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silviculture

Sustaining Oak Forests in Eastern North America: Regeneration and Recruitment, the Pillars of Sustainability

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Oak cover types comprise half of the forestlands in the eastern United States. There is a great desire to sustain these highly valued forests. Unfortunately, reports of the successional replacement of oak are all too common, as they are throughout the world. Sustaining the oak resource requires the ability to both regenerate and recruit oak into the overstory as dominant mature trees. Too often these two critical processes are disconnected in oak management, thwarting the best of intentions to sustain oak. Restoring and sustaining oak forests require active management and long-term commitment. Climate change, high deer populations, invasive species, and social constraints can complicate oak management. Despite these challenges, we have sufficient knowledge to be successful in our efforts despite an uncertain future. Forest landscapes are too homogeneous today and may cause a bottleneck in oak regeneration as mature forests become old-growth. Management is needed to diversify the landscape and create a more balanced age structure that has the capacity to naturally regenerate oak. Landscape diversity is also desired to combat the myriad of forest threats and future uncertainty. Getting private landowners and public managers to manage for oak is key to changing landscapes and ensuring a quality oak resource.

Keywords: oak silviculture, sustainable forests, oak ecology, forest history, regeneration

The difficulty in sustaining the levels of oak (*Quercus* spp.) stocking in eastern North American forests is a relatively recent problem, with increasingly frequent alarms having been sounded in the literature since the 1950s. In the eastern United States, replacement of oak forests by red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), yellow-poplar (*Liriodendron tulipifera*), birch (*Betula* spp.), or aspen (*Populus* spp.) is well established (Abrams 1998, Fei and Steiner 2007, Johnson et al. 2009, Fei et al. 2011). Failure to regenerate oak forests is a worldwide phenomenon, and the replacement of oak by other species in both regenerating and old-growth forests has been reported throughout the natural range of oak in the northern hemisphere (Li and Ma 2003, Götmark et al. 2005, Pulido and Díaz 2005, Johnson et al. 2009).

This article provides an integrated synthesis of the (1) historical development of the oak regeneration problem, (2) current drivers of forest succession toward new forest cover types that are changing the nature of the landscape, (3) oak biology and ecology, and (4) development of oak silvicultural practices over the past 100 years, culminating in innovative and promising practices that promote oak regeneration and recruitment into overstory dominance: the pillars of sustaining oak not only in the central hardwood region but also throughout the range of oak forests. The article concludes with a look toward emerging challenges that may complicate current silvicultural approaches to sustaining oak in the long term and a few suggested areas of research priority.

The Need to Conserve the Oak Resource

In the United States, concerns for the reduction in the oak resource are significant because oak forest types represent 51% of all forestland (78.5 million ha) and about 45% of growing stock volume in the East, where upland oak-hickory is by far the most common forest type (>48.5 million ha) (Smith et al. 2009). Local to international concerns for the sustainability of the oak resource arise because oaks have such high ecological and economic value (McShea and Healy 2002). Oak ecosystems support a high level of native floral and faunal diversity with many species preferring key structural and compositional features of oak forests, woodlands, and savannas (Anderson et al. 1999, Thompson et al. 2012, Starbuck 2013). Declines in the amount of oak forests on the landscape and regional scales have significantly negative impacts on wildlife populations (Rodewald 2003, McShea et al. 2007, Fox et al. 2010). Oak foliage in forest canopies and oak litter fall are important inputs to terrestrial and aquatic ecosystems, and both enhance productivity by supporting a greater diversity and abundance of organisms involved in energy and nutrient cycles than those supported by forested

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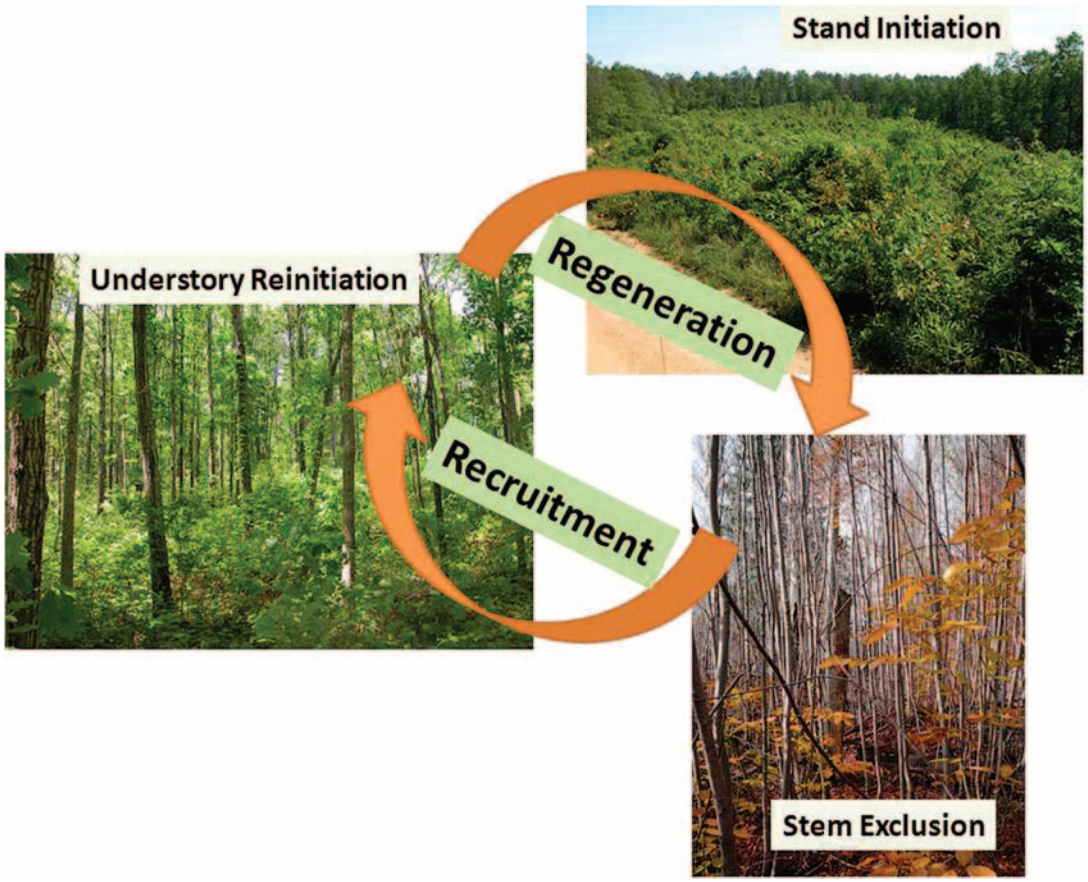

Figure 1. Regeneration and recruitment are processes that direct the stages of stand development (Oliver and Larson 1996). Regeneration begins when disturbance, whether a natural event or management activity, frees up growing space after the removal of overstory trees to permit establishment of reproduction (new seedlings or sprouts) or release of advance reproduction. In some respects, the regeneration potential is set in the latter stages of understory reinitiation when advance reproduction forms in the understory and the overstory determine seed and stump sprout production potential. Regeneration ends at the beginning of the stem exclusion stage, when reproduction can no longer establish and stem density exceeds the capacity of the site to support all trees. This signifies the beginning of recruitment into the overstory as stands mature into the understory reinitiation. Regeneration and recruitment need to be managed in a coordinated planned fashion to ensure that oak stocking meets management goals at stand maturity.

landscapes without oaks (Hansen 2000, Tallamy and Shropshire 2009, Stoler and Relyea 2011).

Sustaining and restoring oak ecosystems (forests, woodlands, and savannas) have become major management goals for many federal and state natural resource agencies and nongovernmental conservation organizations (e.g., Mark Twain National Forest 2005, Upper Mississippi River and Great Lakes Region Joint Venture 2007). Although oaks may live for 200–400 years (Burns and Honkala 1990), oak forests, woodlands, or savannas must at some point be regenerated to sustain oak on the landscape.

The Pillars of Oak Sustainability

Getting oak established through regeneration at the desired levels of stocking to fulfill management goals for oak at maturity is the first pillar of sustaining oak forests into the future (Figure 1). In general, most regeneration occurs during the stand initiation stage of stand development; this stage begins after a disturbance that permits newly germinated seedlings or existing sources of reproduction (e.g., seedling and stump sprouts and root suckers) to compete for available resources, which is largely a competition for light in many oak ecosystems (Oliver and Larson 1996). It ends when the density of sapling reproduction is sufficient to exclude the entry of new seedlings and exceeds the capacity of the site to sustain all individuals. This is the beginning of the stem exclusion stage when intense competition results in mortality, stand self-thinning, and crown differentiation into classes as trees fight for dominance. The regeneration period in eastern oak forests may last for up to 20 years, depending on site productivity, species composition and size structure of the parent stand, and differential growth rates of species present after the disturbance-initiating regeneration (Johnson et al. 2009). Other factors such as deer herbivory and interfering species competition may prolong the regeneration period (Horsley and Marquis 1983, Fredericksen et al. 1998, Horsley et al. 2003, Engelman and Nyland 2006). Successful regeneration is fundamental to perpetuating oak forests in the future, but sometimes seemingly successful regeneration efforts would, over time, turn to failures soon after forest canopy closure during the stem exclusion stage of stand development, especially on the more mesic and productive sites (Hilt 1985, Ward and Stephens 1994, Morrissey et al. 2008, Johnson et al. 2009).

In a way, regeneration in eastern hardwoods begins decades before the disturbance that initiates the establishment and release of reproduction because the composition of the future stand is encoded in the initial floristics (Egler 1954), which determines the regeneration potential of species in the stand (Johnson et al. 2009). Therefore, managers may begin working in mature stands during the understory reinitiation stage well before the planned regeneration event to increase oak regeneration potential through the establishment and development of abundant large oak advance reproduction.

The second pillar, recruitment (Figure 1), or the ascension of saplings into the overstory encompasses Oliver and Larson's (1996) stem exclusion and understory reinitiation stages of stand development in which saplings grow increasingly larger to become poles and then sawtimber-sized trees. Intermediate thinnings are the primary tool managers have to regulate competition, stand density, growth, and composition of the developing mature overstory. Successful recruitment occurs when desired species are able to compete and grow to be dominant and codominant trees in the overstory and they are able to reproduce by sexual or asexual processes.

Thus, the two pillars of sustainable oak management, regeneration and recruitment, encompass the continuum of tree development from seedling to mature tree and the entire life cycle of an oak forest from stand initiation, through stem exclusion, to understory reinitiation. They are both required to sustain oak stocking at desired levels in mature forests. Both regeneration and recruitment must be purposefully planned and the processes linked in the silvicultural prescription.

The Oak Regeneration Problem Has Deep Roots in Human History

Cultural Transformation: Native American to European Transition

Quercus has been a dominant and widely distributed genus throughout eastern North America for thousands of years, and it rose substantially in prominence through anthropogenic fire with the advent of human colonization of the region (e.g., Williams 1989, Abrams 2002, McWilliams et al. 2002). At the end of the Native American culture in the East, mean fire frequency varied spatially, ranging from every 2 years or less in southern areas to every 50–100 years in the Northeast (Guyette et al. 2006, 2012). There was also temporal variation in fire frequency. Fire-free intervals ranged from 1 to 100 years in the historic period before European settlement in eastern North America (Guyette et al. 2002, 2003). The infrequent but extended periods without fire were ecologically significant, for it was during these times that oak and pine trees grew large enough to resist being topkilled by fire, which allowed them to recruit into the overstory.

With European settlement, fire became more consistently frequent and ubiquitous on the Eastern landscape from about the 1850s to the 1930s, too frequent to permit pine or oak recruitment into the overstory (Guyette et al. 2002, 2012, Stambaugh et al. 2007, Arthur et al. 2012). The dynamic interaction between humans and oak forests also changed when colonial populations grew, thus increasing the demand for building supplies and food. European immigrants brought the technology to quickly clear forests for agriculture land uses and to create a forest products industry. The origin of many of today's mature oak forests throughout the region is from forest disturbances operating during this period of dramatic cultural changes in the latter 19th and early 20th centuries.

Modern Expansion of Oak

During the period from the mid-19th to early 20th century, a number of factors contributed to the dominance and widespread distribution of oaks in eastern North America (Crow 1988, Abrams 1992, Dey 2002). Forest disturbances were collectively frequent, of low to moderate intensity, and widespread (Pyne 1982, Williams 1989, Whitney 1994). Timber was selectively harvested (i.e., high grading) or commercially clearcut (i.e., cutting only the merchantable timber) (Clark 1993). Forests were treated as open range in many regions and annually burned to improve forage for livestock. Introduced diseases caused the loss of dominant tree species such as the American chestnut (*Castanea dentata*). Marginal agricultural land was abandoned where it was not economical or sustainable for pasture or crops, and it was allowed to revert to forests. There was a drastic reduction in wildlife populations that consume acorns or browse oak reproduction (Dickson 1992, Ellsworth and McComb 2003, Rooney and Waller 2003).

In areas of charcoal production to fuel the manufacture of iron, forests were coppiced repeatedly on short rotations, which favored hardwood species able to sprout prolifically such as the oaks. From 1860 to 1920, much of the eastern forests were harvested on an unprecedented scale (Williams 1989), which in turn, increased the homogeneity in composition and structure of regional forests (e.g., Schulte et al. 2007). This homogeneity substantially affected forest health, productivity, and resilience to invasive species or environmental stresses, because damage from these agents was now occurring at landscape scales instead of in local to substand scales as occurred previously. In the past, damage from natural disturbances was limited in scale to individuals or groups of stands because of the diverse mosaic of composition and structure in a more heterogeneous landscape.

At the beginning of the 20th century, unregulated private and market game hunting decimated to extinction or near extinction the once abundant populations of wildlife such as the wild turkey (*Meleagris gallopavo*), the white-tailed deer (*Odocoileus virginianus*), and the passenger pigeon (*Ectopistes migratorius*) (Dickson 1992, Ellsworth and McComb 2003, Rooney and Waller 2003). These species fed heavily on acorns or, in the case of deer, also browsed on oak reproduction. At the same time, commercial logging in conjunction with increasing fire on the landscape and high levels of domestic livestock grazing (Pyne 1982, Guyette et al. 2002, 2012) set the stage for the proliferation of oak forests when these disturbances subsided or came under regulation or management.

Oaks were able to persist and develop under this regime of moderate and frequent disturbances that created low-density woodland structures, caused indiscriminate shoot dieback of advance reproduction among all species, and increased mortality in species sensitive to fire. Historically, fire maintained savanna and open woodland structures in which oaks were favored (Curtis 1959, Nelson 2010). However, with European settlement, new land uses also were creating relatively open environments, e.g., forest clearings, recovering old fields, or partial forest canopies, where light was sufficient to promote the development of vigorous oak sprouts. In many cases, fire was the matrix, the background disturbance that favored oak reproduction development in these partially stocked stands.

Young and small diameter oak trees and advance reproduction have a high capacity to sprout after cutting, burning, or browsing. This capacity to sprout vigorously increases exponentially as the basal diameter, a surrogate for size of root system, increases in oak seedlings and saplings (Sander 1971, Loftis 1990a, Johnson et al. 2009). Oak advance reproduction can produce sprouts repeatedly if there is sufficient light and time between disturbances that topkill the regeneration. Through repeated disturbances, oaks are able to build large root reserves as they preferentially allocate biomass to root growth and as light levels increase by repeated culling of the competing vegetation (Johnson et al. 2009). These factors enhance oak's ability to dominate regeneration during extended (10–30 years) disturbance-free periods, especially when the intensity of the final disturbance is sufficient to reduce overstory density and create opportunities for recruitment of regeneration into the overstory.

Because of the widespread nature of this suite of land uses, oaks became dominant after the commencement of fire suppression around the 1930s provided them the opportunity to form forests on a wide variety of sites over much of eastern North America, even on the more mesic and productive sites, where oak regeneration and sustainability is most problematic today. The importance of this history is that much of the current oak forests were regenerated in the early 1900s, at the time that professional forest management and research was being established, and it would take decades of stand development under new disturbance regimes before oak regeneration problems would develop and become apparent. The prevailing sentiment then was that oaks, which had been dominant in the overstory, would continue to be. There were a few early reports in the literature of oak regeneration failures, but it was not until after the 1930s that concern for oak regeneration and sustaining oak timber supply became a priority (Clark 1993).

The Beginning of the Oak Regeneration Problem

Since the early 20th century, the predominant methods for harvesting in eastern hardwoods were selective cutting (high grading) or single-tree selection (McGee 1972, Clark 1993). By the 1960s, it had become obvious that these harvest methods favored shade-tolerant species to replace oak in the absence of fire. Researchers began advocating even-aged management, particularly clearcutting, for regenerating oak and other desired shade-intolerant species (e.g., Roach and Gingrich 1968) and as a way to convert low-quality hardwood forests into productive, diverse forests again (McGee 1972). Early results from experimental clearcuts done in the 1930s showed that oak could dominate regeneration and sustain stocking into maturity (Kuenzel and McGuire 1942, Liming and Johnston 1944, Bey 1964), but after decades of fire suppression and encroachment of shade-tolerant species in forest understories, oaks began to be replaced by other species in clearcuts and group openings (Elliott et al. 1997, Weigel and Parker 1997, Morrissey et al. 2010b). Since the 1950s, it has been increasingly observed that clearcutting Eastern oak forests was resulting in stands being dominated by, in particular, yellow-poplar and red maple (Lorimer 1984, Clark 1993). The decline of oaks across eastern North America and succession to other species was being noted (e.g., Abrams 1998, Fei and Steiner 2007). Although oaks remain dominant in the overstory, the regeneration potential of oak in many stands is decreasing with time under modern disturbance regimes as overstory oaks age and forest understories become increasingly dominated by shade-tolerant species that are recruiting into the overstory.

A Brief History of a Century of Oak Research in the United States

Some of the first efforts in forest research in North America were directed to learning about the basic biology and ecology of the various commercial tree species, and understanding the fundamentals of natural reproduction, tree and stand growth, insect and disease pests, succession, and other silvical characteristics that would serve as a scientific basis for forest management. Early work done by Korstian (1927) on the factors controlling germination and early survival in oaks was key to understanding natural regeneration and for developing cultural methods for nursery production of seedlings. Korstian and Stickel (1927) also recognized the role of advance reproduction in the natural succession to oak in American chestnut-dominated stands after its loss to the chestnut blight (*Endothia parasitica*). Leffelman and Hawley (1925) refined the definition of the various forms of hardwood reproduction (e.g., seedling, seedling sprout, sprout, and root sucker) and alluded to the importance of the initial size of advance reproduction to future growth potential, which they attributed to the large established root system of stems with greater diameter.

Concerns for lack of oak regeneration were few until the 1950s, when an emphasis in research on understanding and managing the oak regeneration problem emerged. Traditional silvicultural regeneration methods were used with inconsistent results. Further research into factors controlling oak seedling competitiveness shed light on the need to integrate control of competing vegetation and other factors such as deer browsing with the regeneration harvest. Differences in observed oak regeneration success among sites throughout eastern North America pointed to the importance of taking site factors into consideration in the design of prescriptions within an ecological framework (Dey et al. 2009). It became apparent that periodic, managed disturbances were needed in preparation for and during stand establishment to reverse the changes in competitive relations wrought by decades of disturbance regimes that favored oak's competitors.

In the 1950s–1960s, the general consensus was that the presence of oak advance reproduction was the single most important factor related to regeneration success and that various site and environmental factors were key to its abundance (Carvell and Tryon 1961). Clark and Watt (1971) stated that the "two basic principles" of oak regeneration were the following: the oak stocking in the new stand will be directly proportional to the amount of oak advance reproduction before regeneration harvesting and oak advance reproduction had to have a well-established root system to be competitive. Sander (1971) was one of the first to model the future growth potential of oak advance reproduction that was released by clearcutting based on its initial size (i.e., stem diameter at the ground) before harvesting. Basal stem diameter is a good predictor of future growth in oak reproduction because it is highly correlated with many metrics of root system size (Canadell and Rhoda 1991, Dey and Parker 1997), which is important to growth potential during regeneration. Sander's early work led to a series of increasingly sophisticated regeneration models for predicting oak regeneration success (mortality and growth) or oak competitive dominance probabilities for advance reproduction and stump sprouts (Sander et al. 1976, 1984, Johnson 1977, Dey et al. 1996, Weigel et al. 2011) and artificial regeneration (e.g., Spetich et al. 2002) in the central hardwood region of the United States. Other oak and forest regeneration models have been developed for the southern and central Appalachian Mountain region (Loftis 1990a, Gould et al. 2006, 2007, Steiner et al. 2008, Vickers et al. 2011) and southern bottomland forests (Johnson 1980, 1993, Belli et al. 1999). We have progressed from basing our assessments of adequacy of oak advance reproduction on a few ecosystem-specific size thresholds to having ecosystem-specific models that determine future dominance probabilities and estimate stand composition and size distributions based on actual stand inventory and site factors. For example, based on data from Illinois clearcuts and stocking relationships developed by Gingrich (1967) for upland central hardwood forests, Sander et al. (1976) determined that 1,070 stems/ha of oak advance reproduction (≥1.4 m tall) were required for 30% of the stocking to be dominant oaks when stand quadratic stem diameter was 7.6 cm. This recommendation for adequacy of oak advance reproduction has been applied throughout the eastern United States as the standard for developing oak regeneration prescriptions. Although a useful starting point, the Sander et al. (1976) oak regeneration guideline often has been applied outside of its original ecological context without appropriate consideration of the following (Ward and Stephens 1999, Dey et al. 2009):

- differences in site productivity;
- variations in the suite of competing vegetation including both native and invasive species;
- differences in silvicultural prescriptions related to the type of regeneration harvest and control of competing vegetation;
- existing problems with disease, herbivory, or flooding; and
- differences in management objectives for stand composition and structure.

These factors along with chosen management practices alter the success probabilities of oak advance reproduction and thus, the number and size needed to meet future stocking goals and other stand objectives.

Several oak regeneration models have been developed for specific regions in eastern North America for natural or artificial regeneration and for use with certain regeneration methods. However, not all regeneration models are readily available to the public or easy for managers to use in assessing oak regeneration adequacy in actual stands. Spetich et al. (2009) have designed a website that allows managers to determine the number of seedlings needed to plant by simulating scenarios of planting northern red oak (*Quercus rubra*) bareroot seedlings by varying site index, planting stock size, shelterwood density, and number of treatments to control competing woody species. Dey et al. (1996) have developed computer software for predicting future composition and size distribution of natural regeneration of upland hardwood forests in the Missouri Ozark Highlands.[1] These models are region and management specific and thus should not be used outside of the geographic area or range of conditions under which the research was conducted.

After 100 years of study, we have learned enough about oak biology and ecology to build a sound knowledge base (e.g., Hicks 1998, McShea and Healy 2002, Johnson et al. 2002, 2009) for developing successful silvicultural prescriptions for oak regeneration (e.g., Roach and Gingrich 1968, Sander 1977, Brose et al. 2008). There still remains the challenge of getting what we know into practice, especially on private lands, and since the 1970s conferences to present knowledge on oak ecology and management have been offered (e.g., US Department of Agriculture 1971, Holt and Fischer 1979, Loftis and McGee 1993, Yaussy 2000, Spetich 2004).

The Regeneration Pillar

Oak Ecology and Silviculture

Acorn Production

Naturally, the oak regeneration process begins with acorn production and dispersal. Acorn production is highly variable among years, stands, species, and individuals (Johnson et al. 2009). Seedling establishment largely occurs in years of masting because seed predators are satiated by the plethora of acorns, e.g., >600,000 acorns/ha (Auchmoody et al. 1993, Johnson et al. 2009). Some of those seed predators such as blue jays (*Cyanocitta cristata*) and squirrels (*Sciurus* spp.) are important in the dispersal of acorns, and birds are capable of moving seed over long distances (e.g., up to 4 km) (Steele and Smallwood 2002).

Tree crown size, volume, mass, area, vigor, and health have all been recognized as important determinants of acorn production (Downs and McQuilken 1944, Christisen 1955, Sork et al. 1993). The major acorn producers in any stand are the dominant and codominant trees with the inherent potential for seed production that have large crowns exposed to direct sunlight. Acorn production has been shown to be highly correlated with tree diameter, which is a surrogate for crown size (Krajicek et al. 1961, Gingrich 1967, Lamson 1987). Downs (1944) and Downs and McQuilken (1944) reported maximum acorn production for five oak species to occur between 50 and 65 cm dbh beyond which production decreased with increasing diameter in the southern Appalachians. A similar pattern has been observed with acorn production and tree age in which yields reach a maximum that is maintained through much of adulthood, but production eventually declines in old age (Gysel 1957, Goodrum et al. 1971). Substantial acorn yields begin at about 40–50 years of age in eastern oaks (Burns and Honkala 1990). The age structure of oak forests in the central hardwood region (Shifley and Thompson 2011) and the northern United States (Shifley et al. 2012) is skewed toward being predominantly mature where 60–70% of the forests are 40–100 years old. Further, only 5–10% of oak forests are <10 years old, respectively, in these two regions, and this age structure is insufficient to sustain the oak resource in the productive, mature age classes. Therefore, oak forests will continue to get much older faster than they are regenerated.

Much of the eastern forests have been made more homogeneous in composition and structure from the extensive logging that took place over a relatively short period from 1850 to 1920 (Williams 1989). Oak species initially benefited from changes in land use during European settlement, but more recently Fei et al. (2011) quantified a decline in oak density and importance in a spatially explicit analysis of the eastern United States. In addition, Fei and Steiner (2007) reported a concurrent rise in red maple dominance throughout its range in the east. Schulte et al. (2007) reported a loss of diversity in canopy species and large-sized trees and simplified landscape compositions and structure in the Great Lakes States region, which included losses of oak in areas that were northern and mesic and had fine-textured soils. Hanberry et al. (2014) reported similar changes in Missouri Ozark forests, where average tree size has decreased and the landscape diversity of natural communities (e.g., savanna, woodland, and forest) has been diminished by increasing tree density and development of forest structure since the mid-1800s.

Currently, oak forests are at their peak capacity to produce acorns throughout the eastern United States, but continued forest aging over the next 50 years without sufficient oak regeneration to correct today's imbalanced age structure may cause a bottleneck in the oak regeneration process as acorn production declines in older stands (McGee 1986, Aldrich et al. 2005, McEwan and Muller 2006). This will occur first for species in the red oak group because they are not as long-lived as those in the white oak group, less shade tolerant and therefore less able to accumulate advance reproduction, and susceptible to mortality from oak decline (Burns and Honkala 1990, Fan et al. 2008).

In addition to having the ability to mast, i.e., produce a tremendously large crop of acorns periodically, oaks have a secondary strategy for regeneration in the ability to accumulate advance reproduction. An abundance of large, competitive advance reproduction can act as a buffer against variations in acorn production by ensuring that seedlings are in place to take advantage of any disturbance that would initiate regeneration. The density of oak seedlings and seedling sprouts in the understory of mature forests may range from a few thousand to as many as 250,000 per ha (Johnson et al. 2009). In general, acorn production and seedling germination are considered sufficient in healthy mature oak forests, and they are not the bottleneck in the oak regeneration process (Lorimer 1993).

Importance of Advance Reproduction

One thing is clear: in a wide range of oak ecosystems throughout eastern North America, sufficient numbers of large (e.g., >12-mm basal diameter) oak advance reproduction are required to sustain oak stocking into the future. The larger stems of oak advance reproduction have higher probabilities of future dominance after regeneration harvesting (e.g., Loftis 1990a, Dey et al. 1996, Belli et al. 1999). Commonly, the sizes of oak advance reproduction in mature forests are small, usually <20 cm tall and 4 mm in basal diameter and have low regeneration potential (Wendel 1980, Gottschalk 1994, Parker and Dey 2008, Johnson et al. 2009) or are absent altogether, especially on the more productive sites. Confounding this problem, the larger and older overstory oak have a lower capacity for producing vigorous sprouts once cut (Sander 1971, Loftis 1990a, Dey et al. 1996). Therefore, the oak regeneration potential is often low in unmanaged mature forests. It may take 20–30 years of active management to increase oak regeneration potential using natural regeneration to achieve management goals for oak stocking (Carvell and Tryon 1961, Clark and Watt 1971, Sander 1972). Few managers or landowners plan for oak regeneration this far in advance of harvesting, can afford the time or money investment to implement an oak regeneration prescription, or can sustain the long-term regime of practices necessary with changes in personnel or landownership.

Not Enough Light and Too Many Deer

Low light in the understory of mature forests is commonly cited as a major limiting factor to survival and growth of oak advance reproduction (Gardiner and Yeiser 2006, Parker and Dey 2008, Lhotka and Loewenstein 2009). Shortly after an acorn crop that results in establishment of a cohort of seedlings, that cohort of seedlings diminishes to near extinction where understory light levels are below the light compensation point for the oak species (e.g., a cohort of northern red oak seedlings may linger for about 10 years) (Beck 1970, Loftis 1983, Crow 1992), thus preempting the accumulation and development of large oak advance reproduction (Johnson et al. 2009). In addition, high deer populations in many areas limit development of advance reproduction. In Pennsylvania, high stumpage prices for black cherry allow foresters to afford fencing to exclude deer and protect forest regeneration. In most other areas, the cost of fencing is prohibitive. Reducing deer densities by hunting is probably the only realistic and long-term solution; however, its effectiveness is being eroded by changing demographics and reduced numbers of hunters, urbanization of rural landscapes, animal rights interest groups, and hunter resistance to changes in game management policies (Brown et al. 2000).

Oak Silviculture to Promote Regeneration

Advance reproduction is still considered the key determinant of oak regeneration success in most mature forest situations because new seedlings that establish after the regeneration harvest cannot compete with other vegetation, and the stump sprout capacity of older (e.g., >80 years) and large diameter (e.g., >20 cm dbh) oak trees is low (Johnson 1977, Johnson et al. 2009, Weigel et al. 2011). Because not all stumps sprout, there will be a decline in oak stocking in the new stand without competitive stems from the pool of oak advance reproduction. Reliance on oak stump sprouting to sustain current oak stocking (Gingrich 1967) is a failed strategy except when young stands are harvested frequently for coppice regeneration as was done in the era of charcoal production in the eastern United States (Williams 1989, Dey 2002). In many current stands originating from clearcutting, stump sprouts comprise anywhere from 50 to 75% of the basal area in oak that is free to grow or in dominant positions (Beck and Hooper 1986, Gould et al. 2002, Morrissey et al. 2008). This is evidence of a lack of sufficient competitive oak advance reproduction in mature forests that are regenerated by clearcutting. Failure of oak advance reproduction to contribute to stocking at maturity is higher on the more productive sites, which makes stump sprouts the predominant source of oak in the new stand.

Regeneration Methods

Promoting development of oak advance reproduction requires active management. *Quercus* is a disturbance-dependent genus (Carvell and Tryon 1961, Dey and Guyette 2000), so passive management, as is used in old-growth, oak-mixed hardwood forest reserves, consistently leads to succession toward the more shade-tolerant species with a loss of oak stocking over time (McGee 1986, Aldrich et al. 2005, McEwan and Muller 2006). Even in secondary oak-mixed hardwood stands where fire and silvicultural treatments are excluded, succession away from oak dominance is a widespread phenomenon (Goebel and Hix 1997, Fei and Steiner 2007, Oswalt et al. 2008).

Clearcutting has been successful in regenerating oak on sites of average or lower productivity, e.g., ≤21.4-m oak site index in the Ohio Valley (Hilt 1985, Ward and Stephens 1999, Groninger and Long 2008) when there has been a sufficient number of large oak advance reproduction to complement any oak stump sprouting. Oak regeneration success has also occurred when competing vegetation in the understory was effectively controlled before clearcutting, and there was a bumper crop of acorns to add to the regeneration pool (Johnson et al. 1989). However, clearcutting on productive sites (e.g., oak site index >21.4 m) usually accelerates succession to a mix of shade-tolerant species from large advance reproduction and fast-growing shade-intolerant species arising largely from seed or young advance reproduction (Hix and Lorimer 1991, Morrissey et al. 2010b, Schweitzer and Dey 2011). Oak regeneration has not fared any better in group selection openings on productive sites where competing vegetation was not controlled and large oak advance reproduction was missing (Smith 1981, Weigel and Parker 1997, Jenkins and Parker 1998), even when oak was planted as bareroot and large container seedlings (Morrissey et al. 2010a). Consequently, the shelterwood method of regeneration became widely recommended as a means of building populations of larger oak advance reproduction and as an alternative to clearcutting on mesic productive sites. The benefits of regenerating oak by the shelterwood method include the following (Loftis 1990b, Schlesinger et al. 1993, Teclaw and Isebrands 1993, Johnson et al. 2009):

- increased available light and soil moisture in the understory after stand density reduction;
- flexibility to vary residual stand density to provide resources to desired reproduction depending on their needs;
- ability to control competition from shade-intolerant species with higher density shelterwoods; and
- protection of reproduction from environmental extremes such as high soil and air temperatures, high atmospheric evaporative demand, or frost.

The initial use of the shelterwood method to naturally regenerate oak produced mixed results. Successful results were attributed to an abundance of oak advance reproduction, control of understory and midstory woody vegetation and vines by site preparation or use of more dense shelterwoods, harvesting on medium and lower quality sites, and control of undesirable stump sprouts by herbicide application at harvest (e.g., Loftis 1990a, Schlesinger et al. 1993). Where it failed, the shelterwood was created by cutting the overstory to a target residual density with no effort to control competing vegetation, oak advance reproduction was either small or absent, and deer browsing was a persistent problem (Gordon et al. 1995, Harmer et al. 2005, Schweitzer and Dey 2011). Short-term improvements in oak growth and survival have been reported after shelterwood harvesting, but this came with a concomitant significant increase in competing vegetation, especially where harvest intensity was high. In the long term, many attempts to regenerate oak by only harvesting the overstory using the shelterwood method resulted in failure and dominance by other species (Rudolph and Lemmien 1976, Lantagne et al. 1990). Promising results are being reported for regenerating oak by combining thinning or shelterwood harvesting with prescribed burning to control competing vegetation (Brose et al. 1999a, 1999b, Albrecht and McCarthy 2006, Iverson et al. 2008a). Because forest regeneration is a process, not an event (Clark 1993), it may take from 10 to 30 years to develop sufficient numbers of large oak advance reproduction using the shelterwood method to promote natural regeneration (Carvell and Tryon 1961, Clark and Watt 1971, Sander 1972).

Role of Prescribed Fire

The use of prescribed fire in oak silviculture is a relatively recent phenomenon. Although fire is a logical tool in oak forest management because of its long history and positive association with oaks, the use of fire has been delayed because of long-standing traditions in forestry to suppress wildfires. This resistance to using fire in hardwood forests is justified, given the history of destructive wildland fires in eastern forests. Throughout the east, it was widely reported in the mid-20th century that 50% or more of the hardwood timber was cull (i.e., not capable of producing a veneer, sawlog, or pulpwood product) (Kaufert 1933, Gustafson 1944, Burns 1955). Wildfires were the primary cause of loss of timber product potential and value. After about 75 years of fire suppression, therefore, we are seeing substantial improvements in the quality of timber in the East, where the percentage of total net volume that is live cull has dropped to a range of 6 to 15% across the Midwest and South (Smith et al. 2009). However, we are now realizing that there were negative ecological consequences from excluding fire entirely from forests that include increases in forest density, loss of biodiversity, and increases in oak regeneration problems.

Fire applied at the wrong time in stand development can scar young saplings, poles, and small sawtimber, which over decades can develop extensive decay in the butt log. This has a significant influence on the value of trees and forest stands because the butt log contains most of a tree's volume and is the log with the greatest value potential due to its size (Stambaugh and Guyette 2008, Dey and Schweitzer 2014). However, fire historically has favored the widespread dominance of oak. By definition, prescribed fires are conducted under controlled conditions and judiciously applied to achieve specific management objectives; hence, they may not necessarily be as destructive as historical wildfires. So the question is, can prescribed fire be used to favor oak as part of a silvicultural system to sustain oak forests without causing unacceptable damage or value loss?

Arthur et al. (2012) provided a comprehensive and reasoned synthesis on the role of fire in sustaining oak forests based on oak biology and ecology. They identified several stages of stand development and times in the life cycle of an oak when fire could benefit oak regeneration, and the equally important times that fire must be suppressed to permit oak recruitment into the overstory. Single fires have little long-term benefit to oak (Brose et al. 2013), but in mature forests that lack oak advance reproduction, multiple fires can be a benefit by reducing thick litter layers, controlling competing vegetation, reducing competitor seed banks, and increasing light at the forest floor by eliminating midstory saplings and understory woody competition. Brose et al. (2008) refer to this as "site preparation burning," making the site ready for the next good acorn crop and promoting seedling establishment.

A large portion of the acorn crop, and any young, smaller oak seedlings are still vulnerable to fire mortality (Johnson 1974, Auchmoody and Smith 1993). With increasing stem diameter and root development, oak seedlings rapidly gain an ability to persist by sprouting after fire, increasing in their ability to compete over time (Brose et al. 2013). Low-intensity fires are effective for managing the mid- and understory vegetation, but higher intensity fire or combining fire with timber harvesting is needed to increase available light to moderate levels (i.e., >30% full sunlight) by reductions in overstory density. Vigorous oak advance reproduction can develop in large group openings, or under shelterwoods when managed with periodic fires (Hutchinson et al. 2012, Brose et al. 2013).

In shelterwoods, after the final overstory trees are removed, or in clearcuts, fire is effective for suppressing competing vegetation and maintaining oak as long as diameters of competing stems do not exceed the ability of low-intensity fires to topkill the reproduction. Once oak reproduction is large enough (e.g., >1.3-cm basal diameter) to survive higher fire intensities, hotter fires in the early growing season can increase oak's relative abundance and ability to be dominant in the regeneration (Brose et al. 2013). This cycle of regrowth after each fire can be repeated to incrementally improve oak's competitiveness to the point that it is ready to recruit into the overstory. After each fire, an assessment of the competitive status of desired species is a necessary step to determine whether another fire is needed and when.

If a sufficient number of competitive oaks have been cultivated, there then needs to be a sufficiently long fire-free period to permit them to recruit into the overstory, perhaps 10–30 years long, depending on the source of oak reproduction, site quality, competing vegetation, and growth rates of reproduction (Dey and Fan 2009, Arthur et al. 2012). Long-term retention of partial overstories reduces oak growth and prolongs the time needed for individual oak trees to grow large enough to be able to resist complete shoot dieback if there is a subsequent fire for other resource reasons (Larsen et al. 1997, Green 2008, Dey et al. 2008). The less shade-tolerant oaks such as black oak (*Quercus velutina*) and scarlet oak (*Quercus coccinea*) are more affected by increasing partial overstory density than is white oak (*Quercus alba*) (Arthur et al. 1998, Groninger and Long 2008, Kabrick et al. 2008).

The Recruitment Pillar

Successful oak regeneration that culminates with what appears to be a satisfactory stocking of oak at the beginning of the stem exclusion stage (i.e., stand crown closure) does not negate the need for active management to achieve oak stocking goals in mature forests. It may be considered the end of regeneration, but competitive dynamics during the process of recruitment into the overstory can reverse any regeneration successes. On more xeric sites of average or lower site quality, oaks have a better chance of rising to dominance in maturing stands without silvicultural intervention (Hilt 1985, Morrissey et al. 2008). However, on higher quality sites and when competing with vigorous growing species such as yellow-poplar, oaks can be suppressed and diminish in the stand. Ward and Stephens (1994) observed that about 75% of northern red oaks in the dominant crown class in 25-year-old stands developing from clearcuts in Connecticut were able to maintain their competitive position for the next 30 years, about 60% of codominant oaks died or dropped into lower crown classes, and most of the intermediate and suppressed crown class oaks died. Most trees in upper canopy positions in mature forests have been in those positions since crown closure in the stem exclusion stage (Wang and Nyland 1996). Many oaks in the upper canopy at crown closure will die or drop into lower crown positions without release from competition (Ward 2009). Zenner et al. (2012) determined that dominant northern red oaks in clearcut stands that were 23–36 years old, i.e., well into the stem exclusion stage, were never more than 2 m shorter than their competitors, and those dominant chestnut oaks (*Quercus prinus*) were never shorter than 1 m than the competition. They recommended that thinning be done at the time of crown closure to maximize oak stocking and the proportion of oak in the dominant crown class. In most situations, this would be a precommercial thinning.

Investing in precommercial thinning in a young stand may not always be financially rewarding, but there is a potential for positive returns when the proportions of high-value species and high-quality trees are increased in the stand through, for example, crop tree release (Miller et al. 2007). The greatest gains can be made in thinning stands where desirable species and quality saplings will be suppressed by low-value competition during the stem exclusion stage of stand development. Careful consideration must be given to each stand to assess the benefit of investing in stand improvement for which the cost will be carried for decades until a commercial harvest is possible.

At stand maturity, there are a relatively few number of trees (~125 trees/ha) in the dominant and codominant crown classes (Miller et al. 2007) in eastern hardwood forests. Thus, when a stand enters the stem exclusion stage, a release of a relatively small number of crop trees per hectare can increase the chance that most of the dominant/codominant trees in a stand are desirable crop trees at maturity. This will substantially increase the value of the stand at maturity compared with that of an unmanaged stand. Crop trees are commonly defined by species, stem form, growth rate, vigor, freedom from disease, and other desired characteristics. Thinning around individual oak crop trees where their crowns are released on all sides maximizes oak stocking at maturity. It is important to maintain oaks in dominant crown positions throughout their development in most competitive associations to provide the greatest flexibility for adjusting oak stocking at maturity. Ward (2009) evaluated the long-term benefits of precommercial crop tree release of northern red oak in stands in the stem exclusion stage in Connecticut. He found that complete release from competition (removal of any tree within 1 m of the crop tree crown) increased survival in intermediate and codominant oaks and doubled the proportion of codominant oaks that were able to persist in the upper canopy. Few intermediate oaks were able to recruit into the upper canopy without thinning, but crown release increased the ability of these oaks to ascend into the upper crown classes. Crop tree release significantly increased diameter growth in dominant and codominant oaks. Ward (2009) concluded that a single crop tree release at the stem exclusion stage could nearly double the probability that a codominant oak sapling would be in the upper canopy of a mature stand at age 85. Other benefits of thinning in developing oak forests have been demonstrated by Healy (1997), who found that acorn production of individual oaks was increased after stand basal area was reduced by 50% through removal of nonoaks and thinning from below in 40-year-old forests in Massachusetts. Thinning did not reduce stand-level acorn production capacity in years of good production compared with that in unthinned stands, but it did increase production in years of low acorn production. Thus, early intervention by thinning to release oak saplings from competition can substantially increase oak stocking at maturity and has additional benefits that include increased acorn production for regeneration and food for wildlife.

Current and Future Challenges

Invasive Species: Diseases

Introduction of invasive species will increase substantially in the future as trade and human traveling continues to increase worldwide. Nonnative species that have become invasive in the United States have caused substantial ecological and economic damage (Corn et al. 1999, Pimentel et al. 2005, Aukema et al. 2011). In the eastern forests, chestnut blight and Dutch elm (*Ophiostoma ulmi*) diseases have caused the respective loss of American chestnut and American elm (*Ulmus americana*) as mature trees in forests. In these cases, not all the effects of invasive species were detrimental to oaks. For example, Elliott and Swank (2008) reported that historically oaks benefited from the decline of American chestnut by being released to recruit into the overstory and become canopy dominants. However, stand conditions are different today with the increase in stand density and development of shade-tolerant mid- and understories in many forests. Now, when single-tree gaps and small openings (e.g., <0.2 ha) are created by the death of overstory trees, the shade-tolerant species are released to recruit into the overstory.

Other diseases do attack oaks directly, causing mortality and threatening oak's dominance in eastern forests. Since the 1990s, sudden oak death, caused by the introduced fungus *Phytophthora ramorum*, has been spreading along the west coast of North America, resulting in widespread mortality in oak and tanoak (*Lithocarpus densiflorus*) species (Rizzo and Garbelotto 2003, Frankel 2008). It is now established in the East, where it threatens to cause sudden death in eastern oak species (Moser et al. 2009, Grünwald et al. 2012). There are at least 16 forest pathogens that pose serious threats to eastern forests (Aukema et al. 2010). Another endemic health issue in oak forests is oak decline, a natural phenomenon of periodic high levels of mortality of mature oaks, especially in the red oak group, caused by a drought-disease-insect complex of vectors that reduce the vigor of trees and cause crown dieback and eventual death.

Invasive Species: Insects

Insects are equally threatening and currently there are at least 455 introduced forest insect species in the United States (Aukema et al. 2010). Gypsy moth (*Lymantria dispar*) is spreading throughout the East, threatening a host of preferred species that includes the oaks. Gypsy moth defoliations reduce tree growth, decrease acorn production, and cause mortality over extensive areas during cyclical outbreaks (Davidson et al. 1999, Lovett et al. 2006). Stressed oak trees may die after a single defoliation. The death of canopy-dominant oaks is accelerating succession to more shade-tolerant species such as red maple and sugar maple (Fajvan and Wood 1996). Since its introduction in New England in 1869, gypsy moth now occupies a range that encompasses the Northeast, North Central, and Mid-Atlantic states.

Emerald ash borer (*Agrilus planipennis*) is another invasive insect that is getting a lot of attention. It began spreading from the Detroit, Michigan, area in the 1990s, causing extensive mortality in all ash species (*Fraxinus* spp.) (Haack et al. 2002, Cappaert et al. 2005, Miles 2013). Ash occurs as an associate species in upland oak forests. Its loss will create single-tree and small group opening gaps in the canopy, which will act to release any shade-tolerant mid- and understory trees and help promote a species shift in the overstory away from oak. If the current rate of spread continues, then the insect will inhabit the entire range of ash in eastern North America by 2050 (DeSantis et al. 2013).

Invasive Species: Plants

There are an estimated 5,000 nonnative plant species that have established themselves in natural ecosystems in the United States (Pimentel et al. 2005). About 300 of those are considered troublesome invasive species in Eastern forests and grasslands, of which approximately 50 are critical threats (Miller et al. 2013). In the southern United States, 23 of the world's top 100 worst invasive plants occur (Oswalt and Oswalt 2011). There are several good reviews of the major invasive plant species in eastern North America (e.g., Miller et al. 2010a, 2010b, Kurtz 2013).

Many invasive plant species prosper in more open environments, so regeneration methods that reduce stand density substantially, such as group selection, shelterwood, and clearcut, provide opportunities for invasive plants to colonize a forest site or act to release isolated populations that have persisted along roadways, stream corridors, old log landings, and other forest clearings (Rebbeck 2012). A common recommendation today is to combine prescribed burning with shelterwood or group selection harvesting to favor oak (Brose et al. 1999a, 1999b, Brose et al. 2008, Hutchinson et al. 2012). Combinations of thinning, harvesting, and prescribed burning create favorable environments for many invasive species to germinate and proliferate (Phillips et al. 2013). Natural disturbances that cause high levels of mortality in canopy trees such as oak decline or insect outbreaks can also trigger rapid expansion of invasive species.

Fire is able to control some invasive species, but it promotes the expansion and dominance of others (Rebbeck 2012, Miller et al. 2013). Much of a species' response to fire depends on plant life stage, available sources of reproduction, competing vegetation, and the fire regime, i.e., intensity, season, and frequency (Huebner 2006). We lack knowledge of fire effects and the proliferation of invasive species; thus, caution must be used in the selection of silvicultural practices to favor oak regeneration and recruitment. Consideration of the physiology and ecology of the key species, in the context of the natural communities being managed, can help to design reasonable prescriptions. Commitment to monitoring and the flexibility to adapt management approaches and practices are essential to success, given that we lack detailed information on many invasive plant species.

Several native plant species can also become detrimental to oak after regeneration treatments. For example, several native ferns such as bracken (*Pteridium aquilinum*), hayscented (*Dennstaedtia punctilobula*), and New York (*Thelypteris noveboracensis*) may proliferate after harvesting and burning (Engelman and Nyland 2006). They can form dense mats of vegetation that cast heavy shade on young seedlings, perhaps inhibit tree regeneration through allelopathy, and physically prevent germination or obstruct small seedlings. These ferns have adaptations that allow them to proliferate after fire, especially when stand density has been reduced to increase available light in the understory. Fern spores in the forest floor and rhizomes buried in soil are able to survive prescribed burns that typically are low intensity and initiate new growth and expansion of ferns in more open environments. Dense fern beds can persist for long periods if they are not treated. High deer populations that overbrowse understory shrubs and tree reproduction can cause fern cover to increase substantially (Horsley and Marquis 1983, Fredericksen et al. 1998, Engelman and Nyland 2006). Other native trees, shrubs, and vines can interfere with forest regeneration and inhibit development of oak seedlings.

White-Tailed Deer Herbivory

Estimates of historical white-tailed deer density range from 2 to 4 deer/km^2 (Rooney 2001). Deer populations have rebounded from all time low levels in the early 1900s (Russell et al. 2001, Rooney 2001). In much of the East, deer densities are $>$10 deer/km^2, and populations in excess of 17 deer/km^2 occur in the Lake States and in an arc that stretches from Texas through the Mid-South to Virginia and Pennsylvania. Deer populations are now high enough that they can cause complete failures of all forest regeneration.

In Pennsylvania and the Mid-Atlantic region, Brose et al. (2008) anticipate shifts in forest composition away from oak-mixed species when deer densities exceed 14 deer/km^2 in landscapes with high food availability, i.e., where forests are interspersed with farmland. In areas of low deer food availability such as large expanses of mature forests, deer densities $>$5 deer/km^2 cause forest compositional shifts and $>$12 deer/km^2 may result in regeneration failure. This situation is not expected to change in the near future. There are few solutions to the deer herbivory problem except to protect tree regeneration from deer, which is expensive, or to reduce the number of deer to levels commensurate with available food supplies and compatible with regeneration goals. In forested landscapes dominated by mature forests, cutting larger areas using even-aged methods may reduce browse pressure on desirable reproduction by promoting browse production to satiate herbivores, providing hiding cover for seedlings and sprouts, and delivering resources for rapid growth.

Will Climate Change Favor Oaks?

In the eastern United States, predictions of 134 tree species' potential suitable habitat in response to a range of emission scenarios and climate models have been made by Iverson et al. (2008b). Their simulations considered many physical properties of location and site for each combination of emission scenario and climate model in determining whether the habitat would be suitable for a species. In general, they found that the potential habitat for most species moves northeastward up to 800 km in the hottest climate change simulation. Similar predicted shifts northward in latitude have been reported by McKenney et al. (2007), who modeled the change in species distributions to climate change scenarios for 130 North American tree species. Iverson et al. (2008b) concluded that the potential habitat for half of the species studied may increase by at least 10%, whereas some species will increase in importance by at least 50%, including commercially valuable oaks and pines. Another prediction that is favorable for the future of oak is that many of its northern, mesophytic competitors, species such as the aspens, birches, striped maple (*Acer pensylvanicum*), and sugar maple, are predicted to decline with climate change.

Both Hilt (1985) and Morrissey et al. (2008) have observed the emergence of oak in regenerating stands on more xeric sites of lower productivity in southern Indiana and Ohio. Here, yellow-poplar is a major competitor that often dominates in former oak stands after clearcutting. Morrissey et al. (2008) attributed the rise in oak dominance to periodic severe droughts that decreased the relative density of the less drought tolerant yellow-poplar, thus releasing the oak early in the stem exclusion phase of stand development. A similar dynamic may favor oak where red maple is a major competitor because oaks are more drought tolerant than maples. Cycles of severe drought every 20 years or less would be timely enough to favor oak before it is lost from a regenerating stand during the stem exclusion stage. Although there is variation in drought tolerance within the genus *Quercus*, oaks are relatively more tolerant than their competitors; however, they are also generally intolerant of shade. Therefore, the regeneration opportunity for oak is largest on xeric sites where available light is inherently higher due to site restrictions on stand density and structure (Hodges and Gardiner 1993). Future climates that include more frequent or severe droughts will favor oak competitiveness during regeneration, especially on current mesic sites. Finally, changes in climate that include higher mean annual temperatures or reductions in precipitation may increase the potential for fire in the future (Guyette et al. 2012), resulting in a longer burning window and facilitating the use of prescribed burning to favor oak. Because drought is the main predisposing agent in oak decline, future increases in drought occurrence and severity may increase catastrophic mortality in mature oaks, particularly for red oak species. This would reduce the oak regeneration potential by reducing acorn production and stump sprout contributions to regeneration.

Social Challenges to Oak Management

Although we have made great progress developing the environmental science of oak forest management, the greater challenge is a social one. We lack a good understanding of how landowners make decisions given their (1) perceptions on oak conservation and management, (2) knowledge base and understanding of ecology and conservation at stand and landscape scales, (3) views on tradeoffs and risks, and (4) sensitivity to external factors such as public policy, parcelization, and development of surrounding lands and education.

Serious efforts to sustain oak on the landscape requires the participation of private landowners, who own most (~83%) of the forestland in the eastern United States (Smith et al. 2009). Currently, most landowners are not concerned with regenerating oak, and the expectation is that the oak resource will decline regionally because of this (Knoot et al. 2010). Getting landowner commitment to adopt the recommended silvicultural prescriptions may be difficult. Knoot et al. (2010) surveyed natural resource managers in the Midwest to better understand the ecological and social dimensions of oak conservation that influence the willingness of landowners to adopt practices for oak restoration and management. They found that there are personal tradeoffs and risks that dissuade landowners from adopting sustaining oak as a goal and that there are multiple ecological and social factors that inhibit the implementation of practices needed to promote oak. Personal tradeoffs that exceed the perceived benefits of having oak include concerns for negative aesthetics associated with oak practices (i.e., clearcutting and burning), the amount of personal investment required to implement oak prescriptions, and conflicts among land management objectives (e.g., cutting and burning versus recreation and aesthetics). The ecological drivers of oak regeneration failure such as deer herbivory, competing vegetation, and high site productivity increase the time and financial investment required by landowners to regenerate oak. Recommended repeated treatments often produce few to no revenues; their costs must be carried for years before being offset with income from commercial thinning and harvest. Intangible environmental, conservation, or ecological benefits are not always known by the landowner, and they are not considered in decisionmaking. Often, on better quality sites, there are desirable alternatives such as managing for maple that are simpler and more profitable than managing for oak, and the uneven-aged silvicultural methods used in maple management are more amenable to other land uses and landowner objectives.

The trend toward fragmentation and parcelization of the forest landscape often inhibits the adoption of oak conservation goals and practices. In the East, 90% of forestland owners have <20 ha and collectively they own 31% of forestlands (Butler and Leatherberry 2004). Oak management is hampered because it is often difficult to interest loggers in bidding on small forest parcels (Knoot et al. 2010). In areas of residential development, access to forest parcels can inhibit harvest operations. Utility lines, septic systems, and other improved developments can be barriers to logging operations. The entire property becomes the landowner's backyard, and he or she is less willing to tolerate shelterwood or clearcutting harvests that remove much of the overstory. Neighborhood forestry co-ops may be one way to overcome some of these barrier to oak management.

Changes in public laws and policies are needed to encourage the use of practices for oak restoration and management. However, treatments such as prescribed burning or changes to deer hunting regulations are often met by resistance from interest groups, have public safety or health issues, or are hampered by liability concerns. Until these barriers are resolved, managers and landowners are limited in the tools they can use to overcome some of the major drivers of oak regeneration failure. Public cost-share programs have been successful in getting landowners to manage for oak (Knoot et al. 2010). However, priority may need to be given to the most promising properties and most willing landowners to efficiently use limited funds for oak restoration. Cost-share program policies and regulations need to specifically promote oak management and the full suite of practices that give maximum flexibility to landowners to integrate them into their overall management goals and ensure that they are compatible with their values. Multiyear treatments need to be accommodated to permit combinations of repeated prescribed burning, herbicide application, and harvesting.

What is often lacking in the public debate is a general awareness and understanding of the economic and ecological benefits of sustaining oak forests and how they are relevant to the general public's welfare and standard of living. Landowners do not always understand why they should make the investment in oak management. The role of their land in the greater landscape and the value they place on intangible benefits can influence landowner willingness to invest in oak management. Education to increase landowner awareness, knowledge, and appreciation for how their property contributes to the greater ecological integrity of the neighborhood, watershed, and region can increase their willingness to adopt new conservation objectives and practices (Gobster 1999, Knoot et al. 2010). New methods of communicating and more effective messages are needed to convey the latest science in a relevant way to landowners.

Planning for sustaining or restoring oak takes a long-term perspective and commitment that many landowners may not have. Short-term tenure of private landownership complicates the implementation of long-term silvicultural prescriptions and forest management plans. Even in public agencies, long-term commitment to a strategy for oak restoration and management is not certain. An upwardly mobile and shifting workforce reduces local manager tenure and continuity in commitment to oak management. One-on-one contacts and long-term personal relationships between natural resource professionals and landowners is critical to education and acceptance of oak conservation goals and practices (Knoot et al. 2010). Mobility in the professional workforce, shifting agency priorities, and changing land ownerships make it hard to develop relationships that foster trust and acceptance. Prioritizing properties and landowners and spending time to get to know their land and them may be the best approach, given these constraints in time and longevity of relationships. A break in the chain of practices to maintain oak in positions of dominance can result in failure of the whole process at the stand level and that impact ripples through the landscape, changing its character. The pillars of sustaining oak forests, i.e., regeneration and recruitment, must be built on the solid ground of ecological and social principles established by science to sustain oak over a varied and large landscape such as eastern North America.

Conclusions

Oaks have long had a presence on this continent, and they will continue to be an important member of forests in the future landscapes of North America. Over the millennia, their distribution and dominance has ebbed and flowed with changes in climate, herbivore populations, wildland fire occurrence, and human land use. Currently, the trend has been a contraction in oak forest distribution and oak dominance due to changes in historic disturbance regimes (Fei et al. 2011, Hanberry et al. 2012, 2014). Most prominent of these changes have been the suppression of fire from the eastern landscape and the adoption of land use practices that cause small-scale disturbances in forest canopies. This has given the advantage to shade-tolerant species under gap-phase replacement disturbance regimes or to pioneer species when stand replacement events occur because the oak regeneration potential is currently low in most forests.

The range of anticipated climate changes predicted by the plethora of models offers some hope for oak managers because most of the oak species have the potential to increase in their distribution in the face of weakened competition. However, climate merely sets broad sideboards for where species may occur; it is site-specific land-use practices that create regeneration opportunities and alter the competitive dynamics among species to favor oak. That is why the USDA Forest Service (2012) 2010 Resources Planning Act Assessment concluded that climate change is not a serious risk to the forest estate or the production of commodities in the near future; rather changes in land use, and, in particular, forest conversion to other uses are responsible for the greatest loss of forests. Forests are inherently resilient and buffered from major shifts in tree composition due to changes in climate. The major tree species such as white oak, black oak, northern red oak, sugar maple, red maple, and yellow-poplar have large natural ranges that encompass a broad climate spectrum over changes in latitude or elevation (Burns and Honkala 1990). Whether any species is dominant locally is determined more by disturbance regimes, site factors, and competitive relations than by climate within the natural range of the mix of species, albeit there is some expectation that ranges will shift slightly in most climate change scenarios.

The decrease in oak regeneration potential must be reversed through active management using combinations of fire, thinning, and timber harvesting. It is imperative to address this now while there still is an adequate source of acorns for natural regeneration. Once the capacity to produce acorns is diminished or lost, the integral base of the regeneration pillar will be irreparably damaged. Under current forest conditions, dominant seed-bearing oaks afford the opportunity to cultivate oak regeneration and to manage its recruitment into the overstory to sustain oak stocking at desired levels. Cost-effective silvicultural prescriptions are needed and landowners need encouragement and knowledge on implementing best management practices for sustaining oak forests.

We have learned much about the biology and ecology of oak in the past 100 years. Although we still have much to learn about the details of implementing silviculture to sustain oak, there is sufficient knowledge to develop strategies and design prescriptions for oak. We know a lot about a few of the more commercially valuable oak species, but there are many other oak species we know little about. We are challenged to find ways to use fire to favor oak regeneration without causing forest damage and devaluation, or exacerbating the spread of invasive species.

Future Directions

Although we have reaped the rewards of a century of research on oak in the form of a substantial body of knowledge that enabled us to move forward on restoration and sustainable management of oak ecosystems, there is still a great need for continued research in the management of this most significant forest type. I proffer a few examples, which in no way is an exhaustive list of priority needs.

The greatest progress in oak ecology and silviculture has come from long-term research, and scientist careers devoted to study of the subject. The need is still strong for long-term research in oak biology, ecology, silviculture, and management. It takes decades for stands to progress through the stages from regeneration to maturity and hence for the final outcomes of stand dynamics resulting from timed sequences of specified silvicultural practices. Innovative practices and their combinations need to be tested in time and space in long-term replicated experiments across the gradient of diverse ecological units. Long-term studies are instrumental in identifying critical size thresholds by reproductive origin that are linked to probabilities of successful regeneration or recruitment outcomes. These data can be used to calibrate local and regional models of regeneration and recruitment.

Short-term studies are also important to discover the basic ecophysiology of the myriad of oak species and their competitors because it is affected by changes in microclimate wrought by practices that alter the structure and composition of vegetation, evaluate wildlife response to the silviculture of oak management and restoration, determine the value of intangible goods and services provided by oak ecosystems at the population, watershed, and landscape scales, and assess the social attitude toward silvicultural practices and their outcomes. Studies need to be more integrated across disciplines and consider synergistic interactions and multidimensional outcomes.

Models of regeneration and recruitment that generalize processes and include major drivers of ecosystem trajectories, but allow for regional calibrations of key parameters, need to be developed, with the addition of modular components to accommodate regionally relevant drivers of oak establishment and development.

Models are needed for the restoration and maintenance of oak woodland and savanna ecosystems. Desired future conditions of oak ecosystems need to be quantitatively defined at appropriate scales (i.e., genetic to population and community to landscape), for a diversity of key ecosystem components, and at critical stages along the path of restoration and maintenance of sustainable oak systems. A better understanding of the range of natural variation in key response variables is needed. Desired future conditions need to account for the uncertainties of climate change, threats from invasive species, changes in demographics and social values, needs and wants, and changes in markets from local to global. Management guidelines are needed for oak forest, woodland, and savanna ecosystems. Monitoring is needed to support adaptive management.

Social research needs to be conducted to better understand perspectives of private forest owners, how they view their lands and recognize and value goods and services from their lands, and what drives their adoption of best management practices and new silvicultural practices for oak management and restoration. Affordable prescriptions are needed for restoration and sustainable management of oak ecosystems. This implies not only that the silvicultural systems be effective and efficient but also that we need to explore new markets and products to improve the financial balance. We need public policy that promotes the goals of conservation and sustainable management of oak ecosystems and that facilitates the use of the array of silvicultural tools needed to give managers the flexibility to restore and maintain quality oak systems. Existing policies that are counterproductive toward these ends must be identified and modified or ended.

Endnotes

1. See www.ncrs.fs.fed.us/4154/products/acorn.html.
2. See the Quality Deer Management Association deer density map available at www.qdma.com/corporate/about.

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