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A suggested approach for design of oak (*Quercus* L.) regeneration research considering regional differences

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Abstract Research on oak (*Quercus* L.) regeneration has generally consisted of small-scale studies of treatments designed to favor oak, including consideration of site quality and topographic effects on oak regeneration. However, these experiments have not consistently factored in broader-scale ecological differences found in the eastern United States. Oak regeneration experiments should be replicated at appropriate ecological scales to address the similarities and differences in regeneration following prescribed silvicultural treatments among ecological units. Patterns in oak regeneration can be better understood in an ecological context by considering how oak species interact in the differing physical environments and are able to maintain dominance in changing complexes of competing vegetation among the selected eco-units. Our understanding of oak regeneration response to specific silvicultural practices and our ability to model regeneration is improved when we use replication, blocking, or factorial deployment of relatively small-scale (0.5–1.0 ha) treatment plots within an ecological classification system. We present an example of this approach to understanding oak regeneration dynamics in a synthesis of research to regenerate northern red oak (*Quercus rubra* L.) by underplanting shelterwoods in Arkansas, Missouri and Indiana. We summarize important considerations to guide the design of future research in oak regeneration.

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Introduction

Of the 40 species of oak (*Quercus* L.) that occur east of the 100th Meridian in the United States, several of high commercial and ecological value such as white oak (*Q. alba* L.), black oak (*Q. velutina* Lam.) and northern red oak (*Q. rubra* L.) are widely distributed (Burns and Honkala 1990). The greatest diversity of oak species is in the southeastern United States, where species including northern red oak, southern red oak (*Q. falcata* Michx.), overcup oak (*Q. lyrata* Walt.), swamp chestnut oak (*Q. michauxii* Nutt.), willow oak (*Q. phellos* L.), and water oak (*Q. nigra* L.), are found distributed across the region. Species such as pin oak (*Q. palustris* Muenchh.), chestnut oak (*Q. montana* Willd.), scarlet oak (*Q. coccinea* Muenchh.), chinkapin oak (*Q. muehlenbergii* Englem.), Shumard oak (*Q. shumardii* Buckl.), post oak (*Q. stellata* Wangenh.), and swamp white oak (*Q. bicolor* Willd.) are common in both the southern and central regions of the eastern United States. Many of the major hardwood competitors of oak reproduction such as sugar maple (*Acer saccharum* Marsh.), flowering dogwood (*Cornus florida* L.), American beech (*Fagus grandifolia* Ehrh.), black cherry (*Prunus serotina* Ehrh.), ironwood (*Ostrya virginiana* (Mill.) K. Koch), yellow-poplar (*Liriodendron tulipifera* L.), the elms (*Ulmus* L.), and red maple (*Acer rubrum* L.) also have wide natural distributions that overlap the ranges of the common oak species (Burns and Honkala 1990). It is the many factors that influence species composition and competitive relationships such as climate, soil, landform and disturbance regime that determines which species will be oak's major competitor.

Research on oak regeneration has consisted of small-scale studies made up of treatment plots ranging in size from <0.5 to 1.0 ha located in a single ecological unit, or within a narrow range of site indices, aspects, and slope positions (e.g., Beck and Hooper 1986; Dey and Parker 1997; Johnson et al. 1989; Loftis 1990a; Sander 1971; Spetich et al. 2002). Early efforts were made to evaluate the effects of site quality on oak regeneration, and relationships between oak advance reproduction and topographic factors (e.g., Carvell and Tryon 1961; Dey 1991; Loftis 1990b; Sander et al. 1984; Schlesinger et al. 1993). Oak regeneration models have been developed that estimate success probabilities for oak advance reproduction based, in part, on aspect, slope position, and site quality (Dey et al. 1996; Loftis 1990b; Sander et al. 1984). However, experiments that relate silvicultural practices to oak regeneration as a function of broader-scale differences among ecoregions that differ in climate, topography, soils, and competing species across the range of oak in the eastern United States are limited.

Lorimer (1993, p. 16) referred to oak regeneration failures as "…unintended conversions of oak forests to other species…" and noted their widespread occurrence (Beck and Hooper 1986; Gammon et al. 1960; Hix and Lorimer 1991; Johnson 1976; Johnson and Jacobs 1981; Loftis 1983; Schuler and Miller 1995; Smith 1993). Sander and Graney (1993, p. 181) cautioned that "There is no guarantee that applying [their] guidelines [for the Central States Region] will regenerate oaks successfully in all situations."; noting that failures were more likely to occur in southern Indiana than Missouri, and on higher quality site indices than on average sites. Forest managers and scientists continue to experience unpredictable and inconsistent responses of oak reproduction to silvicultural practices intended to maintain a desired stocking of oak (Clark 1993).

The challenge to solving the oak regeneration problem throughout the natural range of many oak species in North America lies, in part, in the complexity of interacting factors affecting oak regeneration, which vary spatially and temporally (Johnson et al. 2002; Lorimer 1993). Managers have experienced oak regeneration failures despite application of recommended practices, e.g., the clearcut and shelterwood regeneration methods (Hannah 1987; Loftis 1983, 1990a; Oliver et al. 2005; Sander 1979; Sander and Graney 1993) because they did not account for ecosystem differences in the environmental factors affecting oak regeneration and make adjustments to the prescription. Other factors such as deer browsing can cause oak regeneration failures (Marquis and Brenneman 1981; Rooney and Waller 2003), and this may also have led to inconsistent results in oak regeneration research. However, many of the important environmental factors regulating forest regeneration are either directly or indirectly used as determinants in distinguishing between units in ecological classification systems, and designing research experiments using an ecological framework can help to control unexplained variation in oak regeneration success due to environmental factors.

These past failures in oak regeneration suggest the need to plan oak regeneration experiments that are replicated among known ecological units such as the Section, Subsection or Landtype Association as defined by Bailey (1998) (Table 1). Other ecological classification systems are available to researchers and managers that may be more useful depending on the nature and scope of the research, for example Coffman et al. (1983) and Kotar et al. (1988) in the upper Great Lakes Region, and VanKley et al. (1995) in southern Indiana. Johnson (1993, p. 6) stated that "The development and application of ecological classification systems will be essential to enlightened management of oak-dominated forests. We have struggled too long in our management of oak forests without objective definitions of the different kinds of ecosystems in which oaks occur. Ecological classification has the potential to be an effective silvicultural tool." That is true for both oak research and management. Further support for conducting oak research within an ecological classification system is provide by Lorimer (1993, p. 15) who stated that "The ideal solution to resolving these questions [about oak regeneration] would be to conduct controlled experiments that would simultaneously evaluate a number of factors and would be replicated in several geographical areas." Until recently, a lack of a well-developed ecological classification system has hampered progress in designing oak regeneration research within an ecological framework as suggested by these noted oak authorities.

In the past 20 years, a common ecological classification system for the United States was developed (Bailey 1995, 1997, 1998; McNab and Avers 1994) and in many states work has progressed to the landtype association (e.g., Nigh and Schroeder 2002) and ecological landtype stages (e.g., Nigh et al. 2000). When oak regeneration studies are replicated or blocked by ecological unit, similarities and differences in oak regeneration dynamics can be observed as forests respond to prescribed silvicultural treatments, and trends can be better understood in an ecological context by considering the differences in physical environment and competing species among formally defined ecological units. More local variations in oak regeneration response to planned treatments can be better understood when studies are replicated at finer ecological scales (i.e., ecological landtype (ELT) or ELT phase).

The purpose of this paper is to show how relatively small-scale (0.5–1.0 ha) treatment plots replicated across and within selected Ecological Sections (at a scale of approximately 2,600 km^2 (Table 1)), can be used to improve our ability to predict oak regeneration successes and failures following given silvicultural practices. With further development of ecological classification systems down to the Ecological Landtype phase (<40 ha),

Table 1 National hierarchy of ecological units for classification of ecosystems in the United States (McNab and Avers 1994; Bailey 1995)

Ecological unit	Unit size	Classification factors
Domain	Subcontinental 2.6 million km^2	Macroclimate (continental and regional) & geomorphology (broad soil and vegetation patterns)
Division	Multi-state 259,000 km^2	Macroclimate (continental and regional) & geomorphology (broad soil and vegetation patterns)
Province	Multi-state 25,900 km^2	Macroclimate (continental and regional) & geomorphology (broad soil and vegetation patterns)
Section	Region: –state –multiple counties –national forest 2,590 km^2	Geomorphology (major soil great groups), regional climate & vegetation formations
Subsection	Subregion: –multiple counties –national forest –forest district 26 to >259 km^2	Geomorphology (major soil great groups), subregional climate & vegetation for nations
Landtype association	Landscape: watershed 400 to >2,590 ha	Local climate, landform/topography, geologic parent materials, soil associations, vegetation alliances
Ecological landtype	Multiple stands 0.4 to >40 ha	Landform/topography, geologic parent materials, soil series, vegetation associations
Ecological landtype phase	Stand <40 ha	Landform/topography, geologic parent materials, soil series, vegetation associations

researchers will have the ability to design oak regeneration experiments at the stand scale. We present an example of this cost effective approach to designing oak regeneration research in a synthesis of previously published research on regenerating northern red oak by underplanting shelterwoods in the Boston Mountains of Arkansas, the Ozark Highlands of Missouri and in southern Indiana (Spetich et al. 2002; Weigel 1999; Weigel and Johnson 1998, 2000).

A regional approach for studying oak regeneration

The following research on artificial regeneration of northern red oak by underplanting shelterwoods in diverse ecosystems in Arkansas, Missouri and Indiana (Table 2) was originally conducted by Drs. Paul Johnson and David Graney, and has been reported by Weigel and Johnson (1998, 2000); Weigel (1999) and Spetich et al. (2002). In 1984, Johnson established the Indiana and Missouri study with a common design to evaluate seed source, nursery cultural practices, and shoot clipping on success of underplanted northern red oak 2–0 bareroot seedlings using the shelterwood regeneration method. A year later, he and Graney initiated a similar but expanded study in the Boston Mountains of Arkansas. The Arkansas study included evaluation of site quality and initial shelterwood stocking in addition to the factors embodied in the Missouri-Indiana study.

While all three study sites are in the Central Hardwood Forest Region, they represent three very distinct ecosystems where foresters commonly try to sustain oak dominated

Table 2 Characteristics of the ecological Sections for the three oak regeneration study sites located in the Boston Mountains of Arkansas (Ozark Broadleaf Forest—Meadow Province M222, Boston Mountains Section M222A), the Ozark Highlands of Missouri (Ozark Highlands Section 222A), and the Interior Low Plateau and Highland Rim of southern Indiana (Interior Low Plateau, Shawnee Hills Section 222D and Highland Rim Section 222E)

Geomorphology	Lithology & stratigraphy	Soil taxa	Potential vegetation	Climate
Arkansas—Boston Mountains Section M222A				
Plateau of generally flat-lying marine sediments; strongly dissected region with dendritic drainages; mostly low mountain landforms; some open hills and plains with hills; elevation 200–800 m	Paleozoic era rock formation; bedrock predominately Pennsylvanian marine deposits of sandstone, shale, coal, & limestone; some Mississippian marine deposits (chert & limestone)	Udultsthermic temp. & udic moisture regime; siliceous or mixed mineralogy; medium textured, stony to nonstony, & shallow to mod. deep soils	Oak-hickory & oak-pine forests	Mean annual ppt 1,150–1,320 mm mean annual temp. 14–17°C growing season 180–205 days
Missouri—Eastern Broadleaf Forest (continental) Province 222, Ozark Highlands Section 222A				
Maturely dissected high plateau; elevation 100–600 m; dendritic & radial drainage patterns; mix of rolling and steep hills; karst topography	Quaternary loess deposits widespread; bedrock lower Ordovician dolomite and sandstone	Udalfs & Udults soils cherty developed in loess mantle; soils old, shallow, stony, acidic; siliceous or mixed mineralogy; mesic temp. & udic moisture regime	Oak-hickory & oak-pine forests & woodlands	Mean annual ppt 1,020–1,220 mm mean annual temp. 13–16°C growing season 180–200 days
Indiana—Eastern Broadleaf Forest (continental) Province 222, Interior Low Plateau, Shawnee Hills Section 222D				
Extensive sandstone bluffs; steep sided ridges & hills; gentler hills, karst terrain; elevation 100–325 m; dendritic drainages on maturely dissected plateau	Paleozoic era rock formation; bedrock Pennsylvanian sandstones; interbedded Mississippian limestones, shales, & sandstones	Ultisols & Alfisols well drained to mod. well drained; mesic temp. & udic moisture regime	Oak-hickory & maple-beech-birch forests	Mean annual ppt 1,120–1,140 mm mean annual temp. 13–14°C growing season 185–190 days
Indiana—Eastern Broadleaf Forest (continental) Province 222, Highland Rim Section 222E				
Level-bedded plateau; moderate to deeply dissected surface; open hills & irregular plains; some tablelands; elevation 200–300 m	Layered Ordovician, Silurian, Devonian, & Mississippian marine sediments	Udalfs & Udulfs mesic temp & udic moisture regimes; siliceous and kaolinitic mineralology; deep soils; high subsoil clay content; adequate growing season moisture supply	Oak-hickory forests	Mean annual ppt 1,120–1,370 mm mean annual temp. 13–16°C growing season 180–205 days

Section descriptions are from McNab and Avers (1994) forests. Site quality on the study sites, as measured by site index, was lowest in Missouri compared to sites in Indiana and Arkansas (see site index details in the following section). Only the Indiana study sites lie within the natural range of yellow-poplar, a major competitor with oak regeneration. The major oak competitors in Missouri are often low stature trees such as flowering dogwood, or species such as sassafras (*Sassafras albidum* (Nutt.) Nees) that do not persist for more than 30 years in young stands. These species are often referred to as interference species because they do not dominate growing space in mature forests and may not even have much of a presence, but their abundance, rapid growth and dominance during stand initiation eventually helps determine stand composition (e.g., Ristau and Horsley 2006).

Oak regeneration research locations

Boston Mountains Arkansas (Spetich et al. 2002)

The research was conducted in the southwestern portion of the Central Hardwood Region in the Boston Mountains, Ozark National Forest, northern Arkansas. The study stands were on north and northeast slopes and benches within the Boston Mountains Section (M222A) of the Ozark Broadleaf Forest—Meadow Province (M222) (Table 2). Site index for red oaks (black oak and northern red oak, base age 50 years) ranged from 18.3 to 24.1 m (Graney 1977).

Missouri Ozark Highlands (Weigel 1999; Weigel and Johnson 1998)

The research was conducted on the Mark Twain National Forest in the Ozark Highlands Section 222A of the Eastern Broadleaf Forest (Continental) Province 222 (Table 2). Black oak site index averaged 19 m (base age 50 years, McQuilkin 1974).

Southern Indiana (Weigel 1999; Weigel and Johnson 2000)

This research was conducted on the Hoosier National Forest, southern Indiana in the Interior Low Plateau, Shawnee Hills 222D and Highland Rim 222E Sections of the Eastern Broadleaf Forest (Continental) Province 222 (Table 2). Black oak site index averaged 23 m (base age 50 years, Carmean 1971).

The experimental design

Spetich et al. (2002) provided detailed descriptions of the methods for the establishment of the oak regeneration study in Arkansas, and Weigel and Johnson (1998, 2000) and Weigel (1999) described the Missouri and Indiana studies. Although there are differences in the range of treatments and factors affecting oak regeneration evaluated among these studies, there is a core set of treatments and experimental design common to all. We will focus on the common experimental design elements in this paper, and use them to recommend some design features for research in oak regeneration.

At each research site, a shelterwood of 60% stocking (according to Gingrich 1967) was created by harvesting from below until the target stocking was achieved. Trees

$\geq$3.8 cm dbh were cut to create the shelterwood in Arkansas and trees $\geq$2.0 cm dbh were cut in Missouri and Indiana.

Harvesting in Indiana and Missouri was completed in the fall/winter of 1983/1984 and in Arkansas the fall/winter of 1986. At all sites, the stumps of trees cut during timber harvesting were treated with herbicide (Roundup in Arkansas, Tordon RTU in Missouri and Indiana) to control sprouting.

The initial basal diameter (2.5 cm above the root collar) of 2–0 bareroot northern red oak seedlings was measured before seedlings were planted in the shelterwood stands the spring after harvesting. Three years after planting the shelterwood overstory was removed at all sites and stumps were treated with herbicide. After planting, survival and height of oak seedlings were remeasured for up to 11 years (Arkansas) and 13 years (Missouri and Indiana). In addition, the height of the most dominant woody competitor within 1.0 m of planted northern red oak seedlings was measured as an indicator of the competitive success of planted oak seedlings, a method developed by Spetich et al. (2002); Weigel (1999); and Weigel and Johnson (1998, 2000).

Logistic regression was used to model the probability that a northern red oak seedling was successful (i.e., in a dominant or codominant crown class) at a given time after planting based on its initial basal diameter and the time since final removal of the shelterwood. It is known as the dominance probability, i.e., the probability that oak will be in a dominant or competitive position in relation to its major competitors at any given time during the regeneration period. Oak seedling success was determined by comparing the height of the surviving oak to the mean height of the dominant woody competitor found within a 1.0 m radius of the planted oak. An oak seedling was considered successful if its height was at least 80% of the mean height of the dominant competitors. This result was used to estimate the dominance probability of the planted oak by logistic regression. Models were developed for each study site in the three different ecological sections within the Central Hardwood Region. All dominance probability models were statistically significant at the $\alpha = 0.05$ level (Spetich et al. 2002; Weigel 1999; Weigel and Johnson 1998, 2000).

Dominance probability is a good measure of oak's success in regeneration because it combines the two major determinants of reproduction success: survival and growth with the concept of competitive status, or social position of the oak among its major competitors (Johnson et al. 2002). An oak's dominance among its competition is also directly related to the desired management objective of sustaining oak stocking in mature forests. Oak dominance as defined in this example, oak seedling height exceeding a threshold height based on the height of the major woody competition, is amenable to probability analysis. Finally, dominance probability has great practical utility because its reciprocal defines the number of oak seedlings of a given initial size needed now to produce one successful oak at a specified time in the future, in a given ecotype, for a given set of silvicultural treatments.

Northern red oak dominance probability

Trends in dominance probabilities for 2–0 northern red oak seedlings planted under a 60% shelterwood were similar between Arkansas and Missouri where they were seen to increase with time since final removal of the shelterwood overstory (Fig. 1). In Indiana, however, the reverse trend was observed. Northern red oak dominance probabilities for an averaged sized oak seedling (13 mm initial basal diameter) were highest for Missouri regardless of time since final shelterwood removal. After 10 years, average-sized northern red oak

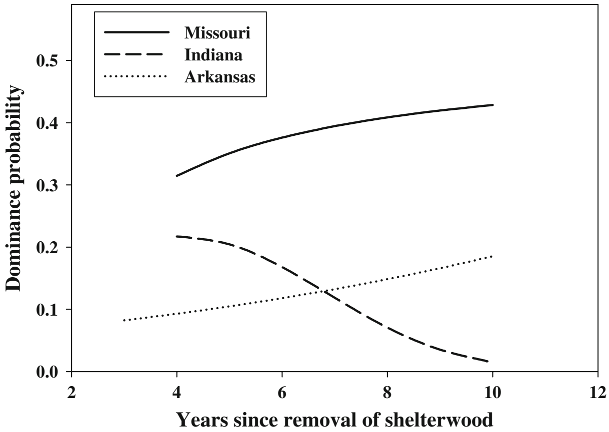

Fig. 1 Dominance probabilities for 2–0 northern red oak seedlings planted under 60% stocked shelterwoods in Missouri, Indiana and Arkansas. Probabilities are calculated for seedlings with initial basal diameter of 13 mm that are not undercut in the nursery nor shoot clipped before planting. The shelterwood is removed three years after planting, and basic woody competition control is done by herbicide treatment of stems cut during timber harvesting. Equations for Indiana and Missouri are adapted from Weigel (1999) and for Arkansas from Spetich et al. (2002)

seedlings had a 40% dominance probability in Missouri, 20% in Arkansas, but few survived in Indiana. The trend in oak dominance probability in Indiana is indicative of limited oak success on high quality sites in the presence of yellow-poplar under even-aged management. Initially, oak dominance probabilities were relatively moderate in Indiana, probably because the shelterwood was limiting development of yellow-poplar, which comprised 75% of the oak competitors. Removal of the shelterwood overstory released the shade intolerant yellow-poplar, and within 6 years it had emerged as the dominant species in Indiana, completely suppressing the northern red oak reproduction (Weigel and Johnson 2000).

In Missouri, the dominant competing species included flowering dogwood, sassafras, hickory (*Carya* Nutt.) and blackgum (*Nyssa sylvatica* Marsh.). Growth rates of hickory reproduction are comparable to those of oak. Flowering dogwood is an important competitor during the first 20 years of the regeneration period but then it is limited by its low stature. Sassafras competes well early in the regeneration period while stand conditions are still open, but is a weak competitor in the long-term (i.e., after crown closure) due to its high intolerance to shade.

In the Boston Mountains of Arkansas, oak competition was dominated by red maple, black cherry, flowering dogwood, blackgum and sassafras. On the more productive sites in Arkansas, red maple and other hardwood reproduction caused low oak dominance probabilities early in the regeneration period. Oak dominance probabilities were as low as 10% upon removal of the shelterwood. Red maple is moderate to tolerant of shade and its development was probably not inhibited by the shade of the shelterwood, at least not to the same extent as that of yellow-poplar. In both Missouri and Arkansas, northern red oaks that are dominant three and four years after final shelterwood removal are capable of maintaining their dominance, but in Indiana oak dominance was highest just after final shelterwood removal and it declined rapidly with increasing time since harvesting.

The importance of time in evaluating oak's success in regeneration is illustrated in Fig. 2. Four years after final shelterwood removal, oak dominance probabilities are actually higher in Indiana than they are in Arkansas, regardless of initial basal diameter of the oak seedlings. But few oak survive another 6 years in Indiana, whereas dominance probabilities continue to increase over time for oak in Missouri and Arkansas for any given initial size of seedling. If one evaluated the success of oak reproduction among the three states at 4 years, you would conclude that dominance probabilities for large oak (initial basal diameter 25 mm) were the highest in Indiana, and that oak was most successful in that ecological unit for the given set of silvicultural treatments. But given six more years, you would find that dominance probabilities have plummeted to near zero in Indiana, representing a complete failure in oak regeneration.

Large northern red oak bareroot seedlings (i.e., 25 mm root collar diameter) have initially significantly greater dominance probabilities than small seedlings among the different ecological units (Fig. 2). This competitive advantage of large oak seedlings is

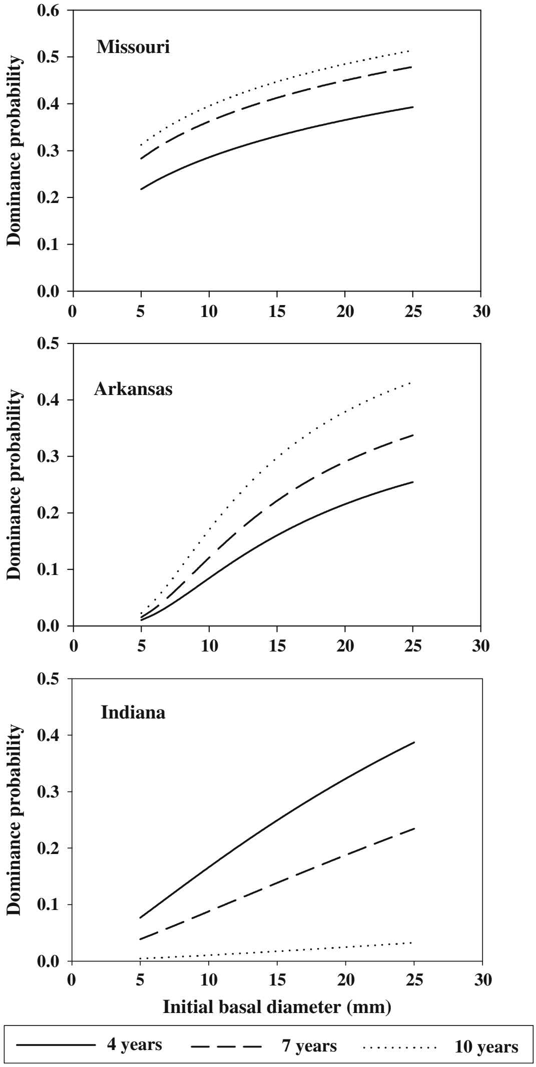

Fig. 2 Dominance probability of planted 2–0 northern red oak seedlings by initial basal diameter and years since removal of the shelterwood overstory in the Missouri Ozark Highlands, Boston Mountains of Arkansas and the Shawnee Hills and Highland Rim of southern Indiana. Probabilities are for seedlings (no nursery undercutting of root systems or shoot clipping) planted under shelterwoods cut to 60% stocking, shelterwood removal after 3 years, and basic woody competition control, which includes herbicide treatment of stems cut during logging operations. Equations for Indiana and Missouri are adapted from Weigel (1999), and for Arkansas from Spetich et al. (2002)

maintained over time in Missouri and Arkansas, but not in Indiana. Performance of large oak seedlings in Missouri and Arkansas is comparable, but small diameter seedlings are only competitive in Missouri, where they have initially moderate probabilities of dominance that increase with time.

The results of this research show the value of designing experiments on oak regeneration within an ecological framework in a planned, a priori manner. In much of the previous oak research a limited number of sites were selected in a way that produced an unbalanced sample of oak reproduction by aspect and slope position classes that were often "replicated" in very different ecological units. No wonder results were inconclusive, contradictory, and hard to repeat in other areas with any reliability.

Failure to consider differences in regeneration dynamics among ecological units severely restricts the inferences that can be made from our research. For example, if we consider the results presented here from the Missouri research site as an example of how oak regeneration research has been conducted on local areas, we might conclude that our method of underplanting northern red oak in shelterwoods with some woody competition control could be used to successfully regenerate oak. When, however, foresters apply our methods in southern Indiana, they would, in time, find that the result was a dismal failure. Likewise, if we had only conducted our experiment in southern Indiana, we would conclude, over time, that there is no promise in underplanting northern red oak in shelterwoods, possibly casting a shadow of doubt on the method and its application in other ecological units.

Failure to consider the importance of time in determining the outcome of the stand initiation phase of stand development carries its own consequences. For example, one might conclude that underplanting large diameter northern red oaks in shelterwoods in southern Indiana can be used to successfully regenerate oaks based on the evaluation of our results after 4 years. But any forest manager who has more time to watch the developing stand would be hard pressed to find any oak after 10 years.

Stand initiation is a dynamic and chaotic period in forest development, which challenges the researcher. We suggest the following ideas to help in designing future research in oak regeneration:

1. First, studies should be designed within an ecological framework with proper controls and replication. The appropriate level of ecological classification will vary depending on the research and management objectives.
2. There should be a core set of treatments within each ecological unit studied to facilitate evaluating regeneration response to treatments among the units. It is possible to add treatments to include consideration of local factors affecting oak regeneration (e.g., fencing to evaluate deer browsing).
3. Evaluate regeneration success early, and commit to periodic assessments for up to 20 years. It is good to know what treatments are more successful than others early in the regeneration period, for if an oak doesn't make it through the first few years, there is no future hope of success. However, early success does not guarantee long-term dominance of oak. Long-term studies are crucial to assessing the final outcome of oak regeneration and to providing knowledge for sustaining future oak stocking with certainty.
4. Probabilistic approaches are more appropriate for modeling forest regeneration because of the stochastic nature of reproduction populations (Johnson et al. 2002).
5. A core set of response and independent variables must be measured at each of the study sites in all the ecological units. This is necessary to evaluate similarities and

differences in forest regeneration among specific and identifiable ecological units, and for development of general models of forest regeneration that contain universally important determinants of regeneration success. These general models can be calibrated with more local regeneration models derived in other studies to account for finer scale ecological differences, or unique perturbations to regeneration such as presence of invasive species, fire, flooding, animal browsing, etc.

6. Response variables should be chosen that:
   a. have ecological significance;
   b. incorporate the biological and ecological processes that are driving forest regeneration
   c. are relevant to the major abiotic and biotic determinants of regeneration
   d. integrate survival, growth and competitiveness of the desired species
   e. can be used in probability analyses
   f. define the desired future state
   g. can be used in a practical sense to establish management standards, thresholds, guidelines; define adequacy of regeneration; set benchmarks for silvicultural prescriptions

By following these simple, and in many ways common sense recommendations, we can make more rapid progress toward understanding stand initiation, how regeneration dynamics vary by ecological unit, how natural disturbances modify regeneration processes and outcomes, and how we can use silviculture to produce the desired future forest. We can be more efficient and economical in our study of oak regeneration, and more powerful in our inference and application if we spend some time planning good experiments with foresight.

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