Artículo de revisión

APPROACHES TO RESTORATION OF OAK FORESTS ON FARMED LOWLANDS OF THE MISSISSIPPI RIVER AND ITS TRIBUTARIES

Avances en la restauración de bosques de roble en tierras bajas agrícolas del Río Mississippi y sus tributarios

Key words: afforestation, oak, *Quercus*, regeneration, restoration, stand development.

Palabras clave: desarrollo de rodales, *Quercus*, reforestación, regeneración, restauración, roble.

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ABSTRACT

The lowlands associated with the Mississippi River and its tributaries historically supported extensive broadleaf forests that were particularly rich in oak (*Quercus* spp.) species. Beginning in the 1700s, deforestation for agriculture substantially reduced the extent of the original forest, and fragmented the remainder into small parcels. More recently, declines in agricultural commodity prices, along with increased awareness of conservation have provided opportunities to restore a substantial base of agriculture land to broadleaf forests. While afforestation of former agricultural land began over 40 years ago in the region, organized, large-scale afforestation efforts have peaked over the last 15 years with increased interest in forest sustainability, biodiversity conservation, carbon sequestration, and water quality. Large-scale implementation of afforestation to restore broadleaf forest cover has raised many issues particular to oak species biology and ecology that impact the restoration process. The purpose of this manuscript is to present knowledge gained from research and experience with oak forest afforestation in the eastern United States as a model for developing approaches to initiate oak forest restoration in other regions. To accomplish this, we outline issues associated with the oak regeneration strategy and natural stand development patterns that have hampered large-scale restoration of oak-dominated forests. Furthermore, we present effective afforestation approaches used to reduce the impact of these challenges, and frame these approaches under the context of oak forest afforestation that addresses multiple management objectives and provides for value and function on a sustainable basis.

RESUMEN

Las zonas bajas asociadas al río Mississippi y sus tributarios albergaron históricamente extensos bosques de latifoliadas particularmente ricos en especies de roble (*Quercus* spp.). A comienzos del siglo XVIII, la deforestación causada por la agricultura sostenible redujo la extensión del bosque original y fragmentó el restante en pequeñas parcelas. Más recientemente, la reducción en los precios de los productos, junto con la creciente conciencia por la conservación, han brindado oportunidades para restaurar una porción considerable de tierras agrícolas en bosques de latifoliadas. Mientras que las primeras reforestaciones de tierras agrícolas comenzaron hace 40 años en la región, los esfuerzos

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para realizar reforestaciones organizadas y a gran escala han tenido su máximo en los últimos 15 años, debido al creciente interés en la sostenibilidad de los bosques, la conservación de la biodiversidad, el secuestro de carbono y la calidad de las aguas. Implementar la reforestación a gran escala para restaurar bosques de latifoliadas involucra muchos aspectos de la biología y ecología de las especies de roble que impactan el proceso de restauración. El propósito de este artículo es mostrar los conocimientos que se han obtenido a través de investigaciones y experiencias en la reforestación de bosques de roble en el oriente de los Estados Unidos, como modelo para desarrollar avances que permitan iniciar la restauración de los bosques de roble en otras regiones. Para lograr esto delineamos aspectos asociados con las estrategias de regeneración de los robles y los patrones de desarrollo natural de los rodales que han limitado la reforestación a gran escala en bosque dominados por roble. Más aún, presentamos avances efectivos en reforestación usados para reducir el impacto de estos cambios, y enmarcamos estos avances en el contexto de la reforestación de bosques de roble que responde a múltiples objetivos de manejo y brinda valor y función sobre una base sostenible.

INTRODUCTION

Alluvial soils of the lowlands flanking the Mississippi River and its lower tributaries historically supported broadleaf forests rich in tree species diversity. Oaks (*Quercus* spp.) contributed much to the diversity and function of these forests with as many as 15 species that can occur in the overstory (Putnam & Bull 1932, Gardiner 2001). The "bottomland oaks" found on these forested lowlands are all arborescent with 6 belonging to the Section *Quercus* (white oaks) and 9 belonging to the Section *Lobatae* (red oaks). In addition to their strong prominence on these lowlands, their functional importance and silvical traits place bottomland oaks among the most ecologically and economically valued trees in these forests.

Early settlers in the region, however, saw the vast forests as an impediment to the cultivation of the alluvial soils of these lowlands which were exceptional for agricultural production. The high productivity of these soils for agricultural crops spurred extensive land drainage and forest clearing beginning in the 1700s (Gardiner & Oliver 2005). Deforestation progressed as the region was populated, and peaked in the 1960s and 1970s with escalating demand for agricultural commodities (Gardiner & Oliver 2005). By this time, more than 70% of the native forests had been cleared relegating much of the remaining forests to relatively small and fragmented parcels (Gardiner and Oliver 2005). Because of the extensive deforestation and drainage for agriculture, bottomland hardwood ecosystems have been considered among the most degraded in the United States (Noss *et al*. 1995, Stanturf *et al*. 2000). However, the late 20th Century witnessed declines in agricultural commodity prices along with an increased awareness of the ecological value of these ecosystems which have provided opportunity for wide-scale forest restoration.

Afforestation is fundamental to catalyzing restoration of oak-dominated ecosystems on former agricultural land (Stanturf *et al*. 2001). Afforestation decisions will largely determine composition and structure of vegetation, and established vegetation will drive the trajectory and ultimate success of restoration (Stanturf *et al*. 2001, Stanturf *et al*. 2009). Because afforestation plays such a key role, efforts to restore oak-dominated forests in the eastern United States have largely concentrated on the afforestation component of the process.

Attempts to establish oak plantations on cleared agricultural land were documented as early as the 1940s (Maisenhelder 1957), but concentrated efforts to research and develop practical afforestation practices were initiated in the 1960s (Gardiner & Lockhart 2007). Traditional plantations were typically single-species oak plantings that were established for timber or mast production, and it was assumed that diversity would later increase through invasion of the oak plantings by other light-seeded tree species (Stanturf *et al*. 2001, Twedt & Wilson 2002, Lockhart *et al*. 2006). Afforestation approaches have evolved over time as numerous shortcomings of early oak plantations were manifest and forest restoration objectives have matured. Today, oak plantations are still designed to provide wood products and mast for wildlife, but approaches also address objectives that include conservation of biodiversity, improvement of water quality, carbon sequestration, and forest sustainability (King & Keeland 1999, Stanturf *et al*. 2000, Schoenholtz *et al*. 2001, Twedt & Best 2004).

While afforestation approaches to oak forest restoration have evolved over time, significant improvements stem from recognition of species biology and ecology inherent to bottomland oaks. Two of the most significant biological and ecological issues involve the natural regeneration strategy of oak species, and stand development patterns exhibited by oaks. The purpose of this manuscript is to present knowledge gained from research and experience with oak forest afforestation in the eastern United States as a model for developing approaches to initiate oak forest restoration in other regions. We outline issues associated with the oak regeneration strategy and natural stand development patterns that have hampered large-scale restoration of oak-dominated forests. Furthermore, we present effective approaches used to reduce the impact of these challenges, and frame these approaches under the context of oak forest restoration that addresses multiple management objectives and provides for value and function on a sustainable basis.

THE OAK REGENERATION STRATEGY

DESCRIPTION

Consistent with other oak species in temperate North America (Crow 1988, Larsen & Johnson 1998), bottomland oaks are considered disturbance-dependent species. For disturbance-dependent species, recruitment of advance reproduction from the understory to the overstory does not proceed without significant stand disturbance. Three primary elements characterize the regeneration strategy of disturbance-dependent bottomland oaks in natural stands. The strategy consists of sporadic masting by overstory trees, accumulation of advance reproduction in an understory seedling bank, and a growth response following disturbance to support recruitment of advance reproduction from the understory to the overstory.

Acorn production by oak trees in the overstory of mature stands is highly variable with only irregular occurrence of large crops. The frequency and magnitude of masting hinges on success of several reproductive processes such as flower emergence, pollination, and fertilization, all of which are strongly influenced by prevailing environmental factors (Cecich 1993). Reports indicate frequency of large mast crops produced by North American oaks can range from every other year to 7 years, but longer periods between large mast crops do occur (Beck 1993, Johnson *et al.* 2002). Studies also indicate that most oak seedling establishment occurs during growing seasons that follow large mast crops, because few acorns produced during smaller crop years avoid insect damage, desiccation, seed predation or other factors that destroy seed or limit viability (Beck 1993, Crow 1988).

Though the temporal nature of oak masting is highly variable, the potential for oak to regenerate in the event of canopy disturbance is increased through formation of a persistent seedling bank. A seedling bank of advance oak reproduction develops as understory conditions favor acorn germination and seedling survival. Provided sufficient moisture and light, oak seedlings can survive several years in the understory of closed-canopy stands (Carvell & Tryon 1961, Streng *et al*. 1989, Crow 1992, Lockhart *et al*. 2000). Streng *et al*. (1989), observed a 5-year survival rate that exceed 90% for water oak (*Q. nigra* L.) reproduction established in a Texas bottomland, while Johnson (1975) reported Nuttall oak (*Q. nuttalli* Palm.) reproduction persisting 5 to 10 years beneath a closed canopy stand in a Mississippi bottomland. The ability to persist in the understory of undisturbed stands enables accumulation of reproduction in a seedling bank over successive mast crops, and can ensure availability of reproduction in the event of canopy disturbance.

Oak reproduction comprising an understory seedling bank often appears inactive because aboveground growth in heavily shaded environments is minimal. However, studies reveal that oak seedlings persist in understory environments by undergoing morphological acclimation that favors root development over shoot survival and growth (Merz & Boyce 1956, Larsen & Johnson 1998, Johnson *et al*. 2002). This morphological acclimation is accomplished through mechanisms that involve shoot dieback when the seedling is under stress (Crow 1992, Johnson *et al*. 2002), and a photosynthate allocation pattern that favors carbohydrate storage and root growth (Dickson *et al*. 1990). Development of a relatively large root system by advance oak reproduction serves to improve survival if the shoot is damaged in the understory, and may facilitate height growth following overstory disturbance (Larsen & Johnson 1998). However, field observations indicate that advance oak reproduction, particularly small seedlings or seedling sprouts, characteristically responds slowly to overstory disturbance. This slow response is attributed to a conservative growth pattern that favors substantial root development prior to an above-ground response to canopy disturbance (Hodges & Gardiner 1993). Indeed, carbon allocation studies support this premise indicating that the root system is a sink for a majority of photosynthates produced after advance reproduction is released (Lockhart *et al*. 2003, Dillaway *et al*. 2007, Lockhart *et al*. 2008). Thus, juvenile oaks inherently build below-ground capacity in open environments in advance of prioritizing above-ground growth.

PROBLEMS IN AFFORESTATION SETTINGS

The inherent propensity to favor root growth which supports the disturbance-dependent regeneration strategy exhibited by oaks in natural stands can cause significant problems when traditional plantation establishment practices are used during afforestation of former agricultural land. Traditional plantation establishment practices for oak stands overwhelmingly involve transplanting 1-year-old bareroot seedlings grown in a nursery bed to the afforestation site (Stanturf *et al*. 1998). Seedling lifting in the nursery bed necessarily reduces the root mass relative to the shoot mass, and outplanted oak seedlings acclimate to this allometric imbalance by favoring belowground growth and/or shoot dieback following transplanting. As with natural reproduction, transplants will not assume vigorous height growth until after the root system is adequately developed. This acclimation period has been described as transplanting stress, and can suppress height growth for several years. Gardiner *et al*. (2007) noted that Nuttall oak seedlings continued to exhibit reduced height growth from transplant stress two growing seasons after outplanting. The slow growth during this period can lead to prolonged exposure to weedy competition, herbivory, and/or flooding. Consequently, seedling mortality during the establishment phase in oak plantations can be high, resulting in poor stocking and delayed stand development to canopy closure (Stanturf *et al*. 2004).

SILVICULTURAL APPROACHES

Researchers and managers have developed various practices to lessen transplanting stress and improve oak seedling survival and growth during the establishment phase on former agricultural land. Improvements to seedling quality, innovations in development of oak stock types, advancement of vegetation control practices, and incorporation of cover crop plantings are among the necessary practices used to improve survival and growth of oak seedlings planted according to traditional methods on former agricultural fields.

Wide disparity in oak seedling field performance has often been attributed to variation in seedling quality. To improve oak seedling field performance, studies have focused on identifying morphological variables, such as root-collar diameter, number of first-order lateral roots, and root volume, which can serve as predictors to seedling survival or growth. Dey & Parker (1997), for example, identified root-collar diameter as a promising index of field performance for the upland species northern red oak (*Q. rubra* L.). Gardiner *et al*. (2009), used root-collar diameter to predict third-year survival for outplanted Nuttall oak seedlings, confirming the importance of this variable to early survival on afforestation sites on lowlands of the Mississippi River. During this research, observations from three different outplanting sites revealed a 26 % range in potential seedling survival based on initial root-collar diameter (Gardiner *et al*. 2009). These findings clearly indicate that knowledge of how seedling morphology relates to field performance can be used to develop nursery protocols for improving seedling quality, and inform land managers concerned with securing quality planting stock.

While advancement of seedling quality standards can improve field performance of traditional bare-root seedlings, recent innovations in development of other oak stock types provides managers with options for oak plantation establishment. Two large stock types, RPM® stock and stock grown under the Kormanik *et al*. (1994) nursery protocol, can be outplanted to reduce risk of mortality on harsh afforestation sites accessible to mechanical planting equipment (Figure 1). Nursery culture for both of these stock types enhances root system development resulting in stock designed to favor the competitive aspects of oak seedling biology. The Root Production Method (RPM®), which involves root pruning with air, produces large container (11 to 19 l) stock with enhanced root volume and mass (Dey *et al*. 2004, Dey *et al*. 2006). The Kormanik *et al*. (1994) nursery protocol focuses on bare-root nursery culture with stringent control of planting density, fertilization and irrigation regimes. Cultural practices in the nursery bed, along with seedling grading to cull inferior seedlings produces a large seedling with an abundance of first-order lateral roots. In addition to reduced mortality relative to 1-0 bareroot seedlings, these large container and bareroot stocks sometimes have the ability to produce acorns within a few years of outplanting (Grossman *et al*. 2003, Kormanik *et al*. 2006). Masting by such young plants accelerates the natural regeneration potential of oak on afforestation sites, and can provide desirable hard mast for wildlife (Grossman *et al*. 2003).

Transplant stress and suppressed growth by oak seedlings can be prolonged by aggressive weeds common on former agricultural land (Gardiner *et al*. 2009). Where heavy competition is a concern, vegetation management provides an approach for improving oak establishment and growth. Soil cultivation and herbicide applications have traditionally proven effective in reducing oak seedling mortality and accelerating growth on degraded agricultural sites. Cultivation can provide superior weed control while increasing aeration, moisture infiltration into soil, and nutrient availability (Kennedy 1981), but large-scale application of mechanical cultivation is only suitable when plantation spacing is precise. Herbicides may provide a cost-effective approach with acceptable efficacy, and utilization of this technology is becoming more frequent in large-scale plantings. Studies on bottomland oaks planted on former agricultural fields report seedling survival can be increased by as much as 25 % with proper herbicide treatment (Stanturf *et al*. 2004). However, few herbicides are suitable for growing season application in oak plantings, so treatments are typically designed for pre-planting or dormant season applications.

A vegetation control alternative to soil cultivation or herbicide application recently applied to oak plantings involves the use of living mulches or cover crops. Properly managed cover crops can exclude establishment of other competing vegetation effectively increasing survival and growth of oak seedlings (Figure 2). For example, a redtop grass (*Agrostis gigantean* L.) cover crop reduced the probability of mortality for pin oak (*Q. palustris* Muenchh.) seedlings planted on a former agricultural field in Missouri (Dey *et al*. 2004). Height growth for a suite of broadleaf species was greatest when established in cover crops rather than in fields that received a single herbicide application for vegetation control (Steele *et al*. 2008). Additionally, properly selected living mulches can be used to reduce herbivory damage, decrease soil erosion, increase soil nitrogen, and improve water quality (Dugger *et al*. 2004, Van Sambeek & Garret 2004, Dey *et al*. 2008).

Along with improving the traditional plantation establishment approach, an afforestation system that incorporates aspects of the oak regeneration strategy has gained recent popularity. This approach involves interplanting oak seedlings beneath an established canopy of a fast growing pioneer species (Figure 3). The afforestation system begins with establishment of an eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) plantation (Stanturf *et al*. 2009). Cottonwood, which is well suited for plantation culture, rapidly provides stand structure developing an understory environment conducive to establishment of other species (Gardiner *et al*.

2001, Gardiner *et al*. 2004). Within two growing seasons after cottonwood establishment, oaks and other compatible bottomland hardwood species are interplanted throughout the plantation. Interplanted oak seedlings develop into robust saplings beneath the cottonwood canopy placing them in a competitive position when released from the cottonwood overstory around year 10 (Gardiner *et al*. 2004).

In addition to addressing oak seedling biology, this afforestation system provides flexibility to manage forest structure on the afforestation site for other objectives. The quick transition from cleared land to forest structure and associated forest functions draws immediate benefits to ecosystem restoration objectives. For example, establishment of the fast-growing cottonwood plantation is known to benefit soil and water quality, because the plantation cover stabilizes soil resulting in reduced erosion (Thornton *et al*. 1998). The vertical structure of the developing plantation can also improve wildlife habitat. Seven years after plantation establishment, Hamel (2003) found twice as many wintering bird species using cottonwood interplanted with oak compared to plantations established with traditional afforestation methods. Additionally, this afforestation system can realize an early financial return on the restoration investment (Stanturf & Portwood 1999). The woody biomass accumulated by cottonwood can be marketed by the landowner for various products including pulp, woody biofuel, or carbon sequestration credit.

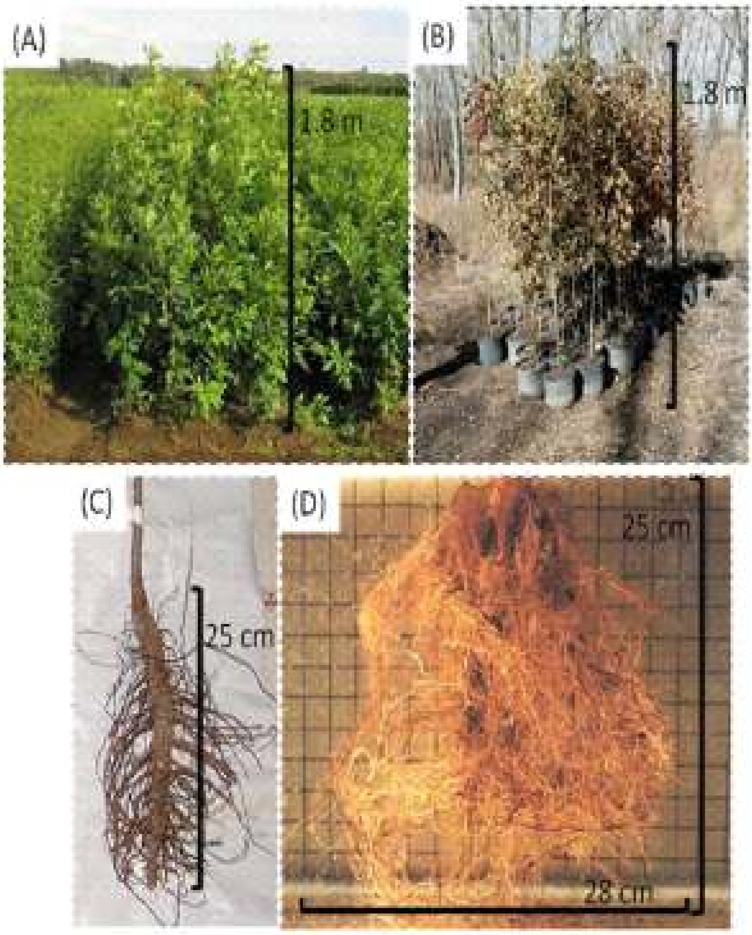

Figure 1. Large oak nursery stock types have been developed to enhance regeneration in harsh or highly competitive environments such as in river floodplains.(A) Large, bareroot Nuttall oak (*Quercus nuttallii*) seedlings grown at the Georgia, USA state nursery following the protocol of Kormanik *et al*. (1994) may reach 1.8 m tall in one year and have a massive root system (C) with high density of first-order lateral roots. (B) Two-year old swamp white oak (*Quercus bicolor*) grown by the Root Production Method® (RPM®) in 19l pots (Dey *et al*. 2004) typically develop (D) highly fibrous and dense roots systems.

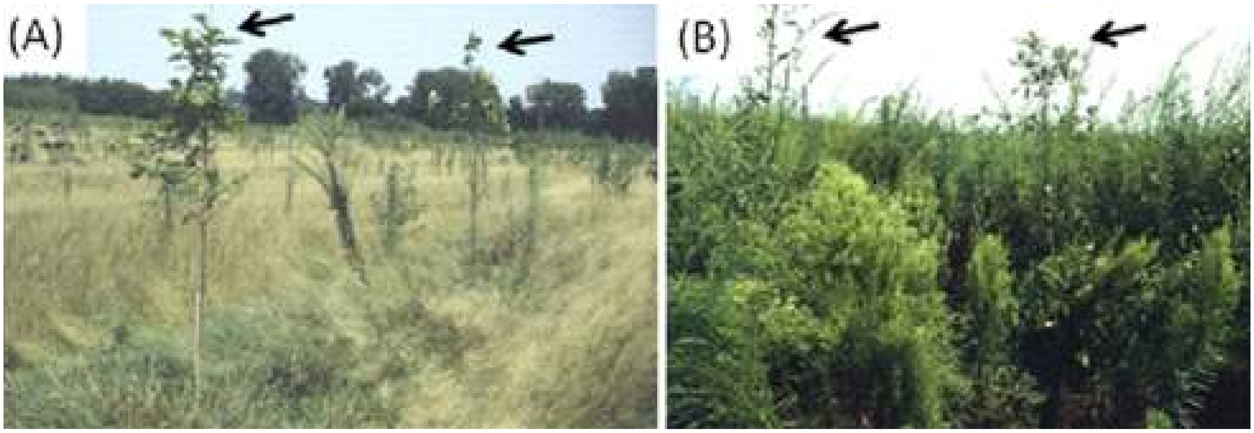

Figure 2. (A) A cover crop of redtop grass (*Agrostis gigantea*) has been used to control competing vegetation and improve oak seedling survival and growth in an afforestation study in the lower Missouri River floodplain, USA (Dey *et al*. 2004). (B) When properly established, redtop grass can rapidly cover the ground with a solid sod cover and limit the rank growth of annual forbs that dominate on former agricultural fields.

OAK STAND DEVELOPMENT

DESCRIPTION

As research and experience continue to improve efficiency and success of oak plantation establishment, managers must also have a clear understanding of how oak stands develop to more effectively approach restoration objectives. Stand development refers to temporal changes in forest stand structure (Oliver & Larsen 1996), and forest stands dominated by bottomland oaks have typically undergone significant, but somewhat predictable change in structure over time (Lockhart *et al*. 2006).

In addition to addressing oak seedling biology, this afforestation system provides flexibility to manage forest structure on the afforestation site for other objectives. The quick transition from cleared land to forest structure and associated forest functions draws immediate benefits to ecosystem restoration objectives. For example, establishment of the fast-growing cottonwood plantation is known to benefit soil and water quality, because the plantation cover stabilizes soil resulting in reduced erosion (Thornton *et al*. 1998). The vertical structure of the developing plantation can also improve wildlife habitat. Seven years after plantation establishment, Hamel (2003) found twice as many wintering bird species using cottonwood interplanted with oak compared to plantations established with traditional afforestation methods. Additionally, this afforestation system can realize an early financial return on the restoration investment (Stanturf & Portwood 1999).

As described above for natural oak stands, canopy disturbance of sufficient magnitude initiates a growth response by advance oak reproduction established in the understory. During this stand initiation stage (*sensu* Oliver & Larsen 1996), the oak growth response is often not as vigorous as the growth response by other shade intolerant species (Hodges & Gardiner 1993). Even well developed oak advance reproduction can struggle to occupy growing space as more competitive species like sweetgum (*Liquidambar styraciflua* L.), green ash (*Fraxinus pennsylvanica* Marsh.) and American sycamore (*Platanus occidentalis* L.) may exhibit faster growth rates during this stage of stand development (Johnson 1975, Clatterbuck *et al*. 1987, Oliver *et al*. 2005). Though bottomland oaks may initially respond slowly during the stand initiation stage, saplings can advance to a competitive position in the stem exclusion stage of stand development if sufficient height growth is sustained to avoid overtopping by competitors.

The stem exclusion stage in stand development marks significant interspecific competition which leads to canopy stratification and tree mortality (Oliver & Larsen 1996). During this stage of stand development, the growth pattern of bottomland

Figure 3. New afforestation systems such as this interplanting of eastern cottonwood (*Populus deltoides*) and Nuttall oak (*Quercus nuttallii*) are can be used to promote restoration of oak-dominated bottomland forests. This image illustrates a 13-year old Nuttall oak sapling developing beneath a 15-year old eastern cottonwood overstory in Mississippi, USA.

oaks is such that they are often able to assert dominance over species with dissimilar growth patterns. For example, Clatterbuck & Hodges (1988) found that sweetgum initially outgrew cherrybark oak (*Q. pagoda* Raf.) in bottomland stands in Mississippi, but 20 to 25 years after stand initiation oak advanced above sweetgum to become the dominant canopy species. The stratification of cherrybark oak over sweetgum was attributed to a rapid increase in the rate of height growth by cherrybark oak, and a slight decrease in the rate of height growth for sweetgum during this stage of stand development. Though natural bottomland oak stands typically initiate as single cohort stands, the dynamics of structural changes over time lead to development of complex stand structure, and promote development of well-formed oaks that dominant the overstory (Bowling & Kellison 1983, Clatterbuck & Hodges 1988, Johnson & Krinard 1988).

PROBLEMS IN AFFORESTATION SETTINGS

Failure to recognize and incorporate knowledge of oak stand development in plantation design regularly leads to establishment of oak plantings with substantially limited management options. Observations in older, single-species plantings illustrate that a stand development pattern conducive to overstory stratification and emergence of well-formed oak in the overstory are not expressed when competition is primarily intraspecific (Lockhart *et al*. 2008) (Figure 4). When grown under intraspecific competition, oaks tend to exhibit suboptimal height and diameter growth, poor stem form, a low capacity to self-prune, and weak crown development (Lockhart *et al*. 2006, Lockhart *et al*. 2008). Additionally, mono-specific oak stands show little canopy stratification and develop an understory adverse to establishment of other species (Stanturf *et al*. 2001, Twedt & Wilson 2002, Lockhart *et al*. 2008). Thus, single-species oak plantations established on former agricultural land are proving to be low quality from a timber management perspective, and also less than desirable from a wildlife habitat perspective (Stanturf *et al*. 2001, Twedt & Wilson 2002).

SILVICULTURAL APPROACHES

Practical and inexpensive steps can be taken to integrate knowledge of oak stand development in plantations designed for restoration purposes. To be successful, the plantation design must facilitate management of interspecific competition between desired canopy species. Selection of suitable species mixtures and determination of proper spatial arrangement in the plantation are primary factors that will determine successful incorporation of natural stand development processes that promote complex stand structure and oak dominance on restoration sites.

Observations that oaks develop poorly in monospecific stands point to the need to establish species rich plantations. However, plantations established with arbitrary mixtures of overstory species may not favor development of desired oaks. Species suitability in a mixture will be determined by compatibility of its silvical characteristics with those of the desired oak (Lockhart *et al*. 2008). In general, oaks will develop best among species that provide a level of interspecific competition that encourages height growth without susceptibility to overtopping. As an example of such a mixture, Lockhart *et al*. (2006) were able to replicate in plantations the stand development pattern of cherrybark oak and sweetgum observed in natural stands (Figure 5). An approach for designing species mixtures suitable for bottomland oak stand establishment on former agricultural fields in the Lower Mississippi Alluvial Valley was forwarded by Lockhart *et al*. (2008), and stand development concepts introduced in that approach can apply to establishment of mixed-species plantations in other regions.

Species compatibility and developmental trajectory of the stand is also driven largely by the spatial arrangement of the mixture. Spatial arrangement of the mixture is determined by plantation spacing (distance between stems) and species distribution (intraspecific and interspecific spacing). In turn, spatial arrangement will control the timing and level of intraspecific and interspecific competition in the developing stand. Clatterbuck *et al*. (1987), demonstrated the importance of spatial arrangement with planted mixtures of American sycamore and cherrybark oak. Because sycamore rapidly outgrows cherrybark oak, oaks planted within 6 m of sycamore were quickly suppressed. But, oaks planted greater than 6 m from sycamore were able to attain a favorable canopy position and assert dominance in the stand (Clatterbuck *et al*. 1987). More subtle but nonetheless significant influence of spatial arrangement on oak stand development was also demonstrated by Lockhart *et al*. (2006) with their work on cherrybark oak and sweetgum described above.

SUMMARY AND CONCLUSIONS

Extensive afforestation on farmed lowlands of the Mississippi River and its tributaries has provided tremendous opportunity to restore keystone bottomland oak ecosystems in this ecologically degraded region. Earliest oak plantations often fell short in promoting restoration of ecological functions or stand value, and have also limited management options for meeting future objectives. More recently, managers are beginning to incorporate knowledge of oak species biology and ecology in plantation design. The oak regeneration strategy accounts for issues often encountered during plantation establishment with the traditional approaches. An understanding of this regeneration strategy has led to the development of improved stock types and silvicultural practices that enhance seedling survival and growth on afforestation sites, and development of alternative afforestation systems that can address multiple objectives such as biodiversity conservation, timber management, water quality and carbon sequestration.

Consideration for factors beyond seedling establishment has also advanced our ability to deploy sustainable plantations for restoration. Planting species mixtures that promote natural oak stand development patterns can improve restoration

Figure 4. Poor stem quality, weak canopy stratification and lack of understory development characteristically result from intraspecific competition in oak plantings such as in this 25-year old water oak (*Quercus nigra*) plantation established on a former agricultural field in Mississippi, USA.

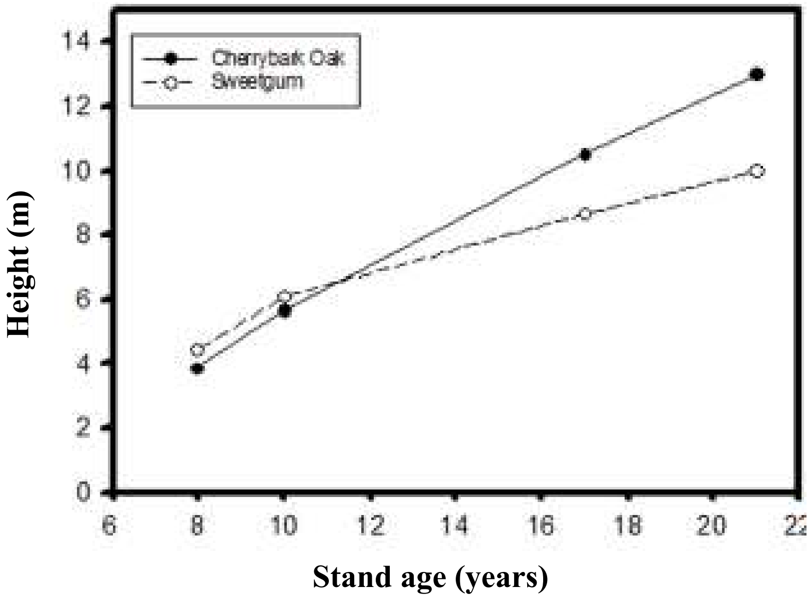

Figure 5. Interspecific competition often leads to a favorable natural stand development pattern of oaks such as for this cherrybark oak (*Quercus pagoda*) and sweetgum (*Liquidambar styraciflua*) plantation mixture established on a former agricultural field in Mississippi, USA.

of ecological functions, and enhance oak stand quality for stand management purposes. In this regard, selecting overstory species that exhibit silvical characteristics compatible with oaks, and thoughtful design of spatial arrangement in the plantation are essential to development of species rich, structurally diverse stand mixtures. Knowledge and experience gained from the progression of oak forest restoration in the eastern United States can be used to develop approaches that encourage long-term restoration success in oak dominated forests in other regions including the northern Andes.

From our experience, we recommend the following approach to developing an afforestation program that promotes restoration of oak-dominated forests. (1) Understand regeneration strategies of native oak species that are of high priority for restoration. Though we have outlined what appears to be a general strategy for temperate *Quercus* species, that of developing an extensive seedling root system and responding to disturbances, local experience should validate this understanding. (2) Know the environmental requirements for establishment of oak regeneration. For example, light acclimation and morphological plasticity of desired oak species, and the optimal light levels for seedling development. These requirements should be incorporated in the design of afforestation practices. (3) Know the environmental requirements of interfering species. This knowledge can be used to reduce impacts of competing vegetation. (4) Finally, develop methods for establishing multiple-species stands based on patterns of stand development for priority oak species and common co-occurring species. Restoration success will be greatest where afforestation practices are designed to catalyze natural stand development patterns.

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