Artificial Regeneration of Major Oak (*Quercus*) Species in the Eastern United States—A Review of the Literature

Daniel C. Dey, Douglass Jacobs, Ken McNabb, Gary Miller, V. Baldwin, and G. Foster

Abstract: Although natural regeneration is often the best method for establishing new oak (*Quercus* spp.) stands, there are increasingly more situations in which high potential for oak regeneration failure dictates the use of artificial regeneration including direct seeding and planting seedlings. Additionally, afforestation planting programs frequently incorporate oak species. Artificial regeneration of oak stands is challenging for numerous reasons. In this article we synthesize the current state of knowledge regarding growing and planting the major oak species in the eastern United States, point out critical research gaps, and provide some general growing, planting, and stand tending guidelines and recommendations. Adequate site preparation, careful planting of healthy, genetically adapted seed or seedlings of high morphological and physiological quality, and subsequent control of competing vegetation and browse damage are necessary actions to assure regeneration success. Oak seedling survival in the early years after planting or seeding is a poor indicator of regeneration success. Successful regeneration may be defined as having a desired proportion of the oak planting stock reach dominant/codominant status in the stand. The costs of all activities required to produce a successful oak tree in the future stand should be considered in economic comparison of alternative prescriptions for oak regeneration. FOR. SCI. 54(1):77–106.

Keywords: reforestation, afforestation, planting seedlings, competition control, direct seeding, regeneration success, *Quercus*, oak, silviculture, animal damage

NATURAL REGENERATION OF OAKS (*Quercus* spp.) is often the best alternative for forest stands when sufficient time is available to apply silvicultural treatments that are required for successful regeneration. However, there are situations in which it is not practical or possible to rely on natural regeneration alone. Such situations may arise after large areas of oak decline, as is currently in progress in the Ozark and Ouachita Mountains, when natural regeneration is inadequate to meet management objectives, when agricultural lands are being converted to oak forests, or when logging occurs before effective natural regeneration regimens can be implemented. Oak seedling planting or seed sowing may be done in open field conditions on former agricultural lands, defined as afforestation, or after a clearcut or planting in the understory of inadequately stocked or shelterwood stands, which will be defined here as reforestation.

The distinction between afforestation and reforestation planting of oaks is important to note because, as will be shown in this article, the silvicultural and regeneration methodologies needed for these two situations are different. In this article we summarize the current state of knowledge about successful artificial regeneration of some of the major oak species and summarize methods to achieve success under a variety of conditions.

Complexity of Oak Species and Ecosystems

There are numerous species of oaks that grow throughout the eastern United States (Hardin et al. 2001). Taxonomically, they are divided into two major groups, red oaks (Section *Lobatae*) and white oaks (Section *Quercus*), with several species within each group. They occur on xeric to hydric sites, in uplands and bottomlands, occasionally in relatively pure stands, and generally in mixed species stands, with various degrees of species dominance (Johnson et al. 2002). There is great variation in the size and shape of mature oak trees across species; some species are highly prized for timber products and others are more valued for attributes such as mast production for wildlife (Hardin et al. 2001, Ross-Davis et al. 2005). Long and Jones (1996) have shown that great differences in growth responses exist among different species of oaks, both in nursery and field settings. Therefore, it is necessary to determine the extent to which research results from one oak species may be extrapolated to guide management of other species.

In this article, we focus on prominent eastern oak species including northern red oak (*Quercus rubra* L.) and white oak (*Quercus alba* L.) in the uplands, and cherrybark oak (*Quercus pagoda* Raf.), Nuttall oak (*Quercus nuttallii* Palmer), and water oak (*Quercus nigra* L.) in the bottomlands because most published information on artificial regeneration is for those species. Information on co-occurring oak species will be presented as available.

Although the focus of this article is artificial regeneration, general principles of silviculture and ecology (mainly light requirements and competition) related to natural oak regeneration for various silvicultural systems common to the eastern United States are reviewed and discussed. This

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is done because we assume that the factors affecting reproduction, survival, and growth should largely apply for planted as well as natural seedlings once planted seedlings have overcome transplant stress (Parker and Dey 2007) and comparatively little has been published about planted oak seedling establishment and growth over time, particularly for reforestation options. The critical importance of the postestablishment environment on artificial regeneration success will be emphasized in this review.

Some key characteristics of eastern oak species are that they are intolerant or intermediate in tolerance to shade, tend to be more drought-tolerant than other hardwood species, and grow at rates slower than or equal to those of associated competitors (Smith 1993). Therefore, they tend to be more competitive on xeric sites of low productivity and less so on productive mesic sites (Hodges and Gardiner 1993). In eastern forests, without sufficient size and number of advance reproduction, oaks are unable to compete with other woody species, particularly yellow-poplar (*Liriodendron tulipifera* L.) and red maple (*Acer rubrum* L.) in stands in which these species are prevalent (Kellison 1993). Even when advance oak reproduction is present, it often fails to compete successfully over time if it is not released from overstory shade (Lorimer 1993).

Indeed, successful artificial regeneration of oaks requires an understanding of a complex of factors that include site quality, prior stand condition, site preparation method after harvest or disturbance, oak species to be regenerated, the desired future stand condition, size of seedlings planted, and stand treatments after planting. In addition, laws or policies such as the prohibition of using herbicides in watersheds, or air quality regulations affecting prescribed burning may preclude some stand treatments. All of these factors are interrelated such that changing one will have an impact on each of the others and limit future options. Thus, there is no universal method for artificially regenerating oak throughout the eastern United States; each silvicultural regeneration prescription has a unique cost and probability of success that is dependent on site and stand conditions and a set of management objectives and constraints.

As an example, in a northern red oak regeneration study in the Boston Mountains of Arkansas, Spetich et al. (2002) found that the key factors to consider in planting success were initial seedling basal diameter (stem caliper 2 cm above the root collar), site quality, intensity of weed control, and shelterwood percent stocking. The authors quantified these relationships and produced a model to predict planted tree dominance probabilities—the probability that a planted tree will live to attain a favorable competitive position at a specified year (Figure 1). As will be shown in other research findings reviewed in this article, this model summarizes many of those factors mentioned above that affect the establishment of planted oak seedlings:

1. Seedling size and balanced shoot-to-root ratio—larger seedlings are better than small because juvenile

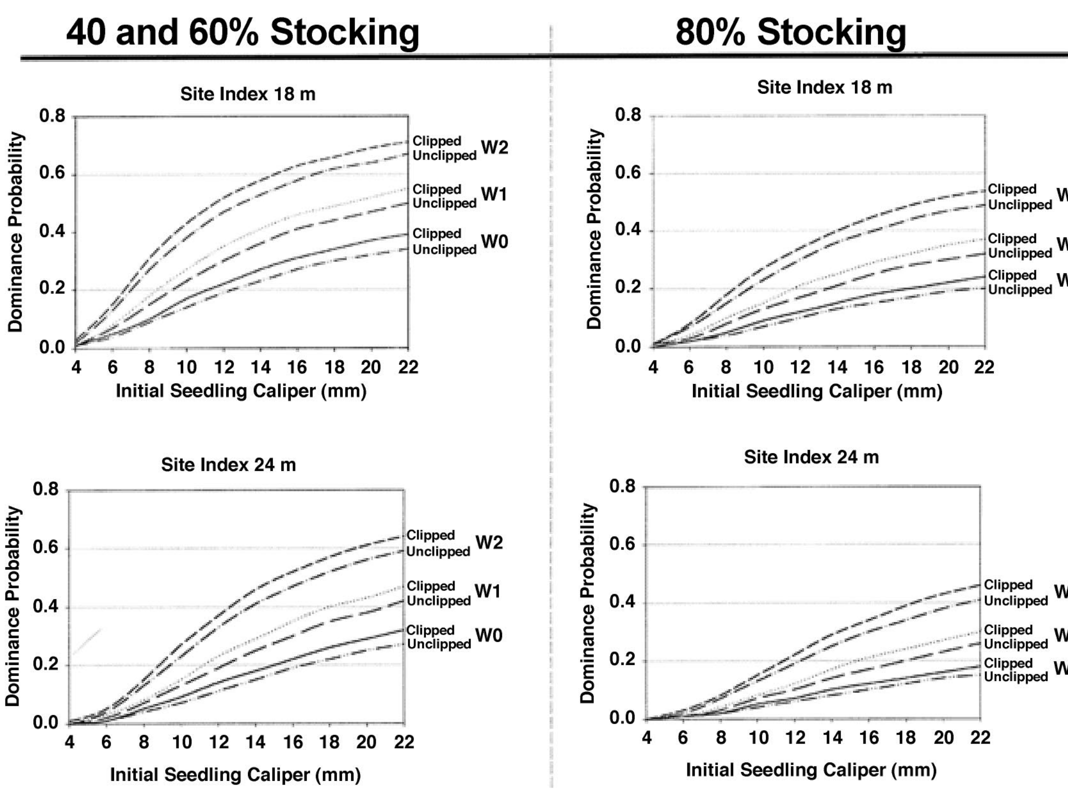

Figure 1. Dominance probabilities for planted northern red oak 2+0 seedlings in relation to initial seedling caliper, shoot clipping (stems clipped at 20 cm above the root collar or not), shelterwood stocking (40, 60, or 80% stocking), site index (18 or 24 m site index for northern red and black oak), and weed control treatment (from Spetich et al. 2002). Seedlings were planted under a shelterwood for 3 years before final overstory removal. Weed control treatments included: none (W0), one (W1), or two (W2) treatments to control competing tree seedlings and saplings (>30 cm tall) by cutting stems and herbicide application to stumps in conjunction with initial shelterwood harvest or final overstory removal. (Reproduced with permission of the authors for Spetich et al. 2002.)

growth in oaks is comparatively slow and an adequate root system increases the competitiveness of oak species.

2. Site quality—more productive sites favor the growth of other species over the oaks.
3. Competition control—this is needed for successful oak establishment because of the slow juvenile growth of oak reproduction and its relative shade intolerance, especially on productive sites;
4. Overstory percent stocking—oaks perform better than shade tolerant species as stocking decreases and understory light intensity increases, but some shade helps to control competing pioneer species that grow aggressively in open environments.

Data to allow direct economic comparison of biologically based alternative methods for artificially regenerating oaks mentioned in this review were generally not available. This is obviously a key research area needing attention. For much of the information presented we assume that the economic factor and resulting suppositions are intuitively understood and considered by managers in meeting their objectives; however, specific cost comparisons are lacking. For example, in certain situations there may be tradeoffs between the expense of growing, planting, and maintaining (e.g., controlling competition) larger seedlings versus the different expenses involved in growing, planting, and maintaining plantings of relatively smaller seedlings and/or direct seedings used in afforestation situations. Therefore, even though the bulk of information presented in this article is from a biological and ecological perspective, we introduce the concept of planting economic efficiency.

Seed Quality

Whether oak is regenerated by direct seeding or planting seedlings, it is important to start with quality, viable seed that is adapted to the planting site. There is tremendous genetic variability between individual trees within an oak species and among stands of oak in different ecoregions (Burns and Honkala 1990) that affects seedling growth habit and rates and survival and competitiveness. For example, Buchschacher et al. (1991) reported that acorns from superior seed trees significantly increased germination and survival of northern red oak seedlings. Generally, it is best to use seed from local sources or ecologically similar environs. Seed should be collected from dominant oak trees that exhibit superior phenotypic traits such as tall straight boles, good diameter growth rates and well-developed crowns (Stroempl 1985, Johnson et al. 1986). Selecting oak seed sources of known quality and growth performance increased percentage of germination and uniformity in nursery beds, resulted in significantly greater heights and diameters, and improved oak seedling quality (Buchschacher et al. 1991, 1993). Collecting seed from unknown sources is not recommended (Teclaw and Isebrands 1991).

Although reports are not always consistent, acorn size can be used as an indicator of seed quality for a wide range of oak species in Europe and North America (Korstian 1927, McComb 1934, Ke and Werger 1999). Farmer (1980) observed a positive correlation between acorn size and seedling height and leaf area for northern red oak, chestnut oak (*Quercus montana* Willd.), white oak and bear oak (*Quercus ilicifolia* Wangenh.). Similarly, Kolb and Steiner (1990) noted that northern red oak seedling biomass and vigor were positively correlated with seed dry mass. Kleinschmit and Svolba (1979) reported strong positive correlation between acorn weight and height growth of English oak (*Quercus robur* L.) and Durmast oak (*Quercus petraea* [Matt.] Liebl.) in Germany. Elsewhere, Bonfil (1998) observed that acorn mass significantly affected height, diameter, leaf area, and biomass of 6-month-old netleaf oak (*Quercus rugosa* Née) and *Quercus laurina* Humb. & Bonpl. seedlings.

The collection of quality seed requires that acorns be gathered when they are fully mature because ripening ceases shortly after acorns are separated from the tree (Bonner 1993). Acorns should be collected immediately after falling from the tree because seed quality can decline rapidly owing to loss of moisture (Teclaw and Isebrands 1986). Bonner and Vozzo (1987) and Bonner (1993) give guidance for collecting quality seed on the basis of physical features that are easily recognized when inspecting acorns. Defective acorns should be discarded, i.e., acorns with small weevil holes, animal damage to and cracks in the pericarp, fallen acorns with cups attached, and moldy seed (Olson 1974). A sample of acorns in a collection can be inspected for soundness, maturity, and internal damage and decay using the cut test (Figure 2). Floating acorns in water is a good method for separating quality acorns from damaged or immature seed, and it also hydrates acorns before they are stratified and stored or sown in the field. For small-scale reforestation projects or research, acorns may be X-rayed to assess viability before sowing (Goodman et al. 2005).

Acorns are recalcitrant, i.e., they have initially high moisture content (e.g., 40–50% for red oaks) and do not tolerate desiccation below about 25–30% moisture content before they begin rapidly losing quality and viability (Korstian 1927, Bonner 1974, 1993, Bonner and Vozzo 1987). The key then to maintaining acorn quality is to avoid seed desiccation. Prompt collection of mature acorns and proper handling, shipping, and storage minimizes loss of seed quality. Guidelines for proper care and handling of seed are given by Olson (1974), Young and Young (1992), Bonner (1993), Dey and Buchanan (1995), and Allen et al. (2004).

Seedling Quality

Successful artificial regeneration of oak begins with planting of the highest quality and most vigorous and competitive seedlings (Duryea 1985). Planting oak seedlings that are capable of early and rapid growth reduces the amount of time that competing vegetation is a problem. A competitive rate of growth for oak reproduction depends on the development of seedlings with a large, physiologically vigorous root system and a high root/shoot ratio (Johnson 1993). Shoot growth increases with increasing root mass, or its correlate, basal diameter of the stem (Dey and Parker 1997, Johnson 1979, Jacobs et al. 2005b). A large root system provides carbohydrates, water, and nutrients in

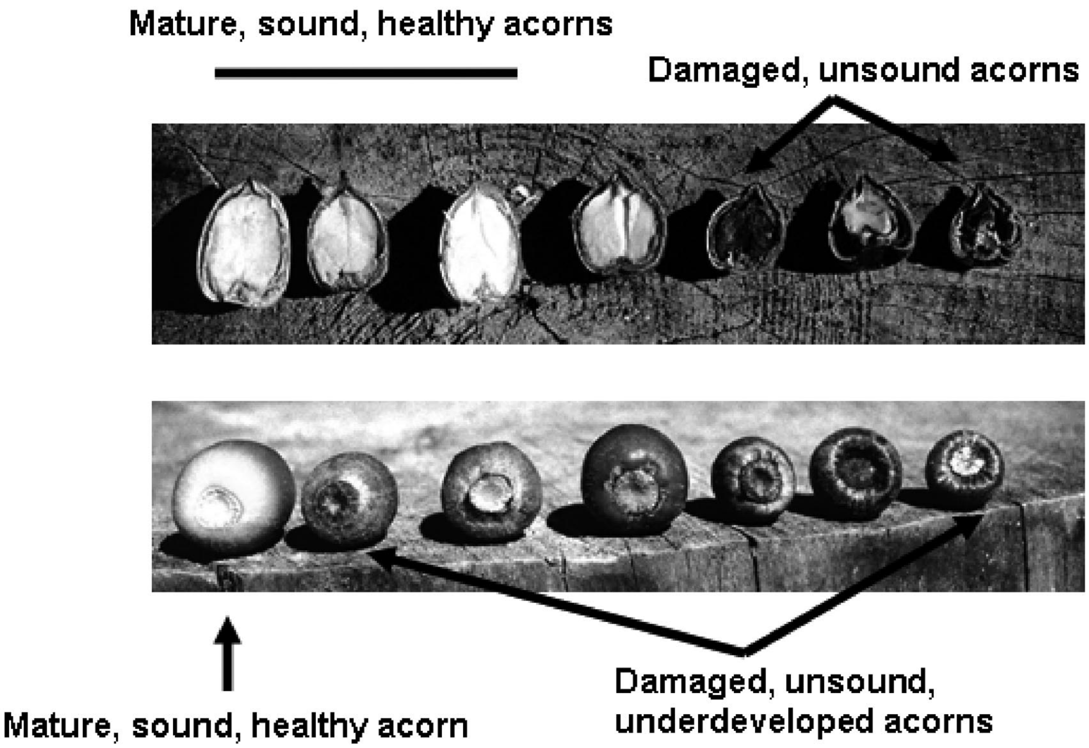

Figure 2. Acorn quality is highly variable, ranging from sound, fully mature acorns (left) to malformed, underdeveloped, and insect-damaged seed (right). It is highly important that artificial regeneration be done with the highest quality seed. The cut test and germination test can be used to evaluate seed lots before sowing seed in the nursery or field. Floating acorns in water or sorting seed by size and weight can be used to identify quality seed.

amounts required to produce new shoots capable of rapid growth after release from overstory cover (Sander 1971, Johnson 1979, Crow 1988), or following planting in agricultural bottomlands (Dey et al. 2003).

In determining seedling quality, hardwood nursery seedlings may be evaluated on the basis of both morphological and physiological indices (Wilson and Jacobs 2006). Morphological variables are those that can be readily observed and easily quantified, such as shoot height, stem caliper, or root system structure. Physiological quality refers to internal characteristics, such as dormancy status or stress resistance. Physiological measures are more difficult to assess, often requiring complex laboratory procedures, yet are of equal or greater value in characterizing overall seedling quality as morphological indices. Numerous research studies have demonstrated the importance of high seedling quality in ensuring artificial regeneration success of oak species in the eastern United States.

Morphological Indicators

Efforts to define stock quality standards have focused primarily on morphological features of northern red oak seedlings that are easy to quantify such as root collar diameter, shoot length, and number of large (>1 mm in diameter at the junction with the taproot) first-order lateral roots (FOLR). Kormanik et al. (1988) and Kormanik and Ruehle (1989) have suggested that the number of FOLR would be good predictors of field performance and competitive ability of planted seedlings. For instance, Kormanik et al. (1995) observed positive correlations between FOLR and field growth and survival of northern red oak and white oak. Good (>12 FOLR), medium (7–11 FOLR), and poor (0–6 FOLR) northern red oak seedlings were outplanted on a productive (30 m site index, base age 50, yellow-poplar) site that was clearcut in North Carolina. After 5 years, competition from tree regeneration, including yellow-poplar, was intense (74,000 stems ha^{-1}). Poor northern red oak seedlings had 65% survival, whereas medium and good seedlings experienced 66 and 70% survival, respectively. However, 52% of good seedlings were free-to-grow compared with 28 and 6% of the medium and poor seedlings, respectively. Thompson and Schultz (1995) reported a significant relationship between the number of FOLR at time of planting and height, diameter growth, and survival of northern red oak. Growth and survival were significantly greater for seedlings with ≥10 FOLR compared with those with ≤4 FOLR. Northern red oak with ≥5 FOLR generally outperform those with fewer FOLR (Teclaw and Isebrands 1991, Bardon and Countryman 1993). Ward et al. (2000) suggested that the initial number of FOLR was more highly correlated with seventh-year height of northern red oak seedlings grown in or out of tree shelters than was initial root collar diameter or initial stem height.

Although field performance is generally improved with increasing numbers of FOLR, it is difficult to determine whether improved performance of seedlings with a higher number of FOLR is directly causal or a function of its correlation with other morphological or physiological variables. For example, Ruehle and Kormanik (1986) found a significant correlation between the number of FOLR in northern red oak seedlings and their height, stem diameter, and shoot and root mass. Furthermore, other studies have given contrasting results concerning the usefulness of FOLR. Ponder (2000) found that the number of FOLR significantly affected 4-year height growth of northern red oak and black oak (*Quercus velutina* Lam.) but not white oak. He found that both FOLR and initial root collar diameter were significantly correlated with 4-year height growth. Similarly, Jacobs et al. (2005b) suggested that FOLR, compared directly with other easily measured variables, was among the least effective predictors of first-year field performance of northern red oak and white oak.

Other morphological indicators of oak seedling quality have also been tested, with the general trend of improved field performance with increasing size. Oak seedlings with root collar diameters larger than 8–10 mm are more competitive than smaller stock planted in clearcut, shelterwood, or old fields (Johnson 1984a, 1992, Stroempl 1985, Johnson et al. 1986, von Althen 1990, Kennedy 1993, Pope 1993, Smith 1993, Dey and Parker 1997) (Figure 1). The growth performance of oak is also improved by planting seedlings with larger initial shoot lengths and stem volumes (Wendel 1980, Kaczmarek and Pope 1993, Dey and Parker 1997). Many researchers recommend planting large oak stock with shoots exceeding 45–50 cm in length (Foster and Farmer 1970, Johnson 1981a, von Althen 1990, Kennedy 1993). Dey and Parker (1997) predicted second-year height and basal diameter of northern red oak bareroot seedlings on the basis of initial stem diameter, shoot length, and number of FOLR. They found that initial stem diameter was the best predictor and FOLR was the weakest predictor of future growth. In addition, they noted that initial stem diameter was associated with many root system traits such as volume, area, and dry mass. Weigel and Johnson (1998a) reported that as white oak seedling stem caliper increased from 6.4 to 12.7 mm, the number of planted trees needed to obtain one dominant or codominant tree 8 years after shelterwood removal decreased from 3.2 to 2.0. Similarly, Spetich et al. (2002), working in the Boston Mountains of Arkansas, estimated that 144 northern red oak bareroot seedlings would need to be planted to obtain one competitively successful tree 11 years after planting (8 years after shelterwood removal) if the seedlings were 6 mm in caliper and shoot clipped at time of planting (Figure 1). In contrast, increasing the initial caliper to 22 mm would reduce the number of trees needed to only five to get one competitively successful tree. In practical applications, total cost per competitively successful tree would determine which of these two options is preferred.

Although a substantial amount of literature on morphological attributes and planting performance exists, seedling quality standards are often not used. Furthermore, recommendations for oak seedling standards that have been proposed are often not based on results from quantitative research. Recommended seedling quality standards may need to be region specific because a tremendous amount of variation exists among oak species and ecotypes. In general, no one seedling characteristic should be used to estimate the quality of planting stock. The bottom line is that, where economic factors and site conditions are equal, planting larger seedlings usually promises a greater probability of success in achieving artificial regeneration objectives.

Physiological Indicators

Several different tests have been used to quantify the physiological quality of oak seedlings. Measurements of root growth potential (RGP) are often used to determine the capacity of seedlings to produce new roots in a favorable environment. Garriou et al. (2000) reported reduced field survival and stem dieback of northern red oak seedlings that had low RGP at the time of planting. A primary disadvantage with RGP testing is that it can take weeks to adequately evaluate seedling condition. Some of the more rapid tests and their potential application to eastern oak species are discussed below.

Shoot water potential provides an indicator of desiccation damage. Webb and von Althen (1980) observed that water potential was positively correlated with RGP readings at planting for northern red oak. Farmer (1978) noted seasonal changes in root carbohydrate content of northern red oak, white oak, chestnut oak, and bear oak seedlings, suggesting that higher levels of root carbohydrates may be an indicator of potential for more vigorous growth as root carbohydrate content decreased during active shoot growth and accumulated as dormancy approached.

Electrolyte leakage (EL) is another physiological test that offers great promise for quality assessment of oak species. The test is used to examine tissue cell damage associated with loss of cell membrane integrity after exposure to low temperatures. Measurement of EL from roots and other plant parts reflects dormancy status, cold hardiness, and stress tolerance, which influence the ability of seedlings to resist physiological damage during lifting, storage, and planting. Little research has been conducted with EL of eastern United States hardwoods, including oaks; most of the research has focused on European hardwood species (Deans et al. 1995, Schute and Sarvas 1999, Sarvas 2001). However, Garriou et al. (2000) observed relationships between fine root EL and factors such as desiccation, RGP, shoot regrowth, and field survival in northern red oak.

The deciduous nature of oak species has limited the application of some physiological quality tests, such as measures of chlorophyll fluorescence (CF) and mineral nutrition. When plants are subjected to stress, changes in the photosynthetic pathways occur. Emission of light energy from the photosynthetic system, termed CF, varies according to the stress level and can be detected through rapid and nondestructive sampling of foliage (Mohammed et al. 1995). Because CF generally involves sampling of foliage during the dormant period, there has been little use of this technique with oak species. However, the potential exists to adapt this measure for use with deciduous hardwoods. Kooistra and Bakker (2002) evaluated CF of western larch (*Larix occidentalis* Nutt.) using chlorophyll from bark tissue. Similar techniques may have application for hardwood species (Makarova et al. 1998, Lennartsson and Ogren 2002).

Mineral nutrition is an important physiological variable that directly affects morphological characteristics such as height or caliper (Birge et al. 2006, Salifu and Jacobs 2006) but also indirectly affects indicators of physiological quality such as cold hardiness (Jozefek 1989). Because foliage is the preferred plant part for nutrient sampling (Landis 1985), timing of measurement is important when mineral nutrient status of deciduous oaks is evaluated. Although testing of conifer foliar nutrient status is typically conducted during winter when nutrient levels stabilize, leaf senescence in oak species necessitates sampling during the growing season. Temporal patterns of nutrient retranslocation can result in large variations in nutrient concentrations over time, which makes comparison and interpretation of results difficult. Thus, additional research may be needed to help refine sampling methodology.

Stocktypes

Success of artificial regeneration may also be influenced by the type of seedling nursery stock used (i.e., "stocktype"), which includes various sizes of bareroot and container seedlings. Nearly all (i.e., >98%) plantings of oak species in the eastern United States are currently accomplished using bareroot nursery stock; in the South only 0.3% of the oak seedlings produced for the 2003–2004 planting season were container seedlings (McNabb and dos Santos 2004).

Seedlings are typically grown to either 1 (1+0) or 2 (2+0) years of age, and these seedlings are rarely graded into size categories. There is typically a large degree of variation in seedling morphological attributes in operational bareroot planting stock, which may translate to a high degree of variability in seedling field performance. Seedlings may also be grown in containers ranging in size from very small (e.g., 150 cm^3) to very large (e.g., 19 L or more). The current constraint to using container stock in oak regeneration is largely associated with the lack of market availability of container seedlings and their cost compared with that of bareroot seedlings. This trend may change, however, as benefits of container seedling performance are realized.

Johnson (1984a) planted northern red oak as various seedling types in clearcut and shelterwood stands in the Missouri Ozarks. Trees were grown in the nursery as either 1+0 bareroot seedlings 10 mm in basal diameter and 88 cm in shoot length, 1+1 bareroot transplants that averaged 10 mm in basal diameter and 56 cm in shoot length, or 1-year-old 492 cm^3 Spencer-Lemaire Rootrainer container seedlings that averaged 7 mm in basal diameter and 61 cm in shoot length. In clearcut stands, the container-grown seedlings had superior growth and demonstrated some of the highest success probabilities, which was defined as the probability that a tree attains a minimum amount of average annual height growth. Small diameter container stock had higher success probabilities than similarly sized bareroot seedlings. In shelterwood stands, height growth of container seedlings ranked just below that of 1+1 transplants, which performed the best of the different seedling types.

Large 11- to 19-L container seedlings with dense and fibrous root systems are being increasingly used in the Midwest for afforesting bottomland crop fields (Dey et al. 2003) (Figure 3). Container stock is more expensive, but there are advantages to planting seedlings with large and intact root systems. Pin oak (*Quercus palustris* Muenchh.)

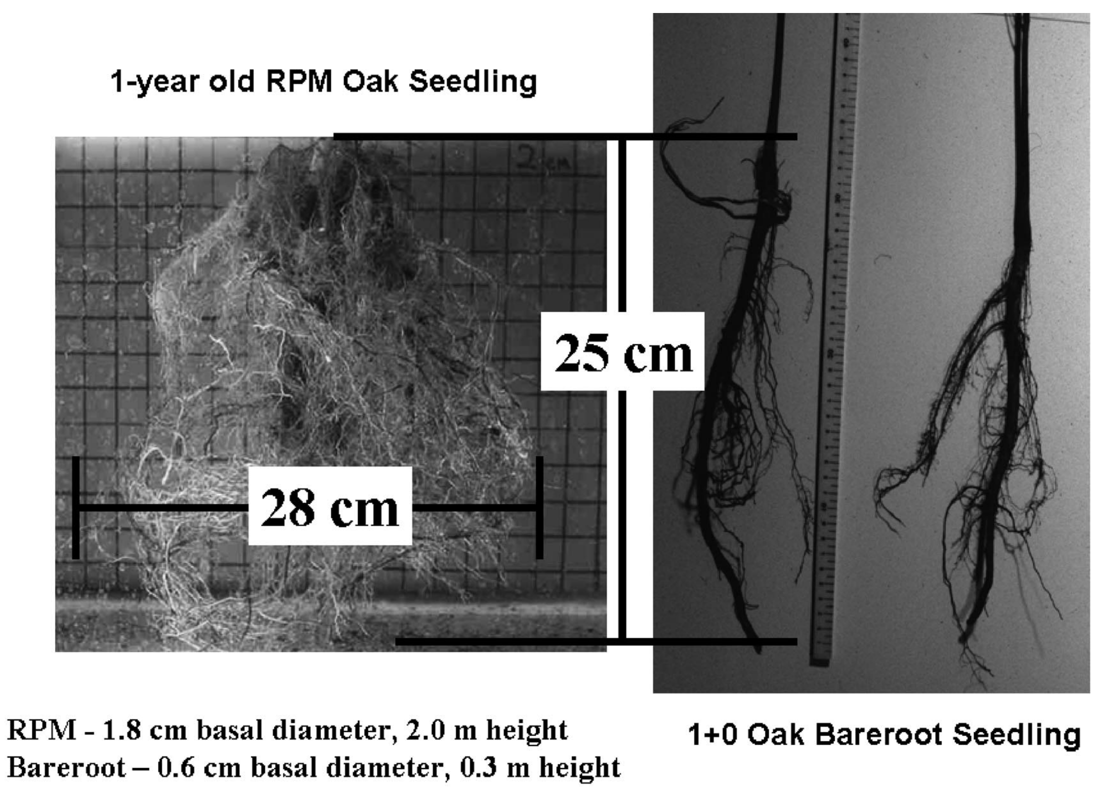

Figure 3. Large, fibrous root systems with abundant FOLR greatly increase the survival and growth of planted oak seedlings in forest and field. Large container stock (RPM) have significantly more root mass and FOLR than bareroot seedlings. Illustrated here are the root systems of 1-year-old swamp white oak seedlings grown by the RPM and typical 1+0 bareroot nursery production method. Kormanik et al. (2004) have developed techniques for growing substantially larger 1+0 bareroot hardwood seedlings with abundant FOLR.

seedlings grown in large containers using the Root Production Method (RPM) (Dey et al. 2004) had nine times the root volume and seven times the root dry weight of 1+0 bareroot seedlings (Shaw et al. 2003). Similarly, RPM swamp white oak (*Quercus bicolor* Willd.) seedlings had four to seven times the root volume and three to six times the root dry weight of 1+0 bareroot seedlings. Oak seedlings can be grown to an average height of 2 m or more with basal diameters averaging 20 mm or more using the RPM in 210 days. Benefits of tall (>1.52 m) oak seedlings include reduced risk of deer browsing terminal buds, decreased probability that tree crowns will be inundated during a growing season flood, and increased ability of oak seedlings to compete with other vegetation for light.

Dey et al. (2003) reported that RPM pin oak and swamp white oak seedlings had significantly greater survival and diameter growth than 1+0 bareroot seedlings 3 years after planting in a Missouri River bottomland crop field. Survival of RPM seedlings was 98% after 3 years, whereas that of pin oak 1+0 bareroot seedlings had dropped to 50% and that of swamp white oak 1+0 bareroot seedlings was 75%. An added advantage of RPM oak seedlings is that they are capable of early acorn production. Grossman et al. (2003) reported acorn production in 18- to 24-month-old RPM swamp white oak seedlings the first fall after they were planted. Dey et al. (2004) observed early acorn production in RPM pin oak seedlings 4 years after planting in a bottomland crop field. The large root mass and high root fibrosity characteristic of the RPM seedling root system may stimulate precocious flowering and fruiting.

Use of container stock offers a means to improve oak regeneration on harsh sites where nutrient or water limitations are likely to induce extended transplant stress in bareroot stock. This is because, unlike bareroot culture, seedling roots are not disturbed at lifting and remain encased within the container media after planting. For example, Davis and Jacobs (2004) reported reduced water stress in container compared with bareroot northern red oak seedlings during the first year after planting on mine reclamation sites.

Shoot Clipping Oak Seedlings

Clipping the shoot of bareroot oak seedlings between 15 and 20 cm above the root collar at or near the time of planting is recommended to improve seedling survival and dominance probabilities (Johnson 1984a, Johnson et al. 1984, 1986, 2002, Zaczek et al. 1997, Weigel and Johnson 1998a, 1998b, 2000, Spetich et al. 2002). Shoot clipping has improved dominance probability of northern red oak bareroot seedlings planted in shelterwood and clearcut stands in various regions including the Missouri Ozark Highlands, the Boston Mountains of Arkansas (Figure 1), southern Indiana, and the Ridge and Valley Province in Pennsylvania. Shoot clipping did not adversely effect water relations or gas exchange in northern red oak bareroot or container seedlings planted in a central Missouri clearcut or shelterwood stand (Crunkilton et al. 1992). Gordon et al. (1995) reported that shoot clipping of northern red oak bareroot seedlings planted in a southern Ontario shelterwood stand negatively affected seedling height 6 years later. They observed heavy deer browsing on planted oak seedlings and suggested that the succulent sprouts from clipped seedlings were heavily browsed by deer. In east-central Mississippi, Lockhart et al. (2000) reported that clipping the shoots of cherrybark oak natural advance reproduction 2.5 cm above the ground at the time of midstory canopy removal in mature bottomland forests did not increase seedling heights above that of unclipped seedlings. After 9 years, heights of clipped and unclipped seedlings were similar. Taller seedlings should not be shoot-clipped when they are planted on bottomland sites that are subject to frequent flooding because of the increased potential for crown inundation.

Growing Quality Seedlings

There are a number of nursery cultural practices that can be used to grow large seedlings. These include seed sizing, spacing, fertilization, and irrigation. Seed sizing is commonly used in pine (*Pinus* spp.) nursery culture as seeds of the same size tend to germinate with the same vigor and timing, resulting in more uniform seedling growth and size (Dunlap and Barnett 1983, Boyer et al. 1985, May et al. 1985). Reducing such variability is important for producing uniform crops. Mexal and Fisher (1987), for example, found that the time of emergence accounted for >80% of variation in the harvest biomass of nursery-produced loblolly pine (*Pinus taeda* L.). The same seems to hold true for hardwoods including large seeded species such as oak. Karfalt (2004) found that the seedling harvest size for both northern red oak and white oak was strongly correlated to seed size. Even so, Kormanik et al. (1998) showed that within oak seed size classes there are considerable growth differences between trees, stating that "the larger the acorn the larger the seedling, but that larger acorns of themselves do not necessarily yield large seedlings." Certainly, the issue of seed quality is crucial to successful nursery culture of oaks. The availability of oak seed of sound quality and known origin is one of the most serious limiting factors to quality seedling production. Nursery managers often buy seed from processors that mix seed lots from diverse origins and ages.

Nursery sowing density is a second well-established factor affecting seedling size. As a general rule, hardwood species demand much more nursery growing space than conifers. The *Hardwood Nursery Guide* (Williams 1994) recommends a spacing of 108–161 seedlings m^{-2} for oak species. Currently, most nursery managers probably grow oaks at 54–108 seedlings m^{-2} (Rentz 1999). At this spacing, a difference of 1 or 2 seedlings can increase or decrease density by a relatively large amount compared with conifers that are grown at around 215 seedlings m^{-2}. Growing northern red oak seedlings at uniform spacings and lower seedbed densities (e.g., 32–86 m^{-2}) produces a high percentage of plantable seedlings and few culls (Barham 1980). Northern red oak seedlings grown at lower seedbed densities have more permanent FOLR and larger root systems than seedlings grown at higher densities (Schultz 1990, Schultz and Thompson 1993). Lower seedbed densities also result in taller and larger diameter northern red oak seedlings (Figure 4) (Taft 1966, Barham 1980, Schultz 1990). Wichman and Coggeshall (1983) found that a spacing of

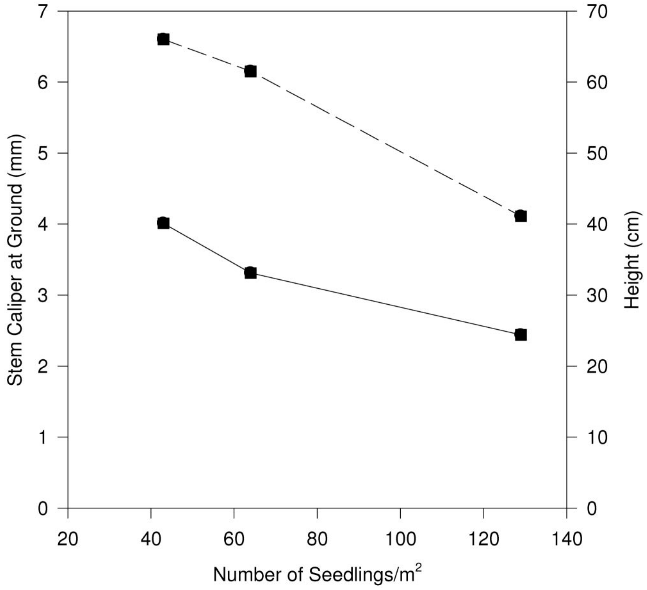

Figure 4. Size of 1+0 northern red oak seedlings in relation to nursery bed density (adapted from Taft 1966). Seedbed densities are often higher than optimal for growing large seedlings with abundant large FOLR, resulting in small diameter oak seedlings that have lower probabilities of regeneration success. (Reproduced with permission from the US Forest Service.)

129 seedlings m^{-2} produced a white oak root collar diameter of 3.1 mm, whereas reducing spacing to 43 seedlings m^{-2} produced a seedling of 4.1 mm. Schultz and Thompson (1997), Barham (1980), and Kennedy (1988) have also documented a positive oak seedling growth response to seedbed spacing.

Scientific literature regarding the nutritional demands of nursery-produced hardwood planting stock is scarce. It appears, however, that hardwoods are generally more demanding of nutrients than conifers. Davey (1994) indicated that hardwood seedling culture requires 50% more nitrogen than conifers, slightly more phosphorus, and approximately 25% more potassium. This demand is partially related to the fact that hardwoods are larger than conifers with considerably more biomass per individual seedling. Recent research has examined the potential to nutrient-load seedlings by inducing luxury consumption of nutrients (Birge et al. 2006, Salifu and Jacobs 2006). Oaks and other hardwoods also require more irrigation (i.e., generally twice that of loblolly pine and slash pine [*Pinus elliottii* Engelm.]) (Davey 1994). Typically, oaks will respond to increased fertilizer and water through increases in biomass, if other factors such as spacing are not limited.

Cultural factors such as seed sizing, seedling spacing, fertilization, and water availability directly and severely affect seedling morphological development. These factors can be manipulated to change seedling morphology, resulting in larger or smaller phenotypes, depending on the objective. However, the complex interaction of genetics with these environmental factors, which ultimately determines seedling phenotype, is not clear. Whereas nursery beds may appear to be uniform, they are actually highly variable, with seedling morphological development affected by changes in growing conditions such as vegetative competition, mulching depth, drainage, and herbicide and/or cultivation damage. Tomlinson et al. (1996), for example, found a complex interaction between mulch depth and the depth of sowing northern red oak with the time to emergence increased by increasing mulch and sowing depths.

It should not be assumed that superior phenotypes (i.e., large seedling sizes) in the nursery are a result of superior genetic traits. Genetic selection on the basis of nursery phenotypes was abandoned early for conifers. In fact, the effect of the nursery environment can bias genetic studies for many years after planting (Wright 1976). At present we know of no reason that the same principle is not true for other genera. In fact, heritability of seedling height in a nursery environment is so low (generally <0.10) that the vast majority of the variation is due to microenvironment rather than genetic effects (Stonecypher et al. 1965). It can be inferred that nursery phenotype selection (i.e., culling) of oaks will not result in selection of superior genotypes.

The vast majority of oak planting is done on nonindustrial private lands, whose ownership group has traditionally been very cost conscious (Royer 1987, Ross-Davis et al. 2005). As afforestation/reforestation costs increase and/or the availability of applicable cost shares decline, nonindustrial owners have historically reduced the area they plant. An increase in seedling cost, the most obvious component of the total regeneration cost, will probably result in fewer hectares planted or fewer seedlings planted per hectare by this group. However, as discussed later, the total stand establishment cost, or total cost per competitively successful tree, not just the seedling cost, is the figure that should be considered when one is comparing regeneration costs.

Direct Seeding

Direct seeding has been used successfully to regenerate oak (Kennedy 1993, Schoenholtz et al. 2005). Johnson and Krinard (1985, 1987) and Johnson (1984b) have successfully regenerated southern bottomland oaks by direct seeding in the Lower Mississippi Alluvial Valley (LMAV), as did Wittwer (1991) in Oklahoma where he regenerated water oak, willow oak (*Quercus phellos* L.), and Shumard oak (*Quercus shumardii* Buckl.) on a poorly drained clearcut bottomland site. Oaks have also been successfully regenerated by direct seeding in the Lake States (e.g., Shirley 1937, Scholz 1964). The greatest use of this method of oak regeneration has been in the LMAV (Twedt and Wilson 2002, Allen et al. 2004, Gardiner and Oliver 2005), where about 6,900 ha of floodplain were regenerated by direct seeding from 1986 to 1997 (King and Keeland 1999).

In the late 1980s, direct seeding was a primary method used to regenerate oak on thousands of hectares in the LMAV (Schoenholtz et al. 2005). Managers adopted this method of regenerating oak because, in part, the initial costs of sowing acorns can be one-third to one-half the expense of planting bareroot seedlings, and a smaller fraction of the cost of planting container trees (Bullard et al. 1992, Pope 1993, King and Keeland 1999). Another advantage of direct seeding is that oak seedlings are able to develop natural root systems on the site, thus eliminating the root injuries associated with planted bareroot seedlings. Direct seeding also has particular advantages in regenerating oaks on shallow-soiled sites, where planting large bareroot or container seedlings is difficult and expensive. A final advantage of direct seeding over seedling planting is that it can be done over a greater part of the year, thus giving managers more flexibility in working around wet site conditions that limit equipment use or droughts and floods that may reduce regeneration success (Savage et al. 1996, Clatterbuck 1997, Allen et al. 2004).

Early interest in direct seeding oak has subsided for a number of reasons and today more managers are turning to planting bareroot and container trees to regenerate oak (Schoenholtz et al. 2005). Research on direct seeding and surveys of operational plantings have revealed that survival and growth of direct-seeded oak are not as good as that of oaks that were established as planted seedlings. Although the germination rate of direct-seeded acorns may be as high as 85% and first-year survival may be comparable to that for other types of oak reproduction (Shirley 1937, Stroempl 1990, Bowersox 1993), acorn germination typically averages 35–40% in field plantings and over time seedling survival is lower than that with planted seedlings (Kennedy 1993). In fact, it is not unusual for only 10–25% of sown acorns to produce seedlings after 10 years (Allen et al. 2004).

In the early years after planting, height growth of direct-seeded oak may be comparable to that of bareroot seedlings. For example, both Bowersox (1993) and Zaczek et al. (1993) reported that height growth of direct-seeded northern red oak was equal to that of 1+0 bareroot seedlings several years after planting in clearcut stands and that survival of direct-seeded oaks was initially high. But, the oft reported long-term result is that direct-seeded oak reproduction is substantially shorter than that for trees planted as bareroot seedlings 10–20 years after establishment in upland clearcut stands (Zaczek et al. 1997) or in bottomland clearcut stands and old fields (Allen 1990, Wittwer 1991, Stanturf and Kennedy 1996, Twedt and Wilson 2002, Stanturf et al. 2004) for a wide variety of oak species.

The net result of lower survival and reduced height growth in direct-seeded oaks is that oak stocking is often inadequate when reforestation is by direct seeding (Allen 1990, Wittwer 1991, Miwa et al. 1993). Managers have less control over forest composition and distribution of oak on the site when regenerating by direct seeding than when planting seedlings, which, in contrast, results in higher and more uniform oak stocking (Twedt and Wilson 2002). Managers are more likely to achieve regeneration goals and have higher probabilities of oak regeneration success by planting seedlings (Allen 1990, Bullard et al. 1992, Williams et al. 1999).

Nursery production of oak seedlings is viewed as a more efficient use of a limited seed supply (King and Keeland 1999), which in years of poor acorn production can limit direct seeding operations. For species in the red oak group, managers can reduce seed supply problems caused by fluctuations in production and losses to insect and mammal seed predators, by collecting surplus seed in years of bumper acorn crops and holding that seed in cold storage for 3–5 years (Bonner 1973, Bonner and Vozzo 1987). In contrast, seed supply for the white oak species is more problematic because it can only be stored for 4 months or less, which is why it is recommended that it be planted immediately in the fall after it is collected (Allen et al. 2004). Lack of local seed that is adapted to the planting environment can seriously limit the amount of area reforested annually. For a given amount of seed, more area can be reforested by planting seedlings than seed because the critical stages of seed germination and initial seedling establishment occur in the nursery where managers have better regulation of the regeneration environment through irrigation, fertilization, and control of weeds, diseases, and other pests. Thus, the seed to viable seedling ratio is lower under nursery production than in direct seeding operations in the field.

Failures in direct-seeded oak plantings are common, and causal factors are numerous (Savage et al. 1996, Stanturf et al. 1998, King and Keeland 1999, Twedt and Wilson 2002, Allen et al. 2004, Schoenholtz et al. 2005, Gardiner and Oliver 2005). Oak regeneration failures have been attributed to poor quality seed, inadequate site preparation, improper species-site selection, improper depth of sowing, seeding when soil conditions are suboptimal, sowing too late to avoid summer drought, failure to control competing vegetation, and high densities of small mammals and rodents, leading to high rates of seed predation and herbivory. Some of these factors affect all types of oak reproduction, but several are weaknesses of the direct seeding method alone. Nonetheless, it is possible to successfully regenerate oak using the direct seeding method if recommended procedures are followed (e.g., Allen and Kennedy 1989, Kennedy 1993, Clatterbuck 1997, Stanturf et al. 1998, 2004, Allen et al. 2004). We present below a summary of key considerations that may improve the likelihood of success in direct seeding oaks when incorporated into a silvicultural prescription.

Predation of Acorns by Small Mammals

Although there have been occasional successes in regenerating oak by direct seeding, the practice has typically not been successful (Mignery 1975, Johnson 1981b, Zaczek et al. 1997). Consumption or destruction of acorns by small mammals is cited as the major cause of direct seeding failures (Shirley 1937, Johnson and Krinard 1985, 1987, Bowersox 1993, Savage et al. 1996). Mice (*Peromyscus* spp.), voles (microtines), chipmunks (*Tamias* spp.), cotton and rice rats (*Sigmodon hispidus* and *Oryzomys palustris*), rabbits (*Sylvilagus* spp.), and squirrels (*Sciurus* spp.) damage acorns before they germinate and young seedlings during establishment (Nichols 1954, Pope 1993, Savage et al. 1996, Dugger et al. 2004). Acorn consumption by small mammals often occurs within weeks after sowing (Smith 1993). Where populations of small mammals are dense as is often the case in agricultural floodplains (Stanturf et al. 2004), direct seeding may be particularly problematic. Successes in direct seeding of oak are often attributed to low population levels of small mammals (Shirley 1937, Marquis et al. 1976, Zaczek et al. 1993).

Control of Small Mammals

Efforts to reduce the amount of acorn predation by rodents have led to the development of a variety of control techniques. Poisoned baits, chemical repellents, and scent-treated acorns have not been successful in reducing acorn predation (Shirley 1937, Nichols 1954, Johnson and Krinard 1987). Physically protecting acorns from rodents by covering seeds with wire mesh screens is one of the more effective means of reducing predation, but it is costly to administer (Shirley 1937, Stoeckler and Scholz 1956, Russell 1971). Plastic tree shelters provide adequate protection for oak seedlings when they are installed immediately after sowing and are set below the soil surface (Allen and Boykin 1991, Smith 1993, Graveline et al. 1998, Stanturf et al. 2004). Unfortunately, most of the control measures are usually cost-prohibitive on large scale reforestation projects, and there are problems in maintaining shelters in floodplains where they can be dislodged by flowing water, flattened by a heavy mat of herbaceous vegetation and woody vines, or filled with flood sediments.

Timing of Sowing

The amount of acorn predation is also influenced by other activities associated with regeneration such as the timing of sowing, site preparation, and vegetation management. It is unclear whether spring or fall sowing is preferred. Those who recommend spring sowing attribute better germination to lower rodent populations in the spring and reduced time of seed availability to rodents (Shirley 1937, Nichols 1954, Pope 1993). Fall sowing may be beneficial because (1) the germination rate is higher than in spring sowings, (2) the need for overwinter storage of seed is eliminated, (3) fall-sown seeds are planted when the availability of alternative foods is high, (4) fall-sown seed germinates in the spring as soon as temperatures are warm enough, which is earlier than for most spring-sowing operations, (5) germination of fall-sown seed is less likely to be affected by a dry spring than that of acorns planted in the late spring, and (6) acorns sown in the fall are less attractive to rodents than spring-planted acorns. However, others report that seasonal time of sowing has little influence on the success of direct seeding, provided the soils are not too dry or wet (Sander 1982, Johnson and Krinard 1985, Pope 1993). For example, sowing in the summer has been used to regenerate Nuttall oak, cherrybark oak, water oak, and Shumard oak (Johnson and Krinard 1987, Kennedy 1993). For white oaks (Section *Quercus*), there is consensus that acorns should be sown immediately after fall collection because white oak lacks embryo dormancy and begins germination in the fall (Arend and Scholz 1969, Sander 1982, Kennedy 1993). Regardless of season, sowing seed during years of good to bumper acorn crops may reduce the amount of predation on planted seed (Timmons et al. 1993).

Depth of Sowing

Broadcast sowing of acorns on forest sites or on open fields results in poor germination and regeneration failures, even when acorns are protected from rodents (Sluder et al. 1961, Sander 1982, Timmons et al. 1993). Oak seeds, which must maintain relatively high moisture content to remain viable (Korstian 1927), desiccate on the soil surface and have lower germination than seed that is under leaf litter or buried in the soil because seed is less subject to drying out (Barrett 1931, Pope 1993). Sowing depths from 1 to 15 cm are suitable, but there is little advantage to sowing deeper than 10 cm (Kennedy 1993, Pope 1993, Zaczek et al. 1993). Acorns should be sown deeper (e.g., 5–10 cm) if surface soil temperature and moisture conditions are expected to be a problem during the growing season (Johnson and Krinard 1987). The depth of sowing has not consistently been linked to the amount of rodent predation, although acorns planted deeper than 5 cm may be less likely to be damaged (Johnson 1981b, Johnson and Krinard 1985, 1987). Wood (1998) found that Nuttall oak and willow oak suffered less rodent predation when planted at 7–10 cm in the soil compared with seed that was sown only 3–5 cm deep. Allen et al. (2004) suggested that planting acorns deeper than 10 cm in the soil affords some protection from predators when afforesting floodplains.

Sowing depth and seed size may influence percentage germination and initial seedling growth (Johnson and Krinard 1985, Kennedy 1993). Sowing acorns 10 cm deep reduced germination rate and percentage compared with seed planted 2.5 cm deep (Johnson 1981b). First-year seedling heights were inversely related to sowing depth for Nuttall oak, cherrybark oak, water oak, and Shumard oak (Johnson and Krinard 1985). Most authors recommend sowing acorns between 2.5 and 5.0 cm deep unless rodents are a problem or soil moisture and temperature are concerns (Johnson 1981b, Kennedy 1993, Pope 1993).

Site Preparation

Site preparation is done for many reasons including managing habitat to reduce animal damage to seed and seedlings. Eliminating rodent habitat over large areas by removal or reduction of forest litter, logging slash, and vegetation may reduce the amount of acorn loss to predation (Shirley 1937, Nichols 1954, Krajicek 1960, Schoenholtz et al. 2005). Small mammal predation on acorns commonly increases with increasing height and cover of vegetation in direct seeding to afforest floodplains (Savage et al. 1996, Burkett and Williams 1998, Buckley and Sharik 2002). Animal herbivory on oak seedlings also increases with increasing vegetation cover (Dugger et al. 2004).

Prescribed burning and mechanical scarification not only aid in controlling competing vegetation but also influence the amount and distribution of rodent habitat. Single burns are effective in reducing habitat, especially the cover provided by fine fuels (Shirley 1937, Russell 1971, Sander 1982). Similarly, heavy mechanical site preparation that removes most of the logging debris in forest openings may reduce predation of acorns to $<5\%$ (Johnson 1981b). Double disking is recommended as a means to prepare crop fields for afforestation (Schoenholtz et al. 2005) and often reduces small mammal cover for 1 to a few years (Stanturf et al. 1998). Herbicides are effective in reducing competing vegetation and habitat before sowing seed and planting seedlings (Stanturf et al. 2004), but may subsequently become problematic as oak seedlings are susceptible to most herbicides used to control their competitors. Mowing is effective for reducing habitat but is not a proven means of controlling competing vegetation (Roth and Mitchell 1982, Ponder 1991). Without site preparation, direct-seeded acorns can be removed by herbivores within 1 week. Common site preparation methods are not foolproof in reducing animal damage to oak reproduction, and failures to improve the establishment of oaks have been reported with direct seeding of old fields and cutover sites (Mignery 1962, Crozier and Merritt 1964, Russell 1971). Mammal species and their habitat needs should guide vegetation management, and removal of cover at critical seasonal periods will help reduce damage to seed and seedling.

Size of Opening

The size of the forest opening and the amount of rodent habitat influence the degree of acorn predation. Litter removal around the seed spot does not by itself reduce loss of acorns to mice (Nichols 1954). Substantial rodent damage to acorns occurs with direct seeding under closed canopies or in single-tree gaps (Johnson and Krinard 1985, 1987, Jacobs and Wray 1992, Pope 1993). Johnson (1981b) reported that rodents removed all acorns planted in undisturbed forests within 1 week and damaged 75% of the acorns sown in 12 m $\times$ 27 m cleared strips. Rodents are less likely to move into large openings that do not provide sufficient security cover and so sowing acorns in large openings has been recommended as a way to reduce seed predation by small mammals (Johnson 1983, Jacobs and Wray 1992). Johnson and Krinard (1987) found that rectangular openings of 76 m $\times$ 76 m had considerably less rodent damage to planted acorns than smaller openings. They recommended that site-prepared forest openings be as least 30 m on a side. Their results are supported by Russell (1971), who observed that the majority of acorn damage by both mice and squirrels occurred in forest openings within 30 m from an adjacent hardwood forest. In general, as opening size increases, rodent predation of acorns decreases, provided that habitat cover has been reduced. Fewer than 5% of sown acorns were damaged by rodents on site prepared forest openings of at least 1 ha in size (Johnson 1981b, Johnson and Krinard 1985, Pope 1993). However, the growth of competing vegetation is favored in larger forest openings and slow-growing oak reproduction is less likely to be competitive without vegetation control (Johnson 1984b, Jacobs and Wray 1992). When afforesting agricultural floodplains and old fields, Clatterbuck (1997) recommended that planting be done in fields larger than 2.0 ha, that planting be done further than 61 m from the field edge, and that planting not be done in long narrow fields. Stanturf et al. (1998) suggested a minimum field size of 1.0 ha. It is important to consider habitat surrounding the planting site because it is hard to control mammals in small fields (e.g., $<$0.8 ha) that are surrounded by forest or old field vegetation (Johnson and Krinard 1985 in Schoenholtz et al. 2005).

Density of Sowing

The required density of sowing depends on desired oak stocking, germination capacity of the acorns, and amount of acorn predation. The germination capacity of any seedlot should be determined before calculating a seeding rate. However, professional experience is required when fall-sowing red oak species because germination tests cannot be performed in the fall. Various recommendations have been offered for determining sowing rates for oaks. Both Kennedy (1993) and Johnson and Krinard (1987) suggested that 35% germination is a typical rate for red oak species; hence, 2,500–3,700 seeds ha^{-1} can be expected to produce 750–1,200 1-year-old seedlings ha^{-1}. These sowing rates could produce from 370–925 free-to-grow oaks ha^{-1} in 10 years (Pope 1993). Jacobs and Wray (1992) recommended sowing at least twice as many spots as trees wanted and that 3–4 seeds should be planted at each spot. Where rodent activity is high and litter is removed, 3.7 acorns should be planted to produce 1 seedling (Nichols 1954).

Old fields in the LMAV are normally sown at 1,700–2,500 seeds ha^{-1} or at 3,000–3,700 seeds ha^{-1} where harsh site conditions (i.e., severe summer drought or heavy clay soil), heavy weed competition, or rodents are expected to be a problem (Stanturf et al. 1998, Allen et al. 2004, Gardiner and Oliver 2005). Savage et al. (1996) improved oak regeneration success by increasing sowing density to 5,900 seeds ha^{-1} in areas where rice and cotton rat populations were high in the LMAV.

There may be no upper limit to sowing density if the strategy is to overwhelm predators, as in a high mast (i.e., bumper crop) year. Acorns are valued food for many species of wildlife and insects, who commonly consume most of the acorn crop in years of low to moderate seed production (Beck 1993, McShea and Healy 2002, Oak 2002). One of several hypotheses to explain masting in oaks is that acorn predators are satiated when oaks produce high mast crops (Silvertown 1980, Kelly 1994, Koenig and Knops 2002). Sork et al. (1993) hypothesized that the periodic production of large seed crops by species such as the oaks may represent an evolutionary response to cope with intense seed predation. Because acorns are such an important energy source for wildlife, insects and diseases, production of sound acorns, and establishment of oak seedlings occurs primarily in high mast years (Downs and McQuilken 1944, Gysel 1957, Oak 2002).

However, when seed is sown in high density (e.g., $>$2,500–3,700 seeds ha^{-1}) to compensate for anticipated low germination or loss of seed and seedlings to predators, flood, or drought, the cost per hectare of seed can equal the cost of seedlings, depending on the particular oak species (i.e., the number of seed per kilogram) and price per kilogram of available seed (Gardiner and Oliver 2005). Most economic comparisons of direct seeding and other regeneration methods do not consider the cost of the entire silvicultural prescription that may include site preparation, vegetation control, and animal damage control measures. A more meaningful cost comparison would be to determine the cost per successful tree (i.e., a free-to-grow tree that does not require further management to maintain its dominance). However, the initial cost of establishment is an important determinant of the method of regeneration that must be balanced with the likelihood of successfully meeting long-term management objectives.

Diversionary Foods

Bowersox (1993) has suggested that animal predation of direct-seeded acorns will be low if alternative food supplies are adequate. Animal predation of direct-seeded acorns may be especially intense in years of low natural acorn production or on nonoak sites that lack a natural acorn supply. Providing predators with alternative food sources has been successful in reducing losses of direct-seeded western conifers. Diversionary foods such as sunflower (*Helianthus* spp.) seeds and oat (*Avena sativa*) kernels have been effective in reducing conifer seed predation by deer mice (*Peromyscus maniculatus*) (Sullivan 1979, Sullivan and Sullivan 1982). However, recommendations for using diversionary foods to assist regeneration of eastern hardwoods have yet to be developed.

Genetic Diversity

Johnson and Krinard (1987) suggested that a mixture of seeds from several parent trees should be sown to maximize the genetic diversity of oak reproduction, provided that all seed sources have good phenotypic traits. Stanturf et al. (2004) recommended planting a mixture of oak species that exhibit variability in flood tolerance as a strategy for matching species to site conditions and hydrological regimens in afforesting floodplains.

Silviculture of Oak Plantings

In forests, successful oak regeneration is generally dependent on adequate numbers of large advance reproduction (Sander 1971, 1972, Hodges and Gardiner 1993, Johnson et al. 2002), and planting oak seedlings or direct seeding acorns can be used to increase densities to adequate levels. In afforestation of agricultural lands, planting and seeding oaks is needed to ensure the presence of oak in the reproduction pool because local seed sources are often lacking and there is no existing oak stock for vegetative reproduction. In either situation, managers need to meet the silvical needs for oak species by planting acorns or seedlings on appropriate sites and by modifying the microenvironment to promote oak survival and growth over that of its major competitors. Modifying the regeneration environment and controlling competing vegetation are achieved through regeneration harvesting and site preparation and vegetation management using fire, chemical, or mechanical methods. Success of oak reproduction also requires planting of high-quality seedlings and minimizing wildlife damage to those seedlings. Specific silvicultural prescriptions need to account for soil conditions, site hydrology, existing vegetation composition and structure, and species of oak involved because oak species vary in their ability to tolerate flooding and saturated soils, to compete for light and other resources, and to tolerate drought (Burns and Honkala 1990)

Managing Light for Oak Regeneration

Low light in the regeneration environment (e.g., <5% of full sunlight in mature forests) along with the intolerance of oak to heavy shade has been singled out as a critical underlying factor in oak regeneration failures and in the successional displacement of oak by more shade tolerant species (Figure 5) (Abrams 1992, Lorimer 1993, Hodges and Gardiner 1993, Lorimer et al. 1994, Dey and Parker 1996, Gardiner and Yeiser 2006). Oak is much less shade tolerant than many of its competitors, and most oak species are classified as intermediate or intolerant of shade (Burns and Honkala 1990). In the low light of a mature forest understory, a population of northern red oak seedlings germinating from acorns on a productive mesic site can become extinct in a matter of 10 years without management (Tryon and Carvell 1958, Johnson 1975, Loftis 1990b, Lorimer 1993). Foresters must intervene by controlling competing vegetation and, hence, the light available for developing

Figure 5. (A) Mature, unmanaged hardwood, Ontario (96% crown cover, 30 m^2 ha^{-1}, 1% full sunlight). Mature, unmanaged hardwood forests have extremely low light levels that are insufficient for survival of oak advance reproduction. Managers have several silvicultural techniques for increasing light in the forest understory including midstory thinning and shelterwood harvesting. (B) Mature bottomland hardwood midstory removal, Mississippi River floodplain (86% crown cover, 34 m^2 ha^{-1}, 16% full sunlight). (C) Red oak shelterwood harvested, Ontario (60% crown cover, 18 m^2 ha^{-1}, 49% full sunlight). Substantial reductions in forest stocking, including removal of midstory trees, is necessary to increase light for maximum oak net photosynthesis and growth, which occurs between 30 and 70% of full sunlight depending on the species.

larger oak reproduction and promoting its growth into the overstory. How much light is required for oak regeneration and recruitment into the overstory varies by oak species, and there is a wide range of availability of detailed ecophysiology information by species.

The light compensation point for northern red oak is low (i.e., approximately 2–5% of full sunlight) (Gottschalk 1987, Hanson et al. 1987), but much higher light levels are needed to maximize seedling net photosynthesis and growth. In general, light saturation of photosynthesis in oak species such as northern red oak and cherrybark oak occurs at 30–50% of full sunlight (Teskey and Shrestha 1985, McGraw et al. 1990, Ashton and Berlyn 1994, Gardiner and Hodges 1998, Gardiner 2002). In Ontario, Parker and Dey (2007) reported that reducing crown cover to 50 or 80% by shelterwood harvesting increased net photosynthesis and leaf conductance to water vapor in northern red oak reproduction (both natural and planted 2+0 bareroot seedlings) by two to three times that of its major competitor, sugar maple (*Acer saccharum* Marsh.). Planted and natural northern red oak seedlings had similar leaf gas exchange and water status under the shelterwoods. These shelterwoods, which increased light intensity in the understory to 27–49% of full sunlight, favored the photosynthetic potential of northern red oak over that of sugar maple and hence increased oak regeneration potential. In general, oak seedling height and diameter growth are often maximized at light intensities approaching 50–70% of full sunlight (Musselman and Gatherum 1969, Phares 1971, Gottschalk 1994, Gardiner and Hodges 1998).

In forests, increasing light to benefit oak reproduction (whether natural or artificial) requires reducing tree stocking and shrub density. This is typically done by removal of mid- and understory stems and by harvesting using one of the regeneration methods (Smith et al. 1997). Removing midstory trees and shrubs alone improves light levels slightly, and oak reproduction does benefit from the increased light (Figure 5). Lorimer et al. (1994) were able to increase understory light from 1% in undisturbed stands to 7–9% of full sunlight in mesic oak-northern hardwood forests by removing the taller woody subcanopy understory stems >1.5 m tall (i.e., trees were cut and stumps were sprayed with Tordon 101R). This level of light increased the survival and growth of planted northern red oak and white oak bareroot seedlings. Similarly, Lockhart et al. (2000) found that removal of the midstory (by cutting and applying Tordon 101R to the stumps of stems ≥2.5 cm dbh) in a mature southern bottomland hardwood forest increased light levels in the understory and improved the survival and height growth of cherrybark oak advance reproduction. However, to achieve the 30–50% of full sunlight needed for maximum growth of oak reproduction requires more significant reductions in stand stocking through harvest of the overstory.

Reducing overstory stocking by single-tree selection creates small canopy gaps and light regimens similar to those of uncut, fully stocked stands, which are insufficient for the long-term survival of oak reproduction (Della-Bianca and Beck 1985, Jenkins and Parker 1998). One notable exception is the use of uneven-aged regeneration methods to manage oak forests on low to moderately productive sites in the Missouri Ozark Highlands (Loewenstein et al. 2000). There, lower stand density and less stand structure, in the absence of a shade-tolerant competitor (white oak is the sugar maple of the Ozarks), permit the accumulation and development of large oak advance reproduction, and its recruitment into the overstory of moderately stocked stands (basal area <14 m^2 ha^{-1}).

More commonly, regeneration methods that create larger openings (i.e., large group openings or clearcut sites) or reduce overstory stocking substantially (i.e., shelterwood harvest) are recommended for oak regeneration (Johnson et al. 1986, Loftis 1990b, Weigel and Johnson 1998a, 1998b, Spetich et al. 2002, Gardiner and Yeiser 2006). Oak reproduction grows well in group selection harvested gaps with a d/h ratio ≤ 1.0, where d is gap diameter and h is the average height of the adjacent stand (Minckler 1961, Marquis 1965). The clearcutting method has been most successful for regenerating oaks in xeric ecosystems **(**Johnson et al. 2002). However, releasing small oak reproduction to full sunlight by clearcut or large group selection harvests without concurrent competition control has not been successful in many places because oak seedlings are quickly suppressed by either well-established shade-tolerant advance reproduction or fast growing, shade-intolerant species (McQuilkin 1975, Smith 1981, Loftis 1983, Beck and Hooper 1986, Ross et al. 1986, Canham 1988, 1989, Loftis 1990a, Lorimer 1993, Orwig and Abrams 1994, Weigel and Parker 1997, Jenkins and Parker 1998, Brose and Van Lear 1998).

Shelterwood harvesting that reduces stand stocking by >40% or basal area by >50% or crown cover by >30%, including the removal of any midstory canopy (Figure 5), can provide sufficient light (i.e., 35–50% of full sunlight) to oak reproduction in forests as different as northern hardwoods in New England (Leak and Tubbs 1983), the Lake States (Godman and Tubbs 1973, Lorimer et al. 1994), and Ontario (Dey and Parker 1996); oak-hickory forests in the Missouri Ozark Highlands (Schlesinger et al. 1993) and northeastern Alabama (Schweitzer 2004); and bottomland forests in Arkansas (Gardiner and Yeiser 2006). Sander (1979) generalized for Central Hardwood forests that thinning or shelterwood harvesting to leave a residual stocking of approximately 40% is necessary to produce light levels from 30–50% of full sunlight (Figure 6).

When the shelterwood method is used on higher quality sites, control of understory competing vegetation is particularly important to promote adequate light for oak, as is the maintenance of higher residual shelterwood density to help control shade-intolerant oak competitors (Loftis 1990a, Schlesinger et al. 1993). Higher overstory densities can be maintained without adversely affecting the growth of oak seedlings when understory competition is controlled (Loftis 1990a, 1990b). Larsen et al. (1997) observed that overstory density >70% crown cover or >14 m^2 ha^{-1} limited oak seedling growth and survival in the Missouri Ozark Highland stands that had no competition control in combination with harvesting. Schlesinger et al. (1993) found that control of taller understory woody competitors in the Missouri Ozark Highlands is not necessary on low quality (i.e., site index 18.3 m, black oak, base age 50) sites where oak reproduction did best growing

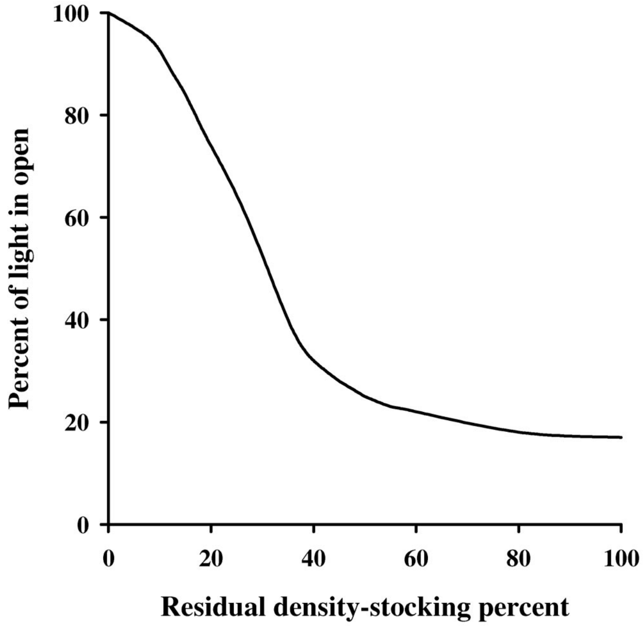

Figure 6. The effect of residual overstory stocking on light intensity at the forest floor in Central Hardwood forest. The general trend is similar in other forest types and at different latitudes. Small reductions in forest stocking hardly affect the understory light intensity. Reducing stocking to 35–45% produces sufficient light of good growth of oak advance reproduction. (Reproduced with permission of the author from Sander, 1979).

under a 40% stocked shelterwood. In contrast, oak reproduction on more productive sites (i.e., site index 21.3 m, black oak, base age 50) did best when stocking was left at 60% and woody understory competition was controlled.

Final removal of the shelterwood overstory when planted or natural oak seedlings are still small results in oak regeneration failures, especially when nothing is done to control competing vegetation. Oaks preferentially direct carbohydrates to root growth at the expense of shoot growth, and if small seedlings do not have sufficient root carbohydrate reserves to support rapid shoot growth, then they lose out to larger shade-tolerant advance reproduction (e.g., maples), or aggressive shade-intolerant reproduction such as yellow-poplar that establish after harvesting (Johnson et al. 2002).

Managing Competing Vegetation in Forest Plantings

Prescriptions for regenerating oaks in forests commonly require control of competing woody vegetation before or at the time of planting and at times after harvesting as needed to maintain oak competitiveness. Competing woody vegetation can be managed by herbicide application, prescribed burning, and mechanical methods. Often combinations of these treatments are used to control competition and benefit oak reproduction. Oaks are prolific sprouters after death of the shoot because they have an abundance of buds around the root collar area and a relatively good supply of root carbohydrates compared with similar-sized hardwood competitors (Johnson et al. 2002). This inherent trait gives oak an advantage when environmental stress, natural disturbances, or management activities cause the death of hardwood shoots (e.g., fire, browsing, drought, or mechanical cutting). Oaks are particularly able to recover from repeated shoot dieback events, and their relative competitiveness is enhanced when such disturbances are frequent during the regeneration period.

Herbicides

Prescriptions to regenerate oak artificially by planting often include the cutting or deadening of stems >2–5 cm dbh at the time of any regeneration harvest (Johnson et al. 1986, Loftis 1990b, Schlesinger et al. 1993, Lorimer et al. 1994, Spetich et al. 2002). Cutting alone reduces competition temporarily because most hardwood species are prolific sprouters for stems in the smaller diameter classes. Unwanted sprout development can be controlled to some extent by leaving a moderate level of overstory stocking (Dey and Jensen 2002), but development of oak reproduction may also be inhibited if too much overstory cover remains.

Loftis (1990b) observed that a moderate residual overstory cover prevented yellow-poplar from establishing and competing with oak advance reproduction before final overstory removal. In southern Indiana, Weigel and Johnson (1998b, 2000) successfully used a 60% stocked shelterwood to suppress yellow-poplar reproduction as they established northern red oak by planting 2+0 seedlings in the shelterwood. However, once they removed the shelterwood 3 years after planting, the yellow-poplar reproduction was released and grew rapidly enough to eliminate the northern red oak over the ensuing 10 years. High overstory shade can effectively hold back the growth of shade-intolerant species, but without reductions in their abundance using herbicides or fire, that competition will intensify with further reductions in overstory density. Crop tree release thinning in young hardwood stands can maintain the development of dominant and codominant oaks and ensure attainment of desired future stocking levels of oak (Schuler and Miller 1999, Miller 2000, Schuler 2006).

Residual overstory density may be kept low if unwanted understory stems are treated with herbicides (e.g., Tordon 101R, Garlon 4, or Roundup) that are applied to the stump surfaces immediately after cutting (Lorimer et al. 1994, Lockhart et al. 2000). Spetich et al. (2002) found that controlling woody competition (trees >30 cm tall) by cutting with a chainsaw and applying herbicides to the stump surface once during the first shelterwood harvest and again during final overstory removal significantly increased dominance probabilities of underplanted northern red oak bareroot seedlings in the Boston Mountains of Arkansas (Figure 1).

Smaller diameter understory and midstory trees (e.g., >1.5 cm dbh) can also be killed by stem injection with herbicides. Effective control of shade-tolerant subcanopy trees has been reported when stems are injected with, for example, Roundup, Chopper EC, Arsenal, or Tordon 101R (Loftis 1990b, Ezell et al. 1999, Peairs et al. 2004, Schweitzer 2004). Others have obtained good control of understory hardwoods and troublesome vines such as honeysuckle (*Lonicera japonica* Thunberg) using foliar sprays such as Escort (metasulfuron-methyl) (Gardiner and Yeiser

1999). In some regions of the eastern United States, ground vegetation interferes with desirable tree reproduction. Hay-scented fern (*Dennstaedtia punctilobula* [Michx.] Moore), New York fern (*Thelypteris noveboracensis* [L.] Nieuwl.), grasses (*Poaceae*), and sedges (*Cyperaceae*) are major interference species on 50% of the forestlands in the Allegheny region (Horsley 1988).

Horsley (1988, 1990) has evaluated numerous combinations of herbicides that, when applied as a mist with air blast sprayers mounted on ground vehicles such as crawler tractors, provide effective control of problem species for several years. For example, mixtures of Roundup and Oust, or Roundup and Surflan are able to control a broad array of competing species. However, if metal cleated tracked crawler tractors are used to air blast spray foliar herbicides, control of ferns is greatly reduced because segmented rhizomes inhibit translocation of herbicides (Horsley 1988). Spraying ground vegetation with tank mixtures that have residual soil activity provides effective control of problem species such as hay-scented and New York ferns and grasses and sedges that germinate profusely after typical logging disturbances to the forest floor (Horsley 1990). Applying herbicides by air blast spraying from ground vehicles in combination with shelterwood cutting can be used to benefit desirable tree reproduction without adversely affecting the diversity of woody and herbaceous species in the understory (Horsley 1994).

Fire

Prescribed fire can be used to control competition around planted oak seedlings. A fire benefits oak reproduction more when seedlings are at least 3 years old, root collars are below ground, and root collar diameters are at least 0.64 cm (Brose and Van Lear 2004). A single fire may kill as much as 70% of oak seedlings that are less than 3 years old (Johnson 1974); it also destroys most acorns that are on the ground surface or lying just under the most recent leaf fall (Auchmoody and Smith 1993). Fire can be delayed after planting until the height of the competition is equal to that of the planted seedlings. Low intensity surface fires are typical for prescribed burns in eastern North America. These fires cause mortality or, more commonly, the death of the aerial portion of the tree (topkill). Fires can easily topkill smaller seedlings and saplings (e.g., $<$10 cm dbh) (Reich et al. 1990, Waldrop and Lloyd 1991, Kruger and Reich 1997, Barnes and Van Lear 1998, Dey and Hartman 2005). The probability of mortality is greatest for seedlings and decreases for larger trees. Stem injection of herbicides can be used to kill larger diameter trees ($>$10 cm) that may be resistant to lower intensity dormant season surface fires. Larger trees may also be girdled or felled to produce smaller diameter sprouts that are extremely vulnerable to being topkilled by subsequent fires. A surface fire can cause topkill or mortality of hardwood seedlings and saplings, but the extent of damage is dependent, in part, on species and season of burning. Summer fires are more damaging than dormant season fires, regardless of species (Waldrop and Lloyd 1991). Oak and hickory (*Carya* spp.) seedlings and young saplings are more tolerant of burning than many of their common associates such as sugar maple, red maple, sweetgum, and yellow-poplar (Swan 1970, Little 1974, Thor and Nichols 1974, Reich et al. 1990, Waldrop and Lloyd 1991, Kruger and Reich 1997, Brose and Van Lear 1998, Barnes and Van Lear 1998).

Younger hardwood trees that are topkilled by fire often produce multiple sprouts from the crown of the surviving rootstock; thus, density of stems often increases after one fire, but tree height is substantially reduced (Figure 7). Consequently, one fire can modify the size structure of hardwood reproduction by concentrating sprouts in the smallest size classes, but it seldom causes major shifts in species composition (Johnson 1974, McGee 1979, Wendel and Smith 1986, Van Lear and Waldrop 1989, Van Lear 1991, Van Lear and Waldrop 1991, Waldrop and Lloyd 1991, Dey and Hartman 2005). However, a single fire designed to enhance oak regeneration has little long-term benefit.

The competitiveness of oak reproduction is improved by a series of fires during regeneration and early stand development (Swan 1970, Thor and Nichols 1974, Kruger and Reich 1997, Brose and Van Lear 1998, Barnes and Van Lear 1998, Dey and Hartman 2005). Several prescribed burns can effectively reduce the reproduction of some species such as yellow-poplar, a major competitor of oak in

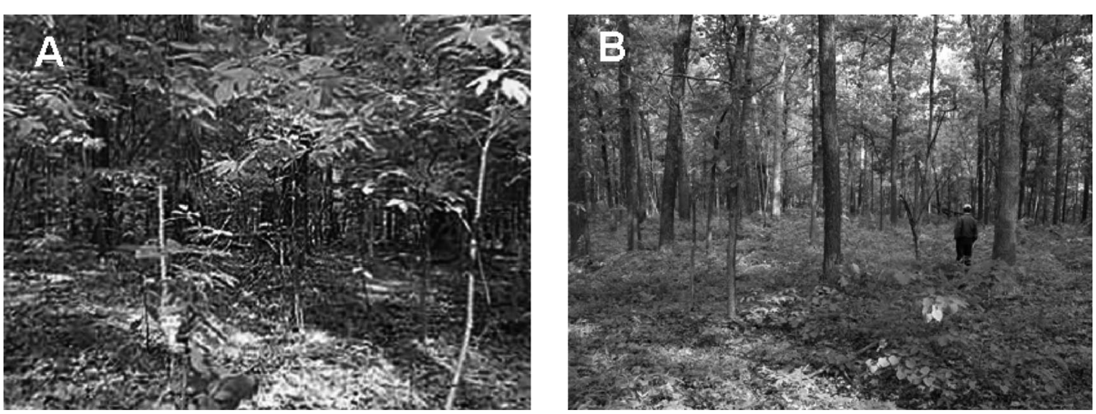

Figure 7. Prescribed burning can reduce forest structure in mature, unmanaged forests (A) by killing or setting back understory hardwood seedlings and saplings (B). Elimination of the hardwood midstory improves environmental conditions for oak advance reproduction primarily by increasing light levels in the understory. Oaks are better adapted than most other hardwood competitors to surviving frequent prescribed fires.

many eastern ecosystems (Barnes and Van Lear 1998). Long-term and relatively frequent, if not annual, burning is needed to effect a significant shift in tree species composition in the regeneration layer of a forest (Waldrop and Lloyd 1991, Van Lear and Waldrop 1991). Thus, one fire can reduce understory structure and favor oak reproduction, but multiple fires are needed to provide longer-term benefits to oak reproduction. Naturally, at some point, there must be a cessation in burning to allow oak seedlings to recruit into the overstory. The specifics for managing fire (i.e., the number and timing of burns in relation to development of oak reproduction and its competition) must be formulated for different ecoregions, stand conditions, and management objectives.

Mechanical

Mechanical scarification with modified anchor chains, disks, or roller chopper drums pulled by rubber-tired skidders or crawler tractors can be used to control competing understory vegetation before planting by shearing off the stems of woody vegetation and uprooting individual plants (Bundy et al. 1991, Jacobs and Wray 1992). Sprouting will probably occur for most hardwood species when root systems remain intact, but planted oaks will benefit in the short term from a reduction in woody competitors. Disking or running metal cleated tracked crawler tractors in forest understories where competitors such as hay-scented fern exist may aggravate the problem because the rhizomes are chopped up and scattered across the site.

Ground scarification may benefit oak reproduction by destroying small rodent habitat. However, scarification should not displace or remove the upper soil horizons. A mixing of leaf litter, humus, and mineral soil provides ideal seedbed conditions, and scarification can release a flush of germination of seed in the soil seed bank, especially when done in conjunction with prescribed burning or timber harvesting. Steep terrain or areas with numerous rock outcrops may limit the use of vehicles for scarification.

Maintaining Oak Dominance by Cleaning and Thinning

Successful regeneration of oak, which may be defined as having the desired stocking of oak in dominant and codominant crown classes at crown closure in a stand, does not ensure the continued dominance of that oak as the forest matures. From crown closure (e.g., stand age 15–25) to stand maturity, trees continue to compete with one another, and stand density of the main canopy declines with advancing age. Mortality takes its toll on some trees, whereas others are relegated to lower crown classes as they lose the battle for growing space to the emerging dominant trees. Ward and Stephens (1994) observed that once northern red oak dropped into the intermediate and suppressed crown classes in maturing northern hardwood stands, there was little hope of it recovering dominance, even if released by crop tree thinning.

Periodic cleanings and intermediate stand thinning may be required to keep oaks free-to-grow until they establish their position of dominance in the canopy of the new stand. Schuler and Miller (1999) described a limited crown release thinning technique that maintained the height growth of planted oaks while limiting the accompanying response of neighboring competitors. Only competitors that were in direct competition with the crown of the planted seedling were cut. This limited cleaning treatment slightly increased height growth of the oaks compared with control trees, yet did not stimulate height growth of competitors as was observed where all neighboring competitors were removed. Once planted oaks reach codominant or better positions in the new stand after canopy closure, one or more crown release treatments as described by Miller (2000) and Schuler (2006) can be used to allocate site resources to the most desirable planted oaks and enhance the probability of long-term survival to maturity.

Managing Competing Vegetation in Oak Afforestation Plantings

If the planting site is in crop production, the best vegetation management protocol is to maintain crops until time for tree-planting. If, however, vegetation has established in former crop fields, then the site must be prepared before planting by removing the ground cover where trees are desired. Vegetation that establishes after tree-planting must also be managed. Within the first summer, oak reproduction can quickly become suppressed by competing vegetation and subjected to extremely low light levels. Bareroot oak seedlings do not compete well in open bottomland fields without some effort to control competing vegetation (Schweitzer and Stanturf 1997). Vegetation management for site preparation before planting or to control competition after planting has been done by various combinations of mowing, burning, disking, cultivating, applying herbicide, or using a physical barrier to weeds such as a fabric mat placed around the seedling. More recently, interest has increased in the use of living mulches to control competing vegetation.

Mowing and Disking

Mowing or disking can be used to improve tree seedling survival and growth on afforestation sites. On heavy clay crop fields in the LMAV, Lockhart et al. (2003) reported that disking before and after sowing acorns or double disking before sowing increased seedling density over that obtained without disking. Krinard and Kennedy (1987a, 1987b) found that mowing or disking between rows of planted Nuttall oak improved seedling height growth after 15 years compared with that of seedlings that received no weed control on Sharkey clay soils in bottomlands of the LMAV. Mowing and disking had been done three to five times per year for the first 5 years. Although the success of these methods has been proven to improve oak regeneration, the method must be applied annually, if not more often, and it is commonly recommended that vegetation control be done for the first 2–5 years after planting.

High growth potential of vegetation on afforestation sites requires significant investment in controlling competing vegetation. Mowing is effective in reducing light competition between tree seedlings and other vegetation but does not affect belowground competition for water and nutrients (Roth and Mitchell 1982, Ponder 1991). Disking can reduce root competition temporarily by physically destroying or disrupting the root systems of competing vegetation, but revegetation of bottomland fields by seed germination and vegetative propagation is rapid. Disking that chops up rhizomes of plants such as Johnsongrass (*Sorghum halepense* [L.] Pers.) can actually increase intensity of competition in the long run and facilitates species spread throughout the plantation.

Herbicides

Herbicides are effective in controlling competing vegetation and improving tree survival and growth, but, as with mowing and disking, annual application may be necessary for approximately the first 2–5 years. Many herbicides used for controlling competing vegetation are capable of killing planted trees. However, oak seedlings can be protected from herbicides by selecting an appropriate application method (e.g., boom application, backpack sprayer, or wick application) that targets the competing vegetation. Seedlings can also be protected by physically shielding them during herbicide application. Care must be taken in applying herbicides to prevent damage to planted trees. Caution should be used in herbicide selection and its application to avoid damage to oak seedlings from chemicals that have soil activity. Stanturf et al. (2004) provided a nice summary of controlling competing vegetation with herbicides in forest regeneration applications.

Plastic and Organic Mulches

Physical barriers such as plastic (Figure 8) or organic mulches provide good control of competing vegetation in the immediate vicinity of the planted seedling, and once installed these barriers provide for many years of weed control (Van Sambeek et al. 1995). However, the weed mat or mulch may provide shelter for small rodents that subsequently cause damage to tree roots and stems. Organic or plastic strips or mats are less effective in controlling vines and taller competing vegetation that may shade planted trees from a distance or physically crush seedlings when the vegetation folds over during the winter. Weed mats and mulches are also less effective in modifying wildlife habitat on the site and thereby reducing animal damage to seedlings, because they are only applied in the planting row or around the seedling.

Living Mulches

Forage crops (Figure 8) and other herbaceous ground covers can be used as a living mulch to suppress more troublesome competing vegetation and improve tree survival and growth (Van Sambeek et al. 2005). At the same time these living mulches may also provide economic benefit to landowners that graze or hay plantations, grow forages for seed production, manage plantings for lease hunting, or produce plant material for the medicinal market. In

Figure 8. Plastic barrier mats can provide control of plant competition in the immediate vicinity of planted oak seedlings. Living mulches such as redtop grass can control the nature and intensity of competition over larger areas. Redtop grass is adapted to moist soil conditions and, therefore, is ideal for afforestation of floodplain crop fields. It quickly develops a sod that reduces the regeneration of annual forbs and fast-growing trees such as eastern cottonwood and willow. Additionally, low-growing redtop grass reduces winter cover for small mammals, which helps to control herbivore damage to planted oaks.

addition, living mulches may be used for soil conservation and to improve water quality. Legume forages as living mulches can improve tree growth by controlling competing vegetation and increasing available nitrogen to trees through microbial fixation in the soil (Van Sambeek et al. 2005). The living mulch must be managed in a way that does not jeopardize tree growth or survival; for example, trees must be protected from grazing livestock.

Living mulches should be adapted to the soils and site hydrological regimen, easy to establish, persist with minimal maintenance, and not increase problems such as damage to seedlings by wildlife, serve as hosts to tree pathogens, or harbor insect pests. It is important that living mulches be capable of forming good sod the first year of establishment to limit development of undesirable vegetation. After canopy closure by trees, living mulches should be at least tolerant of moderate shade if they are part of the overall land management plan. Otherwise, the gradual loss of the living mulch is of little consequence to tree survival and growth because at this stage, trees are dominating growing space and are less affected by competing ground vegetation. Dey et al. (2003) showed that a living mulch of redtop grass (*Agrostis gigantea* L.) improved survival of pin oak and swamp white oak planted in bottomland crop fields along the Lower Missouri River, largely by controlling competing vegetation and by reducing herbivory damage to oak seedlings caused by the eastern cottontail rabbit (*Sylvilagus floridanus* [Allen]). In addition to the living mulch, competition was controlled with a 1.3 m $\times$ 1.3 m fabric weed mat that was placed around each oak seedling.

Soil Management in Floodplains

It is of utmost importance to match the tree species to the site conditions so that silvical requirements are met and survival and growth are optimized. Most species grow best on fertile, well-drained sites, where differential growth potential among species determines dominance in mature forests. Site conditions are seldom ideal, however, and species are variably adapted to tolerate poor soil and hydrological conditions. Selection of species that tolerate or are adapted to specific site limitations can overcome a wide range of problems limiting regeneration. Guidelines are available for some regions to aid in selecting appropriate species for regenerating given sites (e.g., Baker and Broadfoot 1979, Hook 1984, Kabrick and Dey 2001, Allen et al. 2004). Planting oaks will not be appropriate in all situations, especially on sites prone to growing season floods and that have saturated soils throughout the summer. Planting a mixture of species with a range of environmental tolerances is a strategy to buffer against unknown or unexpected disturbances or conditions and avoid complete stand failure. In some instances, managers are able to improve saturated soils through soil bedding or installation of drainage ditches and tiles, control of flooding with levees, ameliorate unfavorable physical soil conditions through tillage, and correct nutrient deficiencies through fertilization on particular sites.

Bottomland afforestation failures are due, in part, to frequent flooding and wet site conditions (Stanturf et al. 1998). Soil bedding (or mounding) is a commonly used site preparation method for establishing tree seedlings in poorly drained soils (Derr and Mann 1977, Londo and Mroz 2001). Surprisingly, there is little published information about the use of soil bedding to establish bottomland hardwoods.

Soil beds (Figure 9) typically are constructed by mounding soil with a moldboard plow, offset disc, rice levee plow, or similar tillage implements and also with backhoe-type excavators (Londo and Mroz 2001). Once constructed, beds range from 1–2 m wide and 15–60 cm tall. Benefits of bedding include improved soil aeration and drainage, concentration of organic matter and nutrients in the rooting zone, and mechanically removing competing vegetation (Schultz and Wilhite 1974, Fisher and Binkley 2000). Variation in microtopography is inherent to many natural forest systems (Lyford and MacLean 1966, Hodges 1997, Kabrick et al. 1997) and bedding can restore microtopography in agricultural fields.

Bedding can be beneficial when one is establishing bottomland oaks and other hardmast-producing tree species because they generally are less tolerant of poorly drained soils than are other bottomland tree species. Bedding increased the height of Nuttall oak seedlings by as much as 35% on poorly drained and frequently flooded soils in the Coastal Plain of Louisiana (Patterson and Adams 2003).

Kabrick et al. (2005) evaluated the effects of bedding on soil properties and on the early survival and growth of different stock types of pin oak and swamp white oak in the Central Hardwood Region. The study locations were representative of the broad range of soil textures and drainage classes commonly encountered in the lower Missouri River floodplain. Overall, bedding reduced soil bulk density, increased soil temperature, and improved the drainage of the bottomland soils, which improved the rooting environment for seedlings. But after 2 years bedding did not benefit the establishment and early growth of planted pin oak and swamp white oak even though half of the seedlings experienced a flood in early June of the second year. There may be longer-term benefits from bedding, but it did not improve oak establishment on these soil types, which were well-drained silt loams and fine sands. Bedding seems to benefit trees most on heavy clay soils in floodplains.

It is not unusual for alluvial soils to have high pH (e.g., $>$7.0) and this severely reduces survival and growth of certain hardwood tree species. Kennedy (1993) reported that Nuttall oak, cherrybark oak, and water oak have low vigor and increased mortality at pH $>$7.0. Similarly, Kabrick et al. (2005) observed low survival and poor growth in pin oak on soils ranging in pH from 7.4 to 8.0 in the lower Missouri River floodplain. In general, species of red oaks are not well adapted to high pH soils with the possible exception of Shumard oak (Kennedy 1984, Kennedy and Krinard 1985). White oak species such as swamp white oak and bur oak are better adapted to high pH (Stanturf et al. 1998, Kabrick et al. 2005).

Sites that have supported agricultural production for long periods may have developed a plowpan and have compacted soils. This is especially common on silty and clayey soils. High soil bulk density and plowpans restrict root growth and impede soil drainage, which adversely affects tree survival and growth. Plowpans can be broken up by deep

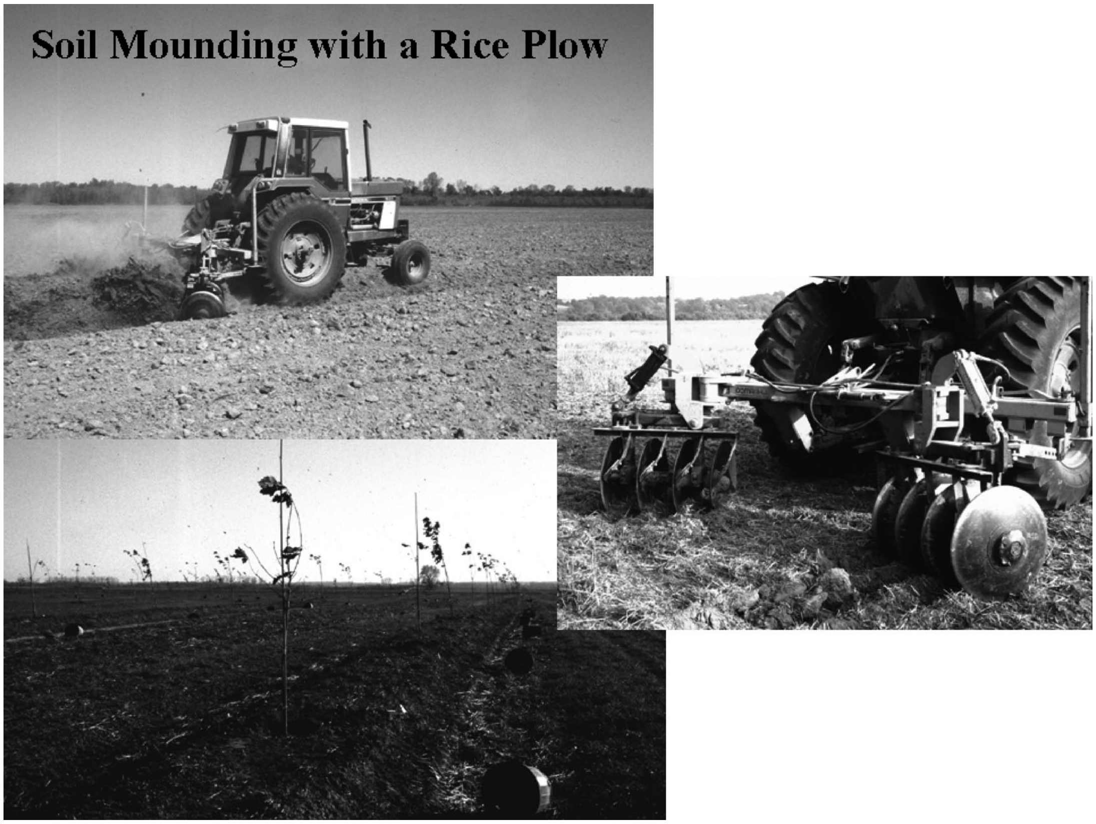

Figure 9. In floodplains, small increases in microtopography can benefit oak reproduction by improving soil drainage and decreasing flood duration. Planting oak bareroot or large container trees in mounded soil may improve regeneration success especially on heavy clay and poorly drained soils. Soil mounds or beds can be constructed quickly and inexpensively using a rice plow.

(45–60 cm) ripping or subsoiling with a chisel plow or ripper (Stanturf et al. 1998). This should be done in the late summer to early fall before a spring planting. Compacted and heavy clay soils can be disked twice within several months of planting (Allen et al. 2004) to improve physical soil properties and tree growth. It is preferable that soils be disked to a depth of 20–35 cm.

Alluvial soils usually have high fertility; however, nutrient deficiencies can occur on soils that have been in agricultural production for decades, where soils have been poorly managed, and on well to excessively drained sandy soils. Agricultural soils may be low in phosphorus (Stanturf and Schoenholtz 1998) or be low in organic matter and nitrogen (Gardiner et al. 2001). Kabrick et al. (2005) measured foliar nitrogen concentrations as low as 1.7% in pin oak and swamp white oak planted on agricultural soils along the lower Missouri River. They noted that pin oak vigor was poor, growth was limited, and trees were commonly severely chlorotic. Soil tests before planting can identify deficiencies and guide corrective fertilization. However, few guidelines are available for fertilization of hardwoods. Broadcast application of fertilizers will cause severe weed competition. More directed application of slow-release fertilizers can be made during tree-planting and applied directly to the planting hole (Jacobs et al. 2005a).

Controlling Animal Damage

White-tailed deer (*Odocoileus virginianus virginianus* [Boddaert]) are responsible for 87% of forest regeneration failures in the Allegheny Plateau in Pennsylvania (Marquis and Brenneman 1981), where the deer population averaged >11 deer km^{-2} statewide in 1992 (DeCalesta 1994). They are causing forest regeneration problems elsewhere throughout the eastern United States where populations have been increasing over the past 50 years. For example, estimates made in 2003 of overwinter deer population densities in Wisconsin ranged from 6 to 27 deer km^{-2}, and 12 deer km^{-2} is common (Wisconsin Department of Natural Resources 2007).

Marquis et al. (1992) projected that successful forest regeneration is possible when deer densities are maintained at about 5 deer km^{-2} when the deer food supply is low. If the deer food supply is considered high, then successful forest regeneration is possible if deer densities do not exceed 12 deer km^{-2}. Many methods to control deer browsing on tree reproduction have been evaluated (Marquis and Brenneman 1981), and the most reliable are to fence areas to be regenerated or fence around individual seedlings (Figure 10). These methods to protect seedlings are even more beneficial where competing vegetation is reduced to favor tree survival and growth because deer browsing is more of a problem when seedlings are grown in the open where deer can detect them more readily. Area fencing should be at least 2.4 m tall, and the best fencing for caging seedlings is chicken wire or plastic mesh that is about 1.5 m tall. Terminal buds of oak seedlings at or above about 1.5 m are at a much lower risk of being browsed by deer. Planting large container or bareroot oak seedlings that are 1.5 m tall

Figure 10. Animal damage to planted trees is often a major factor leading to regeneration failures. White-tailed deer browse branches and bucks rub the main stem of large seedlings and saplings (A), retarding growth and causing shoot dieback. Eastern cottontail rabbits, mice, rats, voles, and other small mammals chew and clip hardwood stems (B), reducing growth and survival of planted oaks. Wire fencing (C), plastic drainage tubing (C), chicken wire (D), and plastic spiral wraps (E) can be used to protect individual seedlings from deer and small mammals. In Pennsylvania, deer population density is so high that entire areas must be fenced (F) to ensure success of any hardwood regeneration, especially for oak.

reduces the damage caused by browsing deer, and minimizes delays in regeneration (Kormanik et al. 1995, Dey et al. 2003, 2004). In the absence of a fence, plastic tree shelters have been used to increase tree growth and reduce animal browsing on smaller seedlings (Frearson and Weiss 1987, Lantagne et al. 1990, Ponder 1995, Gillespie et al. 1996). Once trees emerge from tree shelters, they are susceptible to damage by deer, which can browse to a height of about 1.5 m, or by beavers that can reach tree tops during floods. The plastic shelters also protect seedlings from rubbing damage once they become established, but they must be removed before dbh reaches 10.2 cm. Shelters are expensive to install and maintain, especially in areas subject to flooding; hence, they may have limited use in large plantings. Where deer impact is high and browse damage is likely, the total area or scale of operations will determine whether tree shelters or fencing is the lowest-cost option. Stanturf et al. (2004) summarize the use of shelters in forest regeneration.

Gordon et al. (1995) found that deer browsing on planted northern red oak seedlings was severe when herbicides and prescribed burning were used to minimize competing vegetation in a southern Ontario shelterwood in a northern hardwood stand. Oak seedlings were much taller 6 years after planting on plots where competing vegetation was untreated. Similarly, Ezell and Hodges (2002) reported that deer browsing on Shumard oak seedlings was greater on plots where herbicides were used to control herbaceous weeds on cutover floodplain sites in Mississippi. Thus, there is a balance between controlling vegetation to reduce competition for water, light, and nutrients with planted oaks and maintaining sufficient cover to protect seedlings from deer browsing. However, herbaceous and shrub vegetation provide cover for rodents and access to seedlings, which they browse, clip, and girdle.

Small mammal herbivory of planted oak seedlings can be controlled by managing habitat to limit animal security cover in tree plantings by mowing or disking to reduce herbaceous weed cover in floodplains (Stanturf et al. 1998) or by caging around individual trees (Figure 10). Dey et al. (2004) found that cover crops or living mulches that produce low cover in the winter are effective in reducing herbivory on planted oaks by eastern cottontail rabbits. They observed that the amount and severity of rabbit damage to planted oaks in the winter were much less when trees were planted with a cover crop of redtop grass than when seedlings were competing with natural vegetation that commonly colonizes former crop fields. Plastic tree guards, chicken wire cages, and sections of plastic drainage pipe can be used to provide effective protection from small mammals (Figure 10).

Economic Efficiency of Planting

The economic efficiency (or planting economic efficiency) of artificially regenerating oak is a function of four important factors. These factors include (1) the initial planting cost, (2) the initial performance of individual seedlings after planting, (3) the cost of follow-up treatments to control competing vegetation and animal damage, and (4) the subsequent performance of planted seedlings through the stand initiation phase. The integrated effect of all four factors determines the cost of attaining a given oak stocking goal in the new stand. In general, published research results confirm that long-term growth and survival of planted oaks, from the initial planting operation through the stand establishment phase, are related to both initial seedling characteristics and the effectiveness of follow-up treatments to assure that planted seedlings can compete with neighboring vegetation (Johnson et al. 2002). Economic efficiency also varies, depending on local conditions because the performance of planted oaks is related to site quality, status of competing vegetation, and status of other damaging agents such as herbivory.

Johnson et al. (2002) explained the importance of considering both seedling survival and subsequent growth over a specified time simultaneously to measure the relative success of planting operations. They defined the competitive capacity of planted seedlings in terms of dominance probability, which is the probability that a planted seedling will become dominant or codominant within a certain number of years after planting or after overstory removal. Dominance probability implicitly accounts for the quality of the planting stock, the effect of site quality on competing vegetation, and the manipulation of competition through silvicultural treatments. Investing in higher quality seedlings and more-intensive follow-up treatments can increase dominance probability. Still, artificial regeneration reduces to an economic problem, involving the trade-off between higher costs and higher probabilities of success. In its simplest form, the problem is to attain the desired future oak stocking goal at the lowest cost.

In measuring the economic efficiency of artificially regenerating oak, the initial planting operation and subsequent follow-up treatments required for success are not independent activities. For example, there is an economic trade-off between initial seedling size and cost of follow-up treatments. Planting cost increases as the initial size of the seedling increases, yet larger seedlings may, for instance, reduce or eliminate the need for control of damage from white-tailed deer. However, in the absence of deer damage, the added cost of planting large seedlings may not result in lower costs for subsequent weed control and cleaning treatments. The key to measuring the economic efficiency of alternative planting strategies is to consider both the cost and the performance of planted seedlings (i.e., the total stand regeneration cost, throughout the entire stand initiation phase).

A key factor in assessing economic efficiency of artificially regenerating oak is to attain a good estimate of the number of specific-sized seedlings needed to plant per unit area to meet the future oak stocking goal. The planting factor, defined as the reciprocal of dominance probability, is the number of planted oaks needed to obtain one dominant or codominant tree within a certain number of years after planting or after overstory removal. Johnson et al. (2002) provided planting factors for the Ozark Highlands of Missouri (Table 7.4, p. 293). Their guidelines call for planting of 4.4–5.4 northern red oak seedlings ha^{-1}, varying by initial basal diameter, for each dominant or codominant tree needed 10 years after shelterwood removal. The initial size of the seedlings varied from 0.64 to 2.54 cm basal diameter. Although planting larger seedlings costs more than smaller seedlings, larger seedlings can be planted at lower densities for a given stocking goal. The trade-off between seedling size, planting density, and planting cost determines the appropriate least-cost approach to attaining the stocking goal.

The previous example involved a simple trade-off between two factors, seedling size and planting density, yet artificial regeneration operations become more complex as additional factors are considered. For example, the interaction of multiple factors such as site quality, competing vegetation, and deer impact can affect the competitive capacity of planted seedlings, and soil conditions, terrain, and availability of labor can affect planting costs. Defining the most economical approach to artificially regenerating oak requires information on the expected performance of oak seedlings under numerous alternative courses of action. In many cases, such information is lacking, and the best analytical approach is to use published dominance probabilities based on initial seedling caliper or height to evaluate the economic efficiency of planting options. In the absence of such information, forest managers should implement field trials under various local conditions to develop reliable measures of costs and the associated dominance probabilities so that efficient planting alternatives can be defined for future operations of greater scale.

Economic efficiency of planting operations hinges on many factors, but there is evidence that planted seedlings should be large enough to assure some degree of success after planting. Empirical evidence for natural northern red oak seedlings suggests that seedlings must have at least a 2.54 cm basal diameter at the time of overstory removal to achieve a dominance probability of 15–25%, depending on site quality (Loftis 1990a). Seedlings planted under a 60% relative density shelterwood must have at least a 1.27 cm basal diameter to achieve a similar dominance probability of 25% (Johnson et al. 2002). In the latter case, the shelterwood is retained for 3 years to allow planted seedlings to increase in size before the overstory is removed, so these guidelines are somewhat similar. Although dominance probability can be improved by planting larger seedlings and/or investing in intensive follow-up treatments, it is probably not economical to plant seedlings smaller than 1.27 cm under a shelterwood or smaller than 2.54 cm where the overstory has already been removed. These minimum sizes assure that the rootstocks are large enough to provide both high survival rates immediately after planting and good growth response in subsequent years to keep up with competing vegetation.

Conclusions

Until definitive seed transfer guidelines are established for oak species in the eastern United States, local seed sources should be used and seed should be collected from several parent trees. Seed quality is the most limiting element in production of quality oak seedlings. There is no evidence to support the notion that genetically superior seedlings can be identified in the nursery, and scientific evidence with many species of hardwoods and conifers suggests that selection for genetic superiority for growth cannot be achieved in the nursery. Future success of oak plantings will increasingly depend on improvements in genetic quality through tree improvement programs (Jacobs and Davis 2005).

Production of quality oak seedlings is also dependent on good nursery culture including managing seedbed density, irrigation, and fertilization and controlling weeds, diseases and insect pests. Best nursery practices for the various oak species are still under development and are not as sophisticated as those for conifers. The prevalence of improved seedling stock in conifer production has resulted in increased sensitivity and accuracy in quality testing, though hardwood seedling production has yet to reap these benefits. The current lack of adequate nursery guidelines has resulted in large and often unacceptable variation in seedling size and quality. Thus, nursery managers will need morphological and physiological seedling quality standards to help guide production of oak stock that will be competitive when planted in the field.

Currently, most of the demand for oak seedlings is for afforestation purposes. Silvicultural practices for planting through establishment in these operations are clearly different than those for reforestation of existing or cutover oak forest stands. The optimum seedling requirements for one purpose are not likely to be the same as for the other, but at present there is no differentiation in nursery production to meet differing objectives.

Some progress has been made toward establishing seedling grading standards with a few oak species. We have science-based recommendations for minimum stem diameters, shoot lengths, and numbers of first-order lateral roots for certain oak species, but in many cases, these standards remain to be defined. Compared with that for most conifers, production of quality oak seedlings (that will survive and grow well in the field) is far more difficult. In general and to a limit, larger oak seedlings (i.e., 10 mm or larger root collar diameter) survive and grow better in the field. The most important factors in seedling quality are probably related to root system size, physiological condition of the roots, and a balanced shoot to root ratio. Many morphological traits such as root collar diameter and number of first-order lateral roots correlate to root system size; hence, they have been used as surrogate traits. Unfortunately none of these traits are consistently predictive of survival and subsequent field growth. The reason for this is the variability in the key factors that affect overall success: planting site quality, prior stand conditions, site preparation, proper seedling handling, planting job quality, and control of plant competition and animal damage from time of planting until at least crown closure. An integrated approach to seedling quality assessment (Grossnickle et al. 1991) will be needed to account for the many cultural, environmental, and genetic traits responsible for variability in oak seedling morphology and physiology.

Oak seedlings are generally not aggressively culled at the nursery, resulting in varying quantities of cull seedlings being included in seedling lots shipped to the field. These cull seedlings are often, but not always, planted along with quality seedlings, which may lead to greater mortality and unacceptable stocking rates at crown closure in the stand.

The definition of regeneration success involves more than just an acceptable survival percentage after planting and may differ, depending on the nature of the regeneration environment and competition. In afforestation of agricultural bottomlands, for example, success may be defined as an acceptable stocking of free-to-grow seedlings 2–5 years after planting because the main source of competition comes from grasses and herbs in the early stages of stand development, and once trees grow above these competitors, it is relatively easy for them to maintain dominance through maturity. Also, control of such competition is somewhat predictable because relatively inexpensive methods are available that can control competing vegetation for the fairly short period of time (e.g., 2–5 years) needed for trees to become free-to-grow. However, when oak regeneration is competing with other tree species, which are perennial, long-lived, and capable of growing to large stature, success must be defined as an acceptable number of planted seedlings reaching dominant/codominate status at crown closure 8–10 years after planting. In this case, success can be stated in terms of the probability that a planted or seeded oak commands sufficient growing space to attain a dominant social position after a period of time that allows for differentiation among tree species and stand development through the stem exclusion stage (Oliver and Larson 1996). It is also important to consider how site productivity, seedling quality, site preparation, sowing or planting technique, and vegetation management treatments are related to regeneration success. All of these factors contribute to the proportion of planted trees that eventually reach the main canopy in a new stand. In this sense, oak regeneration success is harder to achieve, requires more management, and is more expensive on higher quality sites as a result of the interaction between more intense vegetation competition and the regeneration ecology of oak species.

Controlling plant competition and animal damage after seedlings are planted is critical. Site preparation, initial seedling quality, planting operation, and follow-up treatments to control plant competition and animal damage are not independent operations. Given high-quality seedlings and a good planting job, regeneration failure can still occur if plant competition and/or animal damage is severe. Good competition control, both before and after planting through to crown closure, is mandatory to regenerate and recruit oaks into dominant/codominant crown classes in the subsequent stand. Where deer damage is a factor, seedlings must be protected until they are at least 1.5 m tall. Rabbits and other small mammals can cause regeneration failure and herbivory damage must be controlled by protecting seedlings or by managing habitat to discourage the pests. Evidence suggests that quality medium size seedlings may be as successful as large ones as long as there is effective competition and animal damage control. New silvicultural practices are needed to address the myriad of combinations of regeneration challenges presented by varying site and environmental conditions, natural disturbances such as fire, flooding, and drought, insect and disease pests, and the complex suite of competing vegetation that is highly variable, depending on initial floristics and type of management disturbances. A better understanding of how silvicultural practices modify the ecophysiology of oak and its major competitors is also needed.

Seedling costs as well as subsequent planting costs increase dramatically with increasing seedling size. There is some indication of a slight trade-off between using larger, more costly seedlings and success with less costly follow-up competition control. The cost of seedlings, planting operation, and follow-up treatments all contribute to total cost of a competitively successful seedling. The actual costs and benefits of this trade-off have not been quantified and should not be relied on as the basis for management policy. In other words, bigger is not necessarily better in terms of total cost, but it may be what it takes biologically and ecologically to ensure the presence of oak in the next forest. Economic analyses should consider the cost per successful oak tree that includes not only the cost of nursery production but also the cost of all other silvicultural practices to promote oak into a competitive position at canopy closure and beyond.

Economic concerns are a paramount issue and must meet landowner objectives. Some landowners are willing to pay more to achieve the faster growth and earlier acorn production afforded by very large seedlings or saplings in large (e.g., 12–20 L) containers. For most landowners, however, expenditures must be balanced between costs associated with seedlings, planting, site preparation, vegetative competition control, and animal damage control. It is a fallacy to expect to invest heavily in one or two of these factors and neglect the others because that may lead to total failure of oak stand establishment. Much more research addressing all of these economic issues is needed.

Although successful large-scale planting of oak seedlings for reforestation or afforestation purposes is in its infancy relative to planting of conifers, the available literature does provide much useful guidance for the present time. Obviously, more research and experience is needed across all aspects of the oak artificial regeneration process. However, the guidelines presented here, gleaned from past and present experiences, will enable us to move forward to help meet the increasing need for oak planting in the eastern United States.

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