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Underplanting to sustain future stocking of oak (*Quercus*) in temperate deciduous forests

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Abstract Oaks (*Quercus* spp.) are one of the most important tree taxa in the northern hemisphere. Although they are dominant in mixed species forests and widely distributed, there are frequent reports of regeneration failures. An adequate population of large oak advance reproduction is a critical prerequisite to successful oak regeneration, and hence sustainability of oak. But, many oak forests lack sufficient density of large and competitive oak advance reproduction. Artificial regeneration of oak by underplanting is done to supplement natural populations of oak seedlings or to introduce oak in stands where it is missing. Planting high quality seedlings is important. Silvicultural practices that regulate stand density such as thinning and the shelterwood method are needed to increase oak's regeneration potential by promoting accumulation and growth of natural and planted seedlings before the final regeneration harvest. Control of competing vegetation and herbivory are important elements in the regeneration prescription. Light in the understory is a limiting factor to the accumulation of large oak advance reproduction. Light levels (20–50 % +) sufficient for biomass production in oak reproduction result through management of stand density and other competing vegetation. We review and synthesize the literature on silvicultural approaches to using artificial regeneration to obtain successful oak regeneration that is grounded in fundamental principles of oak biology and ecology. Principles of oak regeneration presented here may also have relevance to other hydric, mesic and dry-mesic forest environments.

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Introduction

This review of oak (*Quercus* spp.) regeneration by the method of planting seedlings under an existing forest or plantation cover (underplanting) includes research that is focused on relatively few species such as northern red oak (*Q. rubra* L.), white oak (*Q. alba* L.), black oak (*Q. velutina* Lam.), cherrybark oak (*Q. pagoda* Raf.), scarlet oak (*Q. coccinea* Muenchh.), pin oak (*Q. palustris* Muennch.), swamp white oak (*Q. bicolor* Willd.), Nuttall oak (*Q. nuttallii* Palm.), chestnut oak (*Q. prinus* L.), penduculate oak (*Q. robur* L.) and sessile oak (*Q. petraea* Liebl.). The emphasis on these species is related to their economic and ecological value, and because they account for most of the standing volume of oak in their natural ranges. What we know of their biology, ecology and management is of value to managing and conserving other oak species to the extent we know how they are similar in their physiology and silvics.

The artificial regeneration of oak by planting seedlings has been largely applied in afforesting agricultural crop lands and pastures (e.g., Jacobs et al. 2005; Kabrick et al. 2005; Dey et al. 2008a; Gardiner et al. 2010). Natural reproduction has been and will continue to be the primary means of regenerating hardwood forests in eastern North America and elsewhere throughout the temperate deciduous forest region. Although artificial regeneration of oak is increasing in use to convert conifer plantations back to native oak-mixed species forests in Europe, Canada and the United States (Buckley et al. 1998; Beck 2000; Parker et al. 2001; Kenk and Guehne 2001; Löf et al. 2007; Noack 2011). Strategies to enhance or accelerate the development of oak advance reproduction by planting seedlings in the understory have been promoted as a means of ensuring that adequate advance reproduction is present at the time of stand regeneration (Sander et al. 1976, 1984; Dey et al. 1996). This paper provides a synthesis of the use of underplanting practices to sustain or restore oak stocking in future stands.

The importance of oak advance reproduction

Oak has been a dominant genera in much of its range in the northern hemisphere. However, the decline in oak stocking has been increasingly reported worldwide (Watt 1919; Abrams 1998; Galindo-Jaimes et al. 2002; Li and Ma 2003; Götmark et al. 2005; Pulido and Díaz 2005; Zavaleta et al. 2007). Low regeneration potential in oak is due to inherently slow growth in new seedlings, low capacity to sprout in older overstory trees when they are harvested and small advance reproduction. An overriding principle in oak ecology is that the presence of advance reproduction is the single most important factor related to success in natural regeneration, and that various site and environmental factors are important (Carvell and Tryon 1961). Clark and Watt (1971) stated that the "two basic principles" of oak regeneration are: (1) the oak stocking in the new stand will be directly proportional to the amount of oak advance reproduction before regeneration harvesting, and (2) oak advance reproduction has to have a well-established root system to be competitive (Fig. 1). Sander (1971) was one of the first to show that the future growth potential of oak advance reproduction after release by clearcutting was significantly related to its initial size (i.e., stem diameter at the ground) before harvesting. The future dominance of oak originating as advance reproduction increases dramatically with increasing size before regeneration

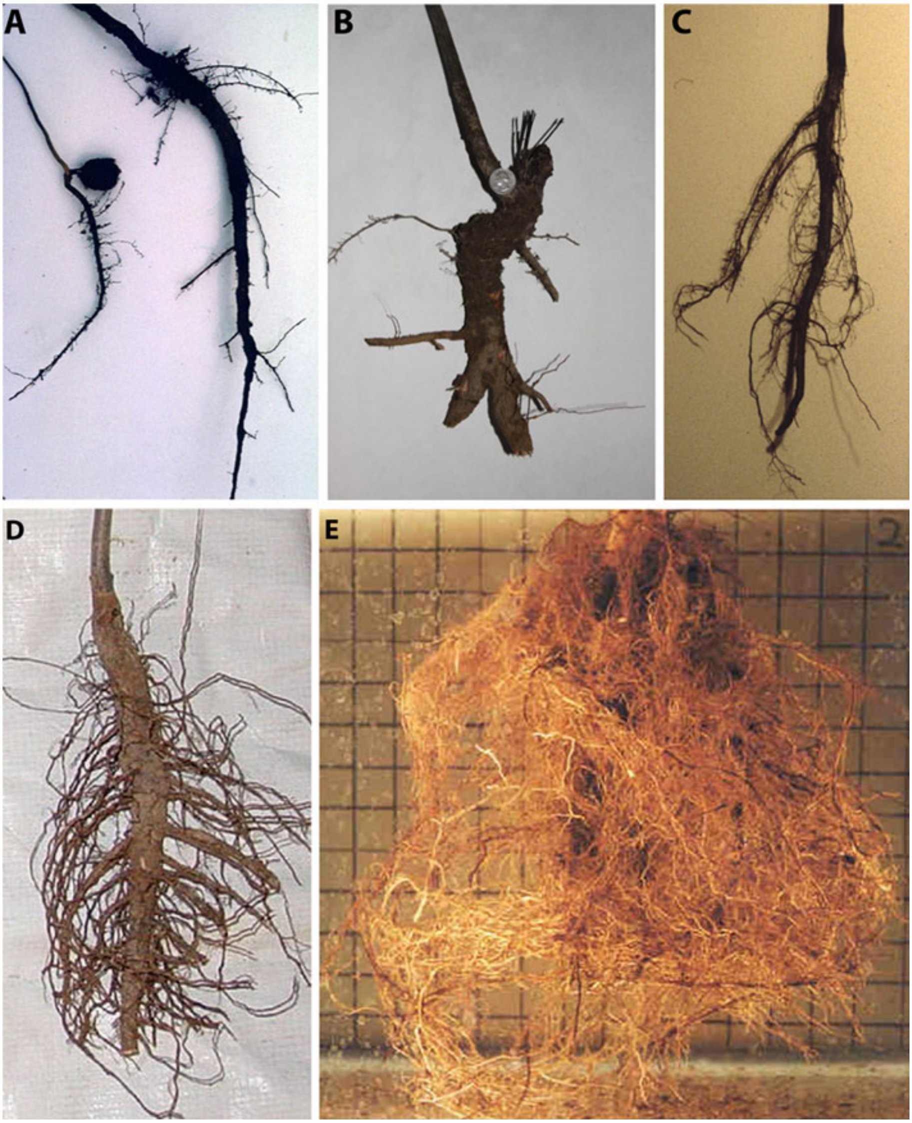

Fig. 1 A well-developed root system is key to oak regeneration competitiveness and success in attaining dominance in young forests. **a** Natural oak root systems develop slowly in the understory of fully stocked stands where available light may be below 5 % of full sunlight: (*left*) first-year root development in natural northern red oak from a germinating acorn and (*right*) a three-year old root system. **b** Oak root systems can accumulate biomass through a cycle of shoot dieback and sprouting provided there is sufficient light: a large root system of a naturally grown black oak growing on the edge of an opening. Nursery production accelerates the development of large root systems in oak in just 1 or 2 years: **c** A typical 1-0 bareroot swamp white oak seedling, **d** 1-0 bareroot cherrybark oak grown under intensive irrigation, fertilization and low seedbed density, and **e** 1-0 container (ll L) RPM® seedling grown by air root pruning

harvesting (Sander et al. 1984; Dey et al. 1996; Loftis 1990a; Belli et al. 1999; Gould et al. 2006; Steiner et al. 2008; Vickers 2009). 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 1997a), which is so important to growth potential during regeneration.

The common problem is that oak advance reproduction in mature forests are small, usually less than 20 cm tall and 4 mm in basal diameter (e.g., Parker and Dey 2008; Fig. 1a), or they are absent (Wendel 1980; Gottschalk 1994). This is most often the situation on the more productive sites (Johnson et al. 2009); and small oak advance reproduction have low regeneration potential (Sander 1971; Loftis 1990a; Dey et al. 1996). Clearcutting to release oak advance reproduction generally results in failure to sustain oak stocking except on sites of average or less productivity that are more likely to have a sufficient number of large oak advance reproduction (Hilt 1985; Ward and Stephens 1999; Groninger and Long 2008). Clearcutting on productive sites usually accelerates succession to a mix of shade tolerant species that originate 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. 2010a; 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. 2010b).

Developing larger oak advance reproduction

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). Promoting oak advance reproduction development requires active management to control stand density so that oak reproduction receives adequate light and other resources. *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). Similar successional trends toward non oak species have been observed in old growth oak forests in northern Europe (Bobiec et al. 2011). Even in secondary oak-mixed hardwood stands where fire and silvicultural treatments are excluded, succession away from oak dominance is a widespread phenomenon in North America (Goebel and Hix 1997; Fei and Steiner 2007; Oswalt et al. 2008).

Thus, to ensure that adequate numbers of large oak advance reproduction are present at regeneration requires managing stand density to promote the accumulation and development of oak advance reproduction. 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 and group selection harvesting. Benefits of regenerating oak by the shelterwood method include:

- increased available light and soil moisture in the understory following 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.

Initial use of the shelterwood method to naturally regenerate oak produced mixed results. Successful results were attributed to having an abundance of larger oak advance reproduction, controlling woody vegetation and vines, and harvesting on medium and lower quality sites (e.g., Loftis 1990a; Schlesinger et al. 1993). Where it failed, there was no effort to control competing vegetation, oak advance reproduction was either small or absent, and deer browsing was a problem (Gordon et al. 1995; Harmer et al. 2005; Schweitzer and Dey 2011). Initial improvements in oak growth and survival have been reported following shelterwood harvesting, but without concomitant and follow-up vegetation management benefits to oak were short-lived, especially where harvest intensity was high. In the long-term, many attempts to regenerate oak using the shelterwood method resulted in failure and dominance by other species (Rudloph and Lemmien 1976; Lantagne et al. 1990). Promising results are being reported for regenerating oak by combining shelterwood harvesting with prescribed burning to control competing vegetation (Brose et al. 1999a, b; Albrecht and McCarthy 2006; Iverson et al. 2008). Underplanting oak in shelterwoods is a viable approach to ensuring that oak reproduction is present to take advantage of the harvest release (Spetich et al. 2002; Dey et al. 2009).

Artificial regeneration of oak

In the history of oak silviculture in eastern North America, oaks were initially planted in clearcuts or old fields, often with poor success (Seifert and Fischer 1985; Clark 1993; Schweitzer and Stanturf 1997). Johnson (1971, 1976) reported that planting 1-0 and 1-1 bareroot northern red oak seedlings was largely a failure despite herbicide control of shrubs for 2 years before clearcutting oak stands in southern Wisconsin. He attributed the failure of oak seedlings to their relatively slow height growth and subsequent suppression and mortality by competition from woody shrubs and stump sprouts of less desirable species. Similarly, McGee and Loftis (1986) observed regeneration failure after planting 1-0 bareroot northern red oak and black oak seedlings in upland clearcuts on medium and high quality sites in the southern Appalachians (North Carolina) and the Cumberland Plateau and Highland Rim (Tennessee) despite herbicide application before harvest and for up to 5 years after planting. Schuler and Robison (2010) found that controlling competing vegetation in the immediate (within 1 m) vicinity of 1-0 bareroot northern red oak seedlings planted in clearcuts was insufficient for good survival and growth because of competition from woody stump sprouts and other advance reproduction in southern Appalachian forests. In contrast, Wendel (1980) achieved success in regenerating northern red oak in a West Virginia clearcut by planting 1-0, 2-0 and 3-0 bareroot seedlings on medium quality sites after doing site preparation with a dozer to remove all stems less than 10 cm dbh. Many other studies of planting oaks in clearcuts have contributed to effective techniques in oak planting including the benefits of large oak seedlings with well-developed root systems (Fig. 1), container seedlings, tree shelters to reduce deer browsing, controlling competing vegetation with site preparation and tending (Lantagne et al. 1990; Zaczek et al. 1997; Ward et al. 2000). Early vigorous height growth in oak seedlings by planting quality stock, and control of competing vegetation and herbivores are key ingredients to successful oak plantings. McGee and Loftis (1986) suggested that control of competing vegetation by maintaining an intact high overstory and by planting larger seedlings may improve oak seedling performance and competitive success.

Underplanting oak seedlings

Planting oak seedlings under a shelterwood can add to the density of natural advance reproduction or can ensure the presence of oak advance reproduction where it is lacking. The shelterwood can lessen transplant shock by moderating environmental stress from high temperature, frost, high atmospheric evaporative demand, and low soil–plant moisture content during oak seedling establishment. Minimizing environmental stress improves early survival and growth of the planted seedlings, which is important to maintaining a competitive edge. In addition, the shelterwood can reduce the growth of aggressive, sun-loving competitors by limiting available light. Knowing the silvical requirements of the desired species and that of their competitors is critical to designing a shelterwood prescription with the appropriate overstory density and composition to create microenvironments favorable to oak.

Underplanting oak seedlings can expedite accumulating sufficient numbers of advance reproduction because in the natural process oaks produce substantial acorn crops only periodically (Burns and Honkala 1990), thus reducing the time it takes to develop adequate advance reproduction by 10–20 years (Carvell and Tryon 1961; Clark and Watt 1971; Sander 1972). Planting oak can be used to improve a manager's ability to schedule silvicultural practices such as site preparation, competition control and regeneration harvesting to benefit oak establishment and release when it is most appropriate. Underplanting is an approach to converting monoculture plantations to more diverse and complex native forests, and can be used in the recovery of forests that have suffered substantial overstory mortality following a decline event caused by combinations of environmental stresses, insects and diseases. The decision to regenerate oak by artificial methods requires a consideration of costs weighed against the time and investment to achieve success by natural processes. Economic comparisons among alternative methods should be based on the economic efficiency (Dey et al. 2008a) or integrated costs (Spetich et al. 2009) of obtaining a successful oak in a position of dominance in the future, e.g., at canopy closure. This approach accounts for all costs associated with success including planting, competition control and other factors required in the regeneration prescription such as control of herbivory, and bases cost comparisons on seedling performance and success probabilities. Underplanting oaks in shelterwoods or after removal of the midstory has proven beneficial to seedling survival and growth in a wide array of forest conditions such as:

- upland mountains (Johnson 1984; Schlesinger et al. 1993; Dey et al. 2009);
- large floodplain forests (Gardiner and Yeiser 2006; Lhotka and Loewenstein 2009; Motsinger et al. 2010);
- northern forests (Gordon et al. 1995; Paquette et al. 2006a; Parker and Dey 2008);
- oak and beech (*Fagus sylvatica* L.) stands in southern Sweden (Gemmel et al. 1996); and,
- conifer plantations in Canada (Parker et al. 2001), Spain (Rodríguez-Calcerrada et al. 2008), Sweden (Löf et al. 2007) and the United States (Buckley et al. 1998).

The underplanting prescription

The basic elements of a prescription for underplanting oaks in shelterwoods includes:

- reducing stand density through manipulation of the mid and overstory in one or more stages;

- controlling woody and herbaceous vegetation before and after planting;
- planting large oak seedlings;
- controlling herbivory especially from large ungulates;
- removing the shelterwood when oak seedlings are competitive; and,
- controlling competing vegetation if needed to maintain oak dominance until crown closure (Johnson et al. 1986; Loftis 1990b; Brose et al. 2008).

The overall intent is to reverse the trend of increasing stand density and limiting available light in the understory that has occurred over the past decades. In the temperate deciduous forest region, water is less often limiting to oak regeneration compared to conditions in Mediterranean climates. Regulation of stand density is probably the most direct and affordable approach to improving the resources needed for successful oak regeneration by providing sufficient light to increase net photosynthesis, and improve both tree water status and water use efficiency (Parker and Dey 2008, Johnson et al. 2009). The challenge is to regulate the forest structure in a way that promotes survival and growth of oak advance reproduction without provoking more intense competition, or exposing the oak seedlings to animal herbivory (Gordon et al. 1995; Truax et al. 2000; Paquette et al. 2006a, b). Stand management and regeneration by this method usually involves combinations of mechanical cutting, and herbicides or prescribed burning (Fig. 2) that are used over time to develop sufficient numbers of competitive oak advance reproduction capable of achieving dominance or codominance at crown closure.

Managing structure for increased light and improved oak regeneration

Managing stand structure is how foresters affect available light in the understory. The relationships between understory light and stand structure are intricate and affected by many factors from inherent crown characteristics of a species to composition, density and spatial arrangement of trees in a stand (Buckley et al. 1998; Paquette et al. 2007). The shape, size and orientation of openings created in the forest by harvesting influence the quantity and quality of available light in the understory (Dey and MacDonald 2001). In general, removal of single trees has little effect on understory light compared to uncut stands, especially when there is a dense shade tolerant midstory. Removal of the midstory canopy alone commonly increases available light to 10–15 % of full sunlight in mixed hardwood stands (Lorimer et al. 1994; Ostrom and Loewenstein 2006; Motsinger et al. 2010).

Herbicide application to kill midstory trees (Fig. 2b) not only increases light but prevents these stems from sprouting or persisting in the future and hence reduces competition with oak when it is released by future shelterwood or clearcut harvests (Loftis 1990b; Gottschalk 1994; Motsinger et al. 2010). Prescribed burning (Fig. 2a) is effective in reducing the density of the midstory (<12 cm dbh) but individuals often resprout requiring additional burns to control competition (Waldrop et al. 1992; Dey and Hartman 2005; Arthur et al. 2012). The common use of dormant or spring prescribed burns has little effect on the overstory, and repeated burns that eliminate the midstory are capable of increasing understory light only modestly (Hutchinson et al. 2005). Mechanical cutting of the midstory is somewhat similar to prescribed burning in that the cut hardwood stumps have a high probability of sprouting (Fig. 2f). It differs from fire because it targets the species and size class of stems to be removed, it does not affect directly smaller woody stems and herbaceous vegetation, or the viability of seed in the forest litter. Sprout growth from undesirable species can be controlled to a degree by maintaining higher overstory density (Loftis 1990b, Dey and Hartman 2005).


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◀ **Fig. 2** Prescribed burning (**a**) or herbicide application, in this case by the hack and spray method (**b**) are effective ways of removing the midstory of shade tolerant trees and controlling understory shrubs and herbaceous vegetation. Mechanical site preparation (**c**, **d**) can be used to reduce competing vegetation, incorporate acorns into the mineral soil, or prepare the site for planting. The application of herbicides to cut stems (**e**) of competing vegetation prevents their sprouting (**f**). Eastern cottonwood (**g**) or red pine (**h**) can be planted at high densities and used as a nurse crop to control competing vegetation in preparation for underplanting of oak seedlings

Oak survival and growth benefit from removal of the midstory, and it is a recommended first step to enhancing existing or planted oak advance reproduction on high quality sites (Loftis 1990b; Lorimer et al. 1994; Lhotka and Loewenstein 2009). Lhotka and Loewenstein (2008) observed that the vertical structure (height to canopy) and residual basal area after midstory removal treatments were significant determinants of underplanted 1-0 cherrybark oak seedling survival and height growth after 2 years in southern bottomland forests in Georgia. Although midstory removal is initially beneficial to oak reproduction, increases in available light after thinning are short-lived, lasting only a matter of 3–5 years (Lockhart et al. 2000; Miller et al. 2004). Thus, additional reductions in stand density are recommended as the oak advance reproduction develop and become more competitive.

Oak species range in shade tolerance from intermediate to intolerant (Burns and Honkala 1990), but specific data on physiology, growth and light relationships are lacking for most of the oak species and their major competitors. The light compensation point for seedlings of some oaks such as northern red oak is low (2–5 % full sunlight) and light saturation of net photosynthesis and high growth rates occur between 30 and 50 % of full sunlight for cherrybark oak and northern red oak (Hanson et al. 1987; Ashton and Berlyn 1994; Gardiner and Hodges 1998). Oaks show a general increase in growth with increasing light, depending on species (Gottschalk 1994; Paquette et al. 2007; Rebbeck et al. 2011). White oak is one of the more shade tolerant oaks in eastern North America and it does not exhibit noticeable shoot growth with increasing light in the range of 6–25 % of full sunlight, but preferentially allocates carbohydrates to the roots resulting in root to shoot ratios that are double that of northern red oak and chestnut oak (Dillaway et al. 2007; Rebbeck et al. 2011).

For northern red oak, Gottschalk (1985, 1987, 1994) stated that growth was good above 20 % of full sunlight. Parker and Dey (2008) observed that increasing available light in the understory from 1 % of full sunlight to 27 and 49 % by shelterwood harvesting to different intensities increased net photosynthesis and leaf conductance to water vapor in planted 2-0 and natural northern red oak advance reproduction by two to three times that of sugar maple (*Acer saccharum* Marsh.). Interestingly, they found that photosynthesis and water relation responses to increasing light were similar between planted 2-0 bareroot and natural northern red oak seedlings in the understory of northern hardwood shelterwoods. Paquette et al. (2007) found that underplanted container northern red oak had the greatest maximum and average annual shoot growth compared to container black cherry (*Prunus serotina* Ehrh.) and natural sugar maple seedlings as light increased from near 0–43 % of full sunlight in gray birch (*Betula populifolia* Marsh.) forests (16–20 m^2/ha basal area) and shelterwoods (10–15 m^2/ha basal area).

Brose (2008) direct seeded acorns of four oak species under variable density overstories that provided from 4 to 89 % of full sunlight and found that root growth of chestnut oak was highest at moderate light levels after 4 years, white oak was somewhat similar in response to increasing light, but northern red oak and black oak had maximum root growth in the highest light treatment. None of the species showed much root growth at 15 % of full sunlight. It is obvious that the more we know about the growth responses, carbon allocation patterns and physiology of each species in relation to environmental variables that are influenced by forest structure; the better we will be able to design regeneration prescriptions. It is generally recommended that available light in the understory be above 20 % of full sunlight to permit biomass accumulation in oak seedlings, and a range of 30–50 % promotes survival and growth in oak advance reproduction without overly encouraging the development of competition (Gottschalk 1985, 1987, 1994; Dey et al. 2008a).

The shelterwood method is able to produce a wide range of light conditions in the understory and is suited to managing incremental increases in available light with a series of planned harvests as oak regeneration develops. Intermediate levels of overstory density have promoted the survival and growth of several oak species underplanted in temperate deciduous forests (Paquette et al. 2006b). Reducing either stand stocking by >40 %, basal area by >50 % or crown cover by >30 % produces 35–50 % of full sunlight in the understory in a wide variety of forest types including southern bottomland hardwoods, northern hardwoods, mesic mixed-oak, and oak-hickory forests (Godman and Tubbs 1973; Sander 1979; Gardiner and Yeiser 2006). Brose (2008) achieved 48 % of full sunlight at 1 m above the ground beneath oak-cherry-maple stands by reducing the basal area by half to 18 m^2/ha in northern Pennsylvania. Parker and Dey (2008) measured light levels near seedlings to be 25 % of full sunlight after removing half of the basal area with a shelterwood harvest that left 16 m^2/ha in an Ontario oak-northern hardwood forest. Substantial reductions in stand density by thinning the overstory and removing any midstory canopy are required to provide sufficient available light for growth of oak advance reproduction.

Underplanting before reducing stand density

Since oak root systems grow slowly in the low light (<15 % full sunlight) of fully-stocked mature forests (Fig. 1; Brose 2008; Rebbeck et al. 2011), it is unadvisable to plant seedlings, in many cases, until stand density has been reduced by midstory removal or shelterwood harvesting, and any other competition control measures have been taken, especially those involving broadcast herbicide application (Dey and Parker 1997b; Schuler et al. 2005). Tworkoski et al. (1986) planted 1-0 bareroot white oak and northern red oak seedlings in the understory of a southern Virginia mature forest (25 m^2/ha basal area) 3 years before clearcutting or shelterwood cutting (11 m^2/ha residual basal area) and found that oak seedlings present at harvest increased in height and diameter for three consecutive years following harvesting. No mention was made of how many of the planted oak seedlings had survived during the 3 years under the mature stand, nor what was the competitive status of the oak after harvesting. They described the forest composition as a mixed hardwood-oak with an understory of small hardwood reproduction and vines. This appears to be a more open stand structure than that of Dey and Parker (1997b) who were working in a dense sugar maple dominated forest in Ontario with a heavy mid and understory of shade tolerant species that resulted in light levels as low as 1 % full sunlight. There, they observed an overall decline in 1-0 bareroot northern red oak seedling shoot and root size and increasing mortality over 2 years in the mature sugar maple forest (21 m^2/ha basal area and 94 % crown cover).

Rapid establishment and early growth rates are essential for planted oak seedlings to realize their inherent growth potential, especially on the more productive sites where competing vegetation can become overwhelming in one season. Oaks are known for their slow juvenile shoot growth rates and developing a large root system (Fig. 1) is necessary for both natural and artificial oak reproduction to exhibit competitive shoot growth

(Johnson et al. 2009). Nursery culture to produce high quality oak seedlings with well-developed root systems is a way to expedite the natural process of growing large oak advance reproduction (Fig. 1). Techniques have been developed to produce large oak seedlings in 1 year as bareroot and container stock for some species (Kormanik et al. 1994; Dey et al. 2004, 2008a; Wilson and Jacobs 2006).

Seedling quality

Underplanting quality seedlings is key to successful oak regeneration. Physiological indicators of stock quality are not well-developed for eastern hardwoods, or fully calibrated to field performance for many species, and they have limited operational use today (Dey et al. 2008a). Most evaluations of artificial regeneration with oak have been done using common morphological indicators of stock quality such as root collar or basal stem diameter, shoot length, and the number of first-order lateral roots (>1 mm basal diameter). A survey of the oak planting literature on standards for high quality seedlings reveals that most of the research has been done on northern red oak; and 1-0 or 2-0 bareroot seedlings and 1-1 transplants should be ≥10–12 mm in basal diameter, ≥50 cm in shoot length and have ≥5 first-order lateral roots (FOLR; and preferably ≥10 FOLR) to improve survival, early growth and competitiveness in clearcuts or shelterwoods (Johnson 1984; Teclaw and Isebrands 1993; Thompson and Schultz 1995; Ward et al. 2000). These size thresholds are determined for specific regeneration prescriptions and are affected by competing species, site quality, browsing pressure, stand density, and control of competing vegetation in the specific studies. Professional judgment must be used for other oak species and when operational conditions differ significantly from those experienced in the research. These thresholds apply specifically to northern red oak and species of similar silvical characteristics when:

- seedlings are underplanted in shelterwoods of about 60 % stocking;
- the site is of average or better quality;
- woody stems >1.5 cm dbh of undesirable species have been controlled with herbicides before planting and at the time of final overstory removal; and,
- deer browsing or competition from herbaceous species are not a problem.

Spetich et al. (2002) provided a nice example of how dominance probabilities for 2-0 bareroot northern red oak seedlings vary by site quality, initial basal diameter, number of treatments to control hardwood sprouts, and shelterwood density. In all cases, dominance probabilities, i.e., that a planted oak will be at least 80 % of the height of its most dominant competitor 11 years after planting (8 years after final overstory removal), increased significantly as the initial basal diameter increased from 4 to 22 mm. General principles can be taken from current research that can be used to design prescriptions for other oak species and forest conditions that will improve success in regenerating oaks.

The general consensus is that no one morphological variable is the best for predicting future survival, growth or dominance probability and that it is better to use a set of variables to determine seedling quality. Basal diameter near the root collar is probably the single most often used measure of quality for oak seedlings as it is significantly related to field performance and is easy to measure. It is also highly correlated to total root dry mass, root area, number of FOLR, and root volume (Canadell and Rhoda 1991; Dey and Parker 1997a, Jacobs et al. 2005). The resounding recommendation is to plant the largest seedling possible given site limitations such as shallow and rocky soils and economic considerations. An important perspective is to assess different stock types and planting approaches using the cost per successful seedling or economic efficiency concept (Dey et al. 2008a) that factors not only the initial stock and planting costs, but also the performance of the individual seedlings and all other silvicultural activities and costs that are part of the regeneration prescription including site preparation, competition control, stand management, and animal damage control that are necessary to get a seedling to the free-to-grow stage and dominance in the new stand.

Seedling stocktype

Bareroot seedlings are the most common type of planting stock used in North America. In evaluations of stocktype performance in oak plantings, various combinations of bareroot 1-0 or 2-0 seedlings (Fig. 1c), and 1-1 or 2-1 transplants have been compared with large (11 L; Fig. 1e) or small (300–500 cm^3) container stock. Both small and large container seedlings often have better performance (survival and growth) than bareroot seedlings or transplants (Johnson 1984; Zaczek et al. 1993, 1997; Motsinger et al. 2010) planted in clearcuts, shelterwoods or where the midstory was removed. The often cited advantage of container seedlings is the well-developed and intact root system that minimizes transplant shock and promotes survival and early rapid growth. Depending on nursery cultural methods, large container seedlings can have significantly larger and more fibrous root systems than bareroot seedlings (Fig. 1e). Shaw et al. (2003) reported that pin oak seedlings grown in 11 L pots by the RPM® method (Dey et al. 2004), an air-root pruning system, had nine times the root volume and seven times the root dry weight of 1-0 bareroot seedlings. Motsinger et al. (2010) underplanted 1-0 bareroot and RPM® pin oak seedlings in a bottomland forest in the Mississsippi Alluvial Basin where the midstory had been removed and found that RPM® seedlings (initially 12 mm basal diameter and 90 cm tall) had the best survival and growth after 3 years. Some species grown by the RPM® method can be 20 mm in basal diameter and 2 m tall in 1 year, e.g., swamp white oak (Dey et al. 2004). This is substantially larger than most 1-0 bareroot oak seedlings, which commonly are 4–6 mm in basal diameter and 30–50 cm tall. In a test of various northern red oak stock types, Zaczek et al. (1993) observed that 2-0 container (8 L) seedlings performed better than 2-0, 2-1, 1-0 and 1-1 seedlings after 3 years in Pennsylvania clearcuts. Height growth after planting was significantly influenced most by initial seedling size. The 2-0 container seedlings were initially the largest averaging 10.5 mm in basal diameter and 63 cm in height. Of the bareroot stock types tested, they found that the 2-0 seedlings were initially the largest and outperformed the other seedling and transplant types. In Missouri Ozark clearcuts and shelterwoods, Johnson (1984) compared northern red oak 1-1 transplants (10 mm basal diameter, 56 cm height), large 1-0 bareroot (10 mm basal diameter, 88 cm height), standard 1-0 bareroot (8 mm basal diameter, 48 cm height) and container (7 mm basal diameter, 61 cm height in 500 cm^3 Spencer-Lemaire Rootrainers) stock. The container stock performed the best in clearcuts, and was a close second to the 1-1 seedlings in the shelterwoods. Growing oak seedlings at low seedbed density, undercutting the roots at 20 cm, and frequent fertilization and watering has been used to encourage large bareroot seedlings with well-developed root systems that have high numbers of FOLR to improve field performance and success in regeneration (Kormanik et al. 1994). It is important to let nursery managers know what seedling standards and stocktypes are desired years in advance of the planting to give sufficient time for seed collection and seedling production. Regeneration models can be used to determine desired seedling standards and planting densities (Johnson et al. 2009).

Control of competing vegetation

Other than the overstory, tall shrubs and understory trees are the major competitors of oak advance reproduction in forests; competing for light and other resources needed for survival and growth (Lorimer et al. 1994; Johnson et al. 2009). Most hardwood trees and shrubs are able to sprout following cutting or burning, and stump sprouts are the most serious competitors of oak reproduction (Dey et al. 1996; Dey and Hartman 2005; Schuler and Robison 2010). Mechanically cutting or burning the midstory and understory woody stems (Fig. 2) can reduce the vertical structure in a forest, but it greatly increases the density of woody stems in the regeneration layer due to sprouting, thereby increasing competition with oak advance reproduction or planted seedlings. In addition, shelterwood harvesting and midstory removal done to promote growth of oak advance reproduction also promotes the growth of its competitors (Gottschalk 1994; Ward and Stephens 1999).

Herbicides

For these reasons, most prescriptions for underplanting oak seedlings include the control of woody stems, generally $\geq$1–2 cm dbh, before and after planting (Fig. 2). Herbicides are effective in eliminating woody competitors but also can kill oak seedlings. Thus, methods of application are used that target the stems and species for control (Fig. 2b, e), or broadcast applications are done before planting where there are few natural oak advance reproduction. Drift from foliar applications of herbicides or use of soil active compounds can cause damage and death to oak reproduction, even when care is taken to protect oak seedlings (Motsinger et al. 2010). Shoot clipping reproduction before spraying foliar herbicides has been suggested as a means of protecting the oak. Commonly, herbicides are used by stem injection (Fig. 2b) to remove the midstory and unmerchantable overstory trees, and are applied to any stumps of stems that are mechanically cut in a harvest (Fig. 2e), cleaning or tending operation. Foliar or basal applications can reduce shrub cover in the understory. At each stage of implementing the shelterwood method, treating stumps of merchantable trees and all smaller stems of undesirable species significantly increases the survival, growth and competitiveness of planted and natural oak reproduction (Johnson et al. 1986; Spetich et al. 2002).

Shrub facilitation

In southern Sweden, understory shrubs have been shown to indirectly facilitate the growth of both natural and planted penduculate oak and sessile oak in conservation harvests by protecting seedlings from deer and moose browsing and by eliminating other competing vegetation. However, shrubs also reduced the probability of occurrence of natural seedlings and the growth of both natural and planted oak seedlings (Götmark et al. 2011; Jensen 2011). In Mediterranean climates, shrubs have been observed to facilitate the establishment of Holm oak (*Q. ilex* L.) by reducing photoinhibition and drought stress, and decreasing other competitors (Cuesta et al. 2010). In most areas in eastern North America, dense understory shrubs need to be controlled in oak plantings and alternative methods of controlling deer browsing include fencing areas to be regenerated, or protecting individual seedlings with wire cages or plastic tree shelters (Ward et al. 2000; Brose et al. 2008). Tree shelters also increase oak height growth in clearcuts and shelterwood plantings and can be used to protect oaks where shrubs and ground vegetation is controlled and deer densities are moderate to high (Lantagne et al. 1990; Ward et al. 2000; Schuler et al. 2005).

Control by mechanical and prescribed burning methods

Mid and understory vegetation can also be controlled using mechanical scarification (Fig. 2d). Lhotka and Zaczek (2003) and Rathfon et al. (2008) used a brush rake or disc mounted on a crawler tractor to scarify the forest floor to bury acorns in mineral soil and to reduce density of competing sugar maple and other woody species. They found that scarification significantly increased the density of oak seedlings and removal of the woody understory improved oak survival.

Prescribed burning (Fig. 2a) before planting can be done in forests or shelterwoods to remove the midstory and control understory vegetation. Even low intensity fires are effective in killing the stems of hardwood species up to about 15 cm dbh (Dey and Fan 2009; Arthur et al. 2012). Usually, the benefit of a single fire is short-lived, as the root systems are able to sprout for many species, repeat burns are needed to achieve the desired control (Brose et al. 2006; Dey and Fan 2009; Arthur et al. 2012). A spring prescribed burn can kill a high proportion of the acorn crop and cause high (70 %) mortality in young, small (4 mm basal diameter) natural red oak advance reproduction (Johnson 1974; Auchmoody and Smith 1993; Dey and Fan 2009). The root systems of these seedlings are small and have low carbohydrate reserves to support vigorous sprouting (Fig. 1a; Brose et al. 2006; Brose 2008). However, Gordon et al. (1995) burned underplanted 1-0 and 1-1 bareroot northern red oak seedlings in a shelterwood 1 year after planting and observed that survival was 75 %. The burn controlled competition from other hardwoods and shrubs but exposed the succulent oak sprouts to deer browsing. Brose et al. (1999a, b) experimented with burning after a shelterwood harvest and found that it promoted development of oak reproduction and was effective in controlling competition from other tree species. Brose et al. (2006) recommended that a late spring or early summer prescribed fire be done about 3–5 years after the initial shelterwood harvest to allow small oak seedlings to grow and attain a size of 19 mm in basal diameter before burning again, which certainly will need to be done on productive sites. Scheduling of future burns will need to consider the developing vegetation and competitive status of the oak for in some regions species such as yellow-poplar can overwhelm planted oaks within 5 years of final overstory removal and cause high mortality in planted oak populations if left uncontrolled (Weigel and Johnson 2000; Dey et al. 2009). Prescribed burning can be used after the final overstory removal as needed to keep competitors in check and oaks in a position of dominance. Once crown closure occurs, an approach using crop tree release can be useful for targeting the relatively few number of trees needed for oak dominance at stand maturity (Schuler and Miller 1999; Schuler 2006; Dey et al. 2007).

Herbaceous and ground vegetation

Herbicide control of the herbaceous understory and woody stems <1.5 m tall has had limited positive benefit to oaks in most cases (Lorimer et al. 1994). It does not increase available understory light much above what is gained by midstory removal (Motsinger et al. 2010), and in some ways makes oak reproduction more susceptible to deer browsing by reducing alternative browse and exposing oak stems (Gordon et al. 1995; Truax et al. 2000). Oaks underplanted in a shelterwood can compete with moderate densities of *Rubus*, which protects oaks from deer browsing (Johnson 1984; Paquette et al. 2006a; Jensen 2011). In some areas such as the Allegheny Plateau and other northern forest regions, ferns and grasses can interfere with oak reproduction development (Brose et al. 2008). Herbicide formulations and application guidelines have been developed that effectively control these competing species (Horsley 1991; Brose et al. 2008).

Care must be taken with all vegetation control methods because removing the target species or size class of vegetation, and the method of control can create other competition problems. For example, Horsley (1991) reported that the use of machines with metal cleats or rigid rubber tires to apply herbicides for fern control can disrupt the translocation of herbicide by cutting up the fern rhizomes. Vegetative reproduction from all the rhizome segments actually increased the density of ferns and their spread throughout the stand. And the use of prescribed burning can favor the spread and dominance of invasive species that are adapted to fire disturbances and can take advantage of the available growing space and resources after burning (Rebbeck 2012).

Managing stand density to control competition

A unique method for control of competing vegetation is to regulate overstory density in a way that balances the resource needs of oak reproduction with that of its competitors. Loftis (1990b) has advocated a method whereby 30–40 % of stand basal area is removed from fully stocked stands by reducing the midstory and occasional intermediate and suppressed stems from the overstory, while leaving the main overstory canopy intact. Stand density reduction is done by herbicide application, which keeps the stems from sprouting. As site quality increases, residual stand density is increased to control the more vigorous growth of competing hardwood advance reproduction. Planted or natural oak advance reproduction is allowed to develop for up to 10 years before reducing overstory density in a shelterwood or final removal harvest. Likewise, Schlesinger et al. (1993) noted that increasing shelterwood stocking from 40 to 60 % and control of tall woody stems in the understory was best for developing large oak advance reproduction on higher quality sites in the Missouri Ozarks.

Using nurse crops to control competition

Another innovative application of underplanting has been developed for afforesting bottomland cropfields (Gardiner et al. 2008, 2010; Stanturf et al. 2009; Dey et al. 2010). The approach involves the use of eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) as a nurse crop for Nuttall oak, which is underplanted after the cottonwood canopy has achieved complete closure (Fig. 2g). The crown architecture of cottonwood makes it a good companion species for oaks that can tolerate moderate shade in the seedling stage. Also, the management system for growing cottonwood for fiber provides timely releases of the underplanted oak when the cottonwood is harvested. Cottonwoods are planted dense enough to achieve crown closure in 2–3 years when the 1-0 bareroot oak seedlings are underplanted. Available light beneath the cottonwood canopy is about 30 % of full sunlight, sufficient for oak growth, but low enough to control competing vegetation (Gardiner et al. 2001, 2004; Stanturf et al. 2009). Biomass of herbaceous vegetation under the cottonwood canopy was reduced by >65 % compared to production in open fields. In 10 years, the cottonwood is harvested and regenerated by coppicing. The second harvest in another 10 years is the final release of the oak.

Similarly, young red pine (*Pinus resinosa* Ait.) plantations have been used as a nurse crop (Fig. 2h) to establish a mix of native hardwood species including northern red oak in southern Ontario (Parker et al. 2001). The closed-canopied plantation, never having been thinned, had nearly completely eliminated any ground vegetation. Underplanting of 2-0 bareroot northern red oak seedlings after various thinning treatments proved a successful method for restoring native hardwood forests. Oak seedling performance improved with the increasing intensity of thinning.

Final release of oak advance reproduction

Release of well-developed oak advance reproduction is accomplished by removal of the shelterwood. This may be done in several harvests depending on site quality and expected competition, but once oak seedlings are deemed competitive (see Johnson 1984; Loftis 1990a; Spetich et al. 2002) delays in final shelterwood removal only act to increase mortality, retard oak growth, and favor the more shade tolerant species, especially with higher shelterwood densities (Oliver et al. 2005; Ward and Stephens 1999). Dillaway et al. (2007) observed that natural white oak advance reproduction regenerated in a clearcut had significantly greater stem basal diameter, root diameter, and root soluble non-structural carbohydrate concentrations after 1 year than seedlings growing under an intact canopy or where the midstory had been removed. Johnson (1984) reported that the largest fifth-year heights for surviving planted northern red oak seedlings occurred in (1) clearcuts, followed by (2) oaks planted under a shelterwood at 60 % stocking (3 years under the shelterwood, 2 years in the open), and finally (3) oaks growing under the shelterwood for 5 years were the shortest. He emphasized that while oaks grow taller in clearcuts over 5 years, so does the competing vegetation, and therefore initial rapid height growth in oak seedlings was key to oak survival and dominance. He found that the most rapid annual height growth occurred for oaks planted under a shelterwood for 3 years before being fully released by shelterwood removal. Trees planted directly in clearcuts did not exhibit rapid shoot growth the first 2 years. This is a critical period when competing vegetation can suppress slow growing oak. Thus, there is some advantage to establishing oaks under a shelterwood for a brief period to allow them to develop a larger root system before being completely released. In his study, Johnson (1984) effectively controlled the woody competition with herbicides and *Rubus* was the main competitor in clearcuts and shelterwoods. The site quality, type of competitor, and response of competing vegetation to silvicultural activity determine whether actual height growth of oak seedlings is sufficient for oak dominance.

A consistent finding across oak forests throughout eastern North America is that residual overstory cover substantially suppresses growth and development of established oak regeneration. Oliver et al. (2005) illustrated that height growth and development of various bottomland oaks in the Mississippi Alluvial Valley were disproportionately reduced more so than shade-tolerant species when regeneration harvests left residual basal area as low as 5 m^2/ha. Miller et al. (2006) found that leaving just 5.3 m^2/ha in overstory trees (36 trees per hectare average dbh 44 cm) had a substantial effect on reducing the growth of reproduction in Appalachian hardwood forests, and 20 years after harvesting the canopy cover (28 %) of residual overstory trees covered most of the stand area favoring the more shade tolerant species at the expense of oak species. Ten years after harvesting, Kabrick et al. (2008) reported that the density of large oak reproduction (>3 m tall but <4 cm dbh) was significantly less in stands regenerated by the single-tree selection method that maintained about 15 m^2/ha of basal area compared to those managed by clearcutting in the Missouri Ozark Highlands. In the same region, Larsen et al. (1997) and Green (2008) showed that the probability of large oak advance reproduction being present is greatly decreased when overstory density exceeds about 14 m^2/ha, and that as little as 4.5 m^2/ha of overstory substantially decreased the height growth of oak advance reproduction. Even the performance of oak stump sprouts, the most competitive source of oak reproduction, was significantly inhibited by overstories resulting from single-tree selection harvesting (residual density >15 m^2/ha) and that their maximum survival and growth occurred in clearcuts (Dey et al. 2008b).

Under single-tree selection, where overstory density averaged 12 m^2/ha, Kabrick et al. (2008) noted a compositional shift toward the more shade tolerant white oak was occurring in the understory in conjunction with a substantial loss of black oak and scarlet oak. Arthur et al. (1998) noted that openings much larger than multiple tree canopy gaps in oak-pine forests in the Cumberland Plateau were needed for black oak and scarlet oak regeneration to be successful. Although oak growth is best in the openness of clearcuts, vigilance is required to monitor the regeneration after final shelterwood removal, especially on higher quality sites where species such as yellow-poplar can suppress the oak in a matter of 5 years (Weigel and Johnson 2000; Groninger and Long 2008; Schweitzer and Dey 2011). Timely release of oak advance reproduction can promote its growth and recruitment into the overstory. Regeneration models and guidelines are used before harvesting to assess the adequacy of oak advance reproduction and schedule release by final overstory removal. Some overstory may be left to meet other resource objectives, but realize that the consequences are expressed in reduced oak growth, increased risk of losing the shade intolerant oak species, and possible reduction in oak stocking at maturity.

Conclusion

We have been practicing modern forest management in eastern North America for a relatively short time, albeit longer in Europe. However, it has been only in the past 50 years that we have recognized the widespread nature of the oak regeneration problem. We often have focused on managing other more valuable conifer and hardwood species to the neglect of oak research and management. We are now realizing the problems in forest health, sustained productivity, and threats to native biodiversity that result from the proliferation of monoculture plantations of exotic species that were established throughout the world in the past 80 years. Concerns for quality of wildlife habitat and sustaining viable populations are emerging because of the projected reductions in mast producing oaks and loss of early successional habitat (McShea and Healy 2002; Greenberg et al. 2011).

Our understanding has matured rapidly about basic ecology and biology for several of the major oak species, the causes and mechanisms of the regeneration problem that vary within temperate deciduous forests, and how to obtain desired outcomes by silvicultural intervention. The ability to regenerate oak is fundamental to sustaining the species and the ecosystems. Artificial regeneration plays an important role when natural processes necessary for oak establishment and dominance have been disrupted by land use past and present. Nursery cultural practices are needed to produce high quality seedlings for a greater number of oak species. Seedling quality standards are needed that are based on field performance and account for variation in site conditions, environmental stresses, competing vegetation and management practices. Much of the past research effort has focused on a relatively few of the more commercially valuable and ecologically dominant species. Therefore, future research should include discovery of basic biology, physiology and ecology of the many other oak species and their major competitors. For example, we need to know how they respond to disturbances, and formulate silvicultural prescriptions for conservation and restoration of oak and other desired species.

Research is needed that establishes how silvicultural practices affect the availability of resources (light, water, nutrients) and seedling physiology through management of vegetation structure and composition. Linking silvicultural practices and their effects on vegetation composition and structure to microenvironment and tree physiology is important to managing oak successfully through regeneration and its ascension to dominance in maturing forests. The use of prescribed burning is rapidly increasing in many places and much remains to be learned on how fire interacts within plant communities to favor oak while protecting other resource values, and human health and property. Innovative combinations of practices to favor oak regeneration and promote its dominance need to be assessed. We need to identify species that are compatible with oak and facilitate its regeneration by reducing competition from more aggressive species and protecting oak from herbivores.

There are models for some ecosystems, select oak species, and specific management regimes that predict regeneration success and oak dominance. Models can be used to assess oak regeneration potential, determine future dominance probabilities, and estimate stand composition and size distributions based on stand attributes and site factors for given silvicultural scenarios. These models are useful for assessing the need for artificial regeneration. Further research is needed to develop regeneration models for other oak species, ecosystems and management systems that take into account:

- differences in site productivity,
- variation in the suite of competing species 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, number and size needed to meet future stocking goals and other stand objectives.

Dey et al. (2009) recommended an approach for conducting oak regeneration research that accounts for variation in dynamics due to differences in environmental factors and competitive relations among species in defined ecological units. For now, general principles from existing research need to be used to develop conservation practices to successfully regenerate oak. Future research should address emerging issues such as ecosystem restoration, landscape scale conservation, integration of prescribed burning as an ecological process, managing for invasive species, and forest response to changing climate.

The lack of specific information should not become a barrier to beginning a regimen of treatments to address the core problems in oak regeneration that have been discussed in this paper. The one thing that is certain is that oak advance reproduction is inadequate in both density and size to ensure successful oak regeneration in many areas in the temperate deciduous forest region. Artificial regeneration can be used to help remedy that situation but success will take more than planting trees. The oak regeneration prescription is a chain made up of links, each critical to a successful outcome. It begins with the establishment of oak advance reproduction and development of seedlings to large, competitive status. This can be accomplished by underplanting high quality seedlings and controlling competing vegetation to provide adequate resources for oak survival and growth. Where deer and other herbivores are troublesome, seedlings need protection.

Developing large oak advance reproduction in sufficient density is a process that can take 10 years or more. Underplanting oak seedlings can be used to supplement natural seedling populations. Planting the largest seedlings possible with well-developed root systems is important, as is providing those seedlings with adequate resources for biomass production and good height growth. Controlling competing vegetation is key to ensuring oak has adequate light, moisture and nutrients, but it also requires the need for future control as nature rushes to fill the available growing space resulting from the silvicultural disturbance. The cost of establishing oak artificially must be weighed against natural regeneration, but much of the cost of applying elements of the regeneration prescription such as controlling competing vegetation and protecting seedlings from herbivores must be incurred regardless of the origin of oak reproduction. With planning, persistence, and patience (Weigel et al. 2012), it is possible to successfully regenerate oak with what we know today. Lest we forget that forest regeneration is a process, not an event (Clark 1993).

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