the establishment and growth of advance reproduction well before the harvest and advance growth-dependent in that advance reproduction should be of sufficient size and number to successfully compete with other species following the final harvest. Additional disturbances through release treatments are necessary to ensure that oak stems do not bottleneck and emerge into the overstory.

ARTIFICIAL REGENERATION

Planting is an alternative for oak regeneration when advance oak reproduction is not present. Oaks can be planted in reforestation or afforestation efforts or as enrichment or supplemental planting when natural oak reproduction is judged to be insufficient to meet regeneration goals. Unfortunately, there have been many more oak planting failures than successes. Planting failure can be nursery and planting related with poor quality seedlings, poor nursery practices from the nursery bed to the planting vendor, or poor planting techniques. However, as expressed earlier, many failures are also from inferior site preparation to control competing species as well as incorrect species-site associations where sites are better suited for growth of other species rather than oaks, or inattention to sunlight relationships that favor oaks rather than other species.

Planting oaks is usually more successful on the better sites (bottomlands, stream valleys and drains, and on lower slopes) where soil moisture is not as limiting. Alternatively, oaks planted on convex surfaces and drier sites where soil moisture holding capacity is poor are not as successful. Natural regeneration is a better option on these sites if a seed source is available.

The condition of planted seedlings is critical for a successful oak planting. Some controversy exists around whether to plant small or large seedlings. Larger seedlings are more difficult to plant and usually more expensive. The question is whether these larger seedlings have a greater probability of success for survival and growth than smaller seedlings. Trees/seedlings try to keep a balanced ratio between the aboveground stems and leaves and the root system (Perry 1982). Seedlings grow well in the nursery where growth components (water and nutrients) are generously provided and competition is controlled. However, once seedlings are lifted from the nursery, usually more than half of the seedling's root system is not retained which stresses the seedling (Watson 1994). With the diminutive root system, the aboveground portion of the seedling is also affected. The outplanted seedling

either is stimulated to regenerate more roots quickly to sustain the top, or the top partially dies back, or both so that the shoots and the roots re-establish equilibrium. After planting, height growth is minimal during the first growing season allowing competitor species to have a growth advantage which can adversely impact the oak seedling. At this time, there is no definitive agreement or peer-reviewed, oak-specific study on whether planting small or large seedlings is more successful.

Although containerized seedlings or plugs have a complete root system when transplanted, the container has limited root and medium volume. Because of restricted root development, most container seedlings are watered frequently during growth and before transplanting creating a hospitable rooting environment. Soil environments on submesic to xeric sites are moisture-limited and are often detrimental to survival of planted seedlings. After planting, the differences in water potentials between the favorable container medium and the native, usually poorer soil will either take water away from the container medium causing water deficits, or draw water into the container medium causing saturation and limiting oxygen to the roots. At either extreme, water uptake is limited and influences seedling growth and survival. Seedlings must compensate between the favorable growing environment in the container medium and the much harsher soil conditions (usually more moisture-limited) at planting sites. These differing water potentials between controlled and planting environments as well as differences in soil substrates (container vs. field) can affect seedling growth and performance.

Another unresolved component of oak seedling quality from nurseries is the impact of top-clipping seedlings to regulate seedling size making them easier to plant and perhaps increasing the root collar diameter of the seedling, e.g., make the seedling stouter. The question is whether top-clipping apical leaders of the seedling has an influence on seedling performance once outplanted. Clipping may influence growth hormones causing multiple leaders to emerge rather than a single shoot with apical dominance and greater height growth. This disruption of overall height growth may concede height advantages to competing vegetation. Again, oak-specific research has not taken place to address whether top-clipping is physiologically beneficial or not to overall outplanting performance. Top-clipping certainly limits seedling size making the seedling easier to lift, handle, and pack by the nursery before outplanting, but seedling performance is unknown.

Seedlings, whether produced in nurseries or in containers, are usually grown in full sunlight, and then transplanted to partial light conditions, especially in enrichment or supplemental plantings. The impact of these different light regimes on seedling performance

is not known and is not referenced well in the literature (McGee 1975, 1986). Further research on seedling size, use of top-clipping, use of bare-root or container seedlings, and light regimes are warranted to improve planted seedling performance and survival so oaks can become viable components of the future stand.

PRESCRIBED FIRE

Burning in hardwood forests is more in vogue today than at any time since fire suppression policies were implemented in the 1940s. Five recent conferences have been held about the role of fire in eastern oak forests and the impacts on people, resources, vegetation, and landscapes (Dey and others 2012, Dickinson 2006, Hutchinson 2009, Varner and others 2016, Yaussy 2000).

Prescribed fire is a silvicultural tool commonly implemented for site preparation for natural or artificial regeneration, fuel reduction, enhancing wildlife habitat, perpetuating fire-dependent species, improving site access and appearance, and providing early successional vegetation structure (Wade and Lunsford 1989). Prescribed burning has environmental impacts on vegetation, soil, water, air, wildlife, and visual appeal. Burning for successful oak regeneration remains challenging with both benefits and detriments to vegetation and sites (Arthur and others 2012, Brose and others 2013).

Prescribed burning to improve wildlife habitat in upland hardwood forests is a subject of this conference, has been thoroughly reviewed (Harper and others 2016), and is not further discussed in this paper. Fire is a component of savanna and woodland systems that have diminished with fire suppression (Dey and others 2017, Keyser and others 2016). One of the concerns with repeated burning in these pyric systems is high-intensity, small-scale, frequent fires do not support oak ingrowth and result in relatively unstable communities (Clatterbuck and Stratton Rollins 2018, Knapp and others 2015). To allow oak ingrowth to occur, land managers should cease burning for a greater period of time or conduct lower intensity burns. With repeated burns, the overstory trees are decrepit with fire scars and decay, and their numbers diminish with time and each burn. The consequence of one longer burning interval to allow ingrowth will shift vegetation to more woody species and less herbaceous vegetation.

The primary disadvantage of burning in standing trees when developing oak reproduction is the potential of damage to tree boles. Most hardwoods are highly susceptible to butt rot, especially from the *Armillaria* root fungus. Even a low-intensity burn with small fire scars will result in greater susceptibility to butt rot. The risk is even greater with repeated burning. The results of burning are often erratic with varying fuels, temperatures,





and durations. Small-diameter trees with thinner bark are much more susceptible to stem damage and topkill, but many will resprout with their root systems. Stem damage from fire reduces sawtimber value. Many of the older trees present today with fire scars were damaged when trees were young.

Wildfires that burned regularly 80 to 100 years ago have been hypothesized as one factor that contributed to the oak forests that are present today (Van Lear and Watt 1993). Prescribed fire could be used to simulate the environmental conditions that favored the growth of oak seedlings amongst the growth of competitors. Other factors that could have contributed to the environmental conditions that promoted oaks are grazing, loss of American chestnut (*Castanea dentata*), and indiscriminant logging. These disturbances (and probably others) jointly created an environment, primarily species composition and stand structures, which is different from the environmental conditions present in forests today.

The remaining discussion concerning oak regeneration assessments with prescribed fire is based on my perspectives of species relationships for various site productivities.

Burning for oak regeneration on lower quality, poor productivity sites [Site Index (SI) <65 feet for oak] is not necessary because oak already proliferates in both the overstory and in the understory. Oak competition is fairly sparse on these sites. Prescribed burning may be appropriate for other purposes such as wildlife habitat but not for oak regeneration that is already in place. On the better, more mesic hardwood sites (SI >80 feet), burning is difficult and rarely occurs. These better sites in cove hardwood areas, lower slopes, and near stream valleys and floodplains are usually too moist throughout the year to ignite and carry a fire. Typically, faster growing species will dominate on these sites. Burning for the purpose of regenerating oak on these higher productivity sites is not realistic. The best opportunity for burning to benefit oak regeneration is on the average or mediocre site productivities (SI 65 to 80 feet) that encompass a narrow range of site productivities but entail hundreds of thousands of acres of forest land in eastern forests. Advance oak reproduction of sufficient number and size must be present because burning will not create oak regeneration. Burning can also damage and decrease the value of standing trees, if present.

Fire is a blunt tool that is difficult to characterize due to variable weather conditions, fuels, vegetation, and moisture. Research with burning is problematic to replicate because different areas tend to have varying conditions (weather, substrate/soils, vegetation, fuels) that will impact the burn and cause different effects.

With most burns, small oak reproduction is as likely to be killed as perpetuated. A successful prescription that favors oaks selectively at the expense of other species is easier said than done. Much of the information that we have is anecdotal or observational at one point in time and has not been verified or replicated by long-term research to the degree that oak regeneration prescriptions using fire predictably result in overstories composed of oaks. There is much more we need to understand about these ecosystems and the ecology of the species involved as suggested by Arthur and others (2012). Some of the fire variables that will influence success include fire properties such as duration, residence time, rate of spread, frequency, intensity, and season and timing of burning; fuel properties such as type, amount, size, and moistures; and susceptibility of species based on size and age.

There has been much discussion about whether repeated burning would selectively favor oaks compared to other species (Arthur and others 2015, Hutchinson and others 2012, Keyser and others 2017). In theory, repeated burning would tend to gradually reduce the sprouting ability of some species (progressively reducing root reserves until they no longer sprout) and perhaps enhance those species (primarily oaks) that may be better adapted to burning through their resprouting ability. Although oaks can be influenced by repeated burns (either positively or negatively), perhaps the more pertinent question is whether a landowner can afford to lose 8 to 10 years of growth by burning three or more times attempting to structure the vegetation for a greater oak component. Repeated burning can degrade and decrease the value of standing trees (Marschall and others 2014, Yaussy and Waldrop 2010). Research has indicated that just one burn is not enough to favor oak over other species. Most all hardwood species will sprout when damaged and stressed! Repeated burns increase the chance of damage to residual trees.

Burning in hardwoods for purposes of regeneration is difficult! Fuels vary based on the species and stand structure present. Intensity of the fire is difficult to regulate. Prescribed fire on slopes is very tricky. Fires will not start or carry on moist lower slopes and stream valleys. Fires are tough to control on upper slopes and ridges where fuels are drier and often directed by gusty, inconsistent winds. A program of prescribed burning should not be undertaken without a full appreciation of the purpose, difficulty, and risks/liabilities involved with each burn. Although there are many proponents of burning to regenerate oak, many uncertainties are present. Care should be taken to ensure that prescriptions using fire are successful for both meeting oak regeneration objectives and increasing the probability for oaks to emerge into the overstory in mixed-species stands. More research and definitive

answers to the following questions are necessary to successfully implement prescribed burning as a practice to manage and regenerate oaks:

1. How can fire be used to develop sufficient size and number of oak advance reproduction?
2. What is a feasible oak regeneration prescription using fire considering that most competitors sprout?
3. How can stands of mature hardwoods or immature stands of developing hardwoods be burned without damaging crop trees?

TAKE HOME SUMMARIES

- Know your species, both oak and non-oak. Know your sites. Evaluate species-site relationships to favor oaks.
- Advance reproduction is necessary to regenerate oak. How to implement partial light conditions (at least 20 to 30 percent available light) relies on the skill of the silviculturist. Several methods are available: shelterwood, midstory removal, expanding gap, and variable overstory retention as well as opening sizes.
- Oaks are disturbance-dependent and advance growth-dependent. Regenerating oak is a process and not an event. Growth of competing species often displaces the development of oak (bottleneck effect) before oaks are able to emerge into the overstory.
- Prescriptions to successfully regenerate oak using prescribed fire are largely unknown, untested and unpredictable. An intensive regeneration survey is necessary before the harvest and the burn to evaluate the impacts on oaks in conjunction with other species. Most all hardwood species resprout. Several factors influence burning properties including fire duration, residence time, rate of spread, frequency, air temperature, intensity, and season and timing of the burn as well as type, amount, size and moisture content of the fuels, and individual species' tolerances to burning. Many of these properties and combinations are difficult to prescribe and implement consistently for desired effects. Each fire has different impacts on vegetation.
- Most research has been oak-centric. More focus should be given to oak ecosystem dynamics, particularly other species and site characteristics than relying on an oak-only mentality, especially when implementing practices/treatments in mixed-species stands.

LITERATURE CITED

- 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(5): 257-266.
- Arthur, M.A.; Blankenship, B.A.; Schorgendorfer, A. [and others]. 2015. Changes in stand structure and tree vigor with repeated prescribed fire in an Appalachian hardwood forest. *Forest Ecology and Management*. 340: 46-61.
- Baker, J.B.; Broadfoot, W.M. 1979. A practical field method of site evaluation for commercially important southern hardwoods. Gen. Tech. Rep. SO-26. New Orleans, LA: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 51 p.
- 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.; 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.
- Burns, R.M.; Honkala, B.H., tech. cords. 1990. *Silvics of North America: 2. Hardwoods*. Agriculture Handbook 654, Vol. 2. Washington, DC: U.S. Department of Agriculture Forest Service. 877 p.
- Clatterbuck, W.K.; Hodges, J.D. 1988. Development of cherrybark oak and sweetgum in mixed, even-aged bottomland stands in central Mississippi, U.S.A. *Canadian Journal of Forest Research*. 18(1): 12-18.
- Clatterbuck, W.K.; Stratton Rollins, R.L. 2018. Implications of frequent high intensity fire on the long-term stability of oak barrens, woodlands and savannas. In: Kirschman, J.E., comp. *Proceedings of the 19th biennial southern silvicultural research conference*. e-Gen. Tech. Rep. SRS-234. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 444 p.
- Craig, J.M.; Lhotka, J.M.; Stringer, J.W. 2014. Evaluating initial responses of natural and underplanted oak reproduction and a shade-tolerant competitor to midstory removal. *Forest Science*. 60(6): 1164-1171.
- Dey, D.C. 2014. Sustaining oak forests in eastern North America: regeneration and recruitment, the pillars of sustainability. *Forest Science*. 60(5): 926-942.
- Dey, D.C.; Kabrick, J.M.; Schweitzer, C.J. 2017. Silviculture to restore oak savannas and woodlands. *Journal of Forestry*. 115(3): 202-211.
- Dey, D.C.; Stambaugh, M.C.; Clark, S.L.; Schweitzer, C.J., eds. 2012. *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. 292 p.
- Dickinson, M.B., ed. 2006. *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. 303 p.
- Dickson, R.E.; Isebrands, J.G.; Tomlinson, P.T. 1990. Distribution and metabolism of current photosynthate by single-flush northern red oak seedlings. *Tree Physiology*. 7: 65-77.





- Dillaway, D.; Stringer, J. 2006. Effects of shade on the growth and development of naturally and artificially established white oak (*Quercus alba*) regeneration. In: Buckley, D.S.; Clatterbuck, W.K., eds. Proceedings, 15th central hardwood forest conference. Gen. Tech. Rep. SRS-101. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 638-643.
- Ffolliott, P.F.; Gottfried, G.J.; Bennett, D.A. [and others], tech coords. 1992. Ecology and management of oak and associated woodlands: perspectives in the southwestern United States and northern Mexico. Gen. Tech. Rep. RM-218. Fort Collins, CO: U.S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station. 224 p.
- Gardiner, E.S.; Hodges, J.D. 1998. Growth and biomass distribution of cherrybark oak (*Quercus pagoda* Raf.) seedlings as influenced by light availability. *Forest Ecology and Management*. 108(1-2): 127-134.
- Gottschalk, K.W. 1994. Shade, leaf growth and crown development of *Quercus rubra*, *Quercus velutina*, *Prunus serotina* and *Acer rubrum* seedlings. *Tree Physiology*. 14: 735-749.
- Harper, C.A.; Ford, W.M.; Lashley, C.E. [and others]. 2016. Fire effects on wildlife in the Central Hardwoods and Appalachian regions, USA. *Fire Ecology*. 12(2): 127-159.
- Hodges, J.D. 1989. Regeneration of bottomland oaks. *Forest Farmer*. 49(1): 10-11.
- Hodges, J.D.; Gardiner, E.S. 1993. Ecology and physiology of oak regeneration. In: Loftis, D.L.; McGee, C.E., eds. Oak regeneration: serious problems, practical recommendations. Symposium proceedings. Gen. Tech. Rep. SE-84. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station: 54-65.
- Holt, H.A.; Fischer, B.C., eds. 1979. Proceedings, regenerating oaks in upland hardwood forests. West Lafayette, IN: John S. Wright Forestry Conference, Purdue University, Department of Forestry and Natural Resources. 132 p.
- Hutchinson, T.F., ed. 2009. 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. 154 p.
- Hutchinson, T.F.; Yaussy, D.A.; Long, R.P. [and others]. 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, J.E., ed. 1985. Challenges of oak management and utilization: proceedings of a conference. Madison, WI: University of Wisconsin-Extension, Department of Forestry, Cooperative Extension Service. 161 p.
- Kern, C.C.; Burton, J.I.; Raymond, P. [and others]. 2017. Challenges facing gap-based silviculture and possible solutions for mesic northern forests in North America. *Forestry*. 90(1): 4-17.
- Keyser, P.D.; Harper, C.A.; Anderson, M.; Vander Yacht, A. 2016. How do I manage for woodlands and savannahs? In: Keyser, P.D.; Fearer, T.; Harper, C.A., eds. Managing oak forests in the eastern United States. Boca Raton, FL: CRC Press: 223-245.
- Keyser, T.L.; Arthur, M.A.; Loftis, D.L. 2017. Repeated burning alters the structure and composition of hardwood regeneration in oak-dominated forests in eastern Kentucky, USA. *Forest Ecology and Management*. 393: 1-11.
- Knapp, B.O.; Stephan, K.; Hubbart, J.A. 2015. Structure and composition of an oak-hickory forest after over 60 years of repeated prescribed burning in Missouri, U.S.A. *Forest Ecology and Management*. 344: 95-109.
- Lhotka, J.M. 2013. Effect of gap size on mid-rotation stand structure and species composition in a naturally regenerated mixed broadleaf forest. *New Forests*. 44(3): 311-325.
- Lhotka, J.M.; Loewenstein, E.F. 2009. Effect of midstory removal on understory light levels availability and 2-year response of underplanted cherrybark oak seedlings. *Southern Journal of Applied Forestry*. 33(4): 171-177.
- Lhotka, J.M.; Stringer, J.W. 2013. Forest edge effects of *Quercus* reproduction within naturally regenerated mixed broadleaf stands. *Canadian Journal of Forest Research*. 43(10): 911-918.
- Loftis, D.; McGee, C.E., eds. 1993. Oak regeneration: serious problems, practical considerations. Symposium Proceedings. Gen. Tech. Rep. SE-84. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 319 p.
- Loftis, D.L. 1990a. Predicting post-harvest performance of advance red oak reproduction in the southern Appalachians. *Forest Science*. 36(4): 908-916.
- Loftis, D.L. 1990b. A shelterwood method for regenerating red oak in the southern Appalachians. *Forest Science*. 36(4): 917-929.
- 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(2): 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.
- McGee, C.E. 1975. Change in forest canopy affects phenology and development of northern red oak and scarlet oak seedlings. *Forest Science*. 21(2): 175-179.
- McGee, C.E. 1986. Budbreak for twenty-three upland hardwoods compared under forest canopies and in recent clearcuts. *Forest Science*. 32(4): 924-935.
- McNab, W.H.; Cleland, D.T.; Freeouf, J.A. [and others], comps. 2007. Description of ecological subregions: sections of the conterminous United States [CD-ROM]. Gen. Tech. Rep. WO-76B. Washington, DC: U.S. Department of Agriculture Forest Service. 80 p.
- Miller, G.W.; Stringer, J.W.; Mercker, D.C. 2007. Technical guide to crop tree release in hardwood forests. Professional Hardwood Notes. Publication PB1774. Knoxville, TN: University of Tennessee Extension. 24 p.
- Miller, R.A. 1974. The geologic history of Tennessee. Bulletin 74. Nashville, TN: State of Tennessee, Department of Conservation, Division of Geology. 63 p.
- Northeastern Forest Experiment Station. 1970. The silviculture of oaks and associated species. Res. Paper NE-144. Upper Darby, PA: U.S. Department of Agriculture Forest Service, Northern Forest Experiment Station. 66 p.
- Northeastern Forest Experiment Station. 1971. Oak symposium proceedings. Upper Darby, PA: U.S. Department of Agriculture Forest Service, Northern Forest Experiment Station. 161 p.
- Nowacki, G.J.; Abrams, M.D. 2008. The demise of fire and "mesophication" of forests in the eastern United States. *BioScience*. 58(2): 123-138.

- Oxford Dictionaries. 2017. Paradox definition. Oxford University Press. <https://en.oxforddictionaries.com/definition/paradox>. [Date accessed: September 19, 2017].
- Perry, T.O. 1982. The ecology of tree roots and the practical significance thereof. *Journal of Arboriculture*. 8(8): 197-211.
- Phares, R.E. 1971. Growth of red oak (*Quercus rubra* L.) seedlings in relation to light and nutrients. *Ecology*. 52(4): 669-672.
- Rebbeck, J.; Gottschalk, K.; Scherzer, A. 2011. Do chestnut, northern red, and white oak germinant seedlings respond similarly to light treatments? Growth and biomass. *Canadian Journal of Forest Research*. 41(11): 2219-2230.
- Sander, I.L. 1972. Size of oak advance reproduction: key to growth following harvest cutting. Res. Pap. NC-79. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 6 p.
- Sander, I.L.; Johnson, P.S.; Watt, R.F. 1976. A guide for evaluating the adequacy of oak advance reproduction. Gen. Tech. Rep. NC-23. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 7 p.
- Schnur, G.L. 1937. Yield, stand, and volume tables for even-aged upland oak forests. Tech. Bull. No. 560. Washington, DC: U.S. Department of Agriculture. 88 p.
- Signell, S.A.; Abrams, M.D.; Hovis, J.C.; Henry, S.W. 2005. Impact of multiple fires on stand structure and tree regeneration in central Appalachian oak Forests. *Forest Ecology and Management*. 218(1-3): 146-158.
- Smalley, G.W. 1986. Site classification and evaluation for the Interior Uplands, forest sites of the Cumberland Plateau and Highland Rim/Pennsylvanian. Technical Publication R8-TP-9. Atlanta, GA: U.S. Department of Agriculture Forest Service. Combined edition of six regional guides for joint publication by Southern Region 8 and the Southern Forest Experiment Station.
- Spetich, M.A., ed. 2004. Upland oak ecology symposium: history, current conditions, and sustainability. Gen. Tech. Rep. SRS-73. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 311 p.
- Stringer, J.W. 2006. Oak shelterwood: a technique to improve oak regeneration. Professional Hardwood Notes. Publication PB676. Knoxville, TN: University of Tennessee Extension. 8 p.
- Stringer, J.W. 2016. Oak regeneration challenges. In: Keyser, P.D.; Fearer, T.; Harper, C.A., eds. *Managing oak forests in the eastern United States*. Boca Raton, FL: CRC Press: 63-71.
- USDA Forest Service. 1980. Proceedings, Mid-South upland hardwood symposium for the practicing forester and land manager. Tech. Publ. SA-TP-12. Atlanta, GA: U.S. Department of Agriculture Forest Service, State and Private Forestry, Southeastern Area. 186 p.
- Van Lear, D.H.; Watt, J.M. 1993. The role of fire in oak regeneration. In: Loftis, D.L.; McGee, C.E., eds. *Oak regeneration: serious problems, practical recommendations*. Symposium Proceedings. Gen. Tech. Rep. SE-84. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station: 66-78.
- Varner, J.M.; Arthur, M.A.; Clark, S.L. [and others]. 2016. Fire in eastern North American oak ecosystems: filling the gaps. *Fire Ecology*. 12(2): 1-6.
- Wade, D.D.; Lunsford, J.D. 1989. A guide for prescribed fire in southern forests. Technical Publication R8-TP-11. Atlanta, GA: U.S. Department of Agriculture Forest Service, Southern Region, State and Private Forestry. 56 p.
- Watson, G.W. 1994. Root development after transplanting. In: Watson, G.W.; Neely, D., eds. *The landscape below ground: proceedings of an international workshop on tree root development in urban soils*. Savoy, IL: International Society of Arboriculture: 54-68.
- Yaussy, D.A., comp. 2000. Proceedings: workshop on fire, people, and the central hardwood landscape. Gen. Tech. Rep. NE-274. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northeastern Research Station. 129 p.
- Yaussy, D.A.; Waldrop, T.A. 2010. Delayed mortality of eastern hardwoods after prescribed fire. In: Stanturf, J.A., ed. *Proceedings of the 14th biennial southern silvicultural research conference*. Gen. Tech. Rep. SRS-121. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 609-612.

