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ORIGINAL ARTICLE

Innovations in afforestation of agricultural bottomlands to restore native forests in the eastern USA

DANIEL C. DEY[1], EMILE S. GARDINER[2], JOHN M. KABRICK[1], JOHN A. STANTURF[3] & DOUGLASS F. JACOBS[4]

[1]*US Forest Service, Northern Research Station, 202 Natural Resources Building, Columbia, MO 65211, USA,* [2]*US Forest Service, Southern Research Station, PO Box 227, Stoneville, MS 38776-0227, USA,* [3]*US Forest Service, Southern Research Station, 320 Green Street, Athens, GA 30602, USA, and* [4]*Hardwood Tree Improvement and Regeneration Center, Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN 47907-2061, USA*

Abstract

Establishing trees in agricultural bottomlands is challenging because of intense competition, flooding and herbivory. A summary is presented of new practices and management systems for regenerating trees in former agricultural fields in the eastern USA. Innovations have come from improvements in planting stock and new silvicultural systems that restore ecological function more quickly than traditional afforestation with single-species stands. Advances in nursery production of large (e.g. 1–2 m tall; 1.5–2.0 cm basal diameter) bareroot and container seedlings with well-developed root systems have led to increases in survival and growth, and early seed production. In addition to planting high-quality seedlings, managing vegetation is critical to regeneration success. Planting seedlings with cover crops such as redtop grass (*Agrostis gigantea* Roth) may improve tree survival and growth by controlling competing vegetation and reducing animal herbivory. An innovative strategy that simulates natural succession involves interplanting later seral species such as Nuttall oak (*Quercus nuttallii* Palm.) in young plantations of pioneer species such as *Populus deltoides* Bartr. ex Marsh. *Populus* L. acts as a nurse crop for *Quercus* L. by reducing biomass of competing vegetation without seriously limiting *Quercus* L. seedling growth or function. Harvest of the short-rotation *Populus* L. crop releases the well-established *Quercus* L. trees. Success in afforestation requires planting high-quality seedlings using management practices that promote survival and growth. Restoration based on ecosystem processes, using tree species that have complementary ecological requirements, will be more successful and affordable than other methods.

Keywords: *afforestation, artificial regeneration, bottomland forest, restoration, silviculture.*

Introduction

The Great Flood of 1993 on the Mississippi and Missouri Rivers, USA, inundated over 41,500 km^2 of farmlands for up to 200 days, severely damaging lands through soil scouring or by leaving deep sand deposits (Lott, 1993). The flood focused national attention and debate on the status of wetlands and their ecological integrity. Now, restoration of bottomland forests is a priority for natural resource agencies, and federal conservation programs are promoting forest restoration on privately owned lands, which comprise the majority of the landbase (>90%) in most areas in the eastern USA (e.g. Wigley & Sweeney, 1992).

Forest restoration on Mississippi and Missouri River floodplains is problematic because they are among the most altered ecosystems in North America (Noss et al., 1995). Since the 1780s, more than half (53%) of the original wetlands have been developed for agricultural production in the coterminous USA (Dahl, 1990). Several states in the midwestern and southern USA have lost more than 85% of their original wetlands, many of which were originally forested (Bragg & Tatschl, 1977; Nature Conservancy, 1992). Historically diverse, mixed-species forests covered the 10 million ha Lower Mississippi Alluvial Valley (LMAV) in the south–central USA but, through conversion to

Correspondence: D. C. Dey, US Forest Service, Northern Research Station, 202 Natural Resources Building, Columbia, MO 65211, USA. E-mail: ddey@fs.fed.us

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agriculture, only 26% of the original forest cover is left (Gardiner & Oliver, 2005).

Historically in the eastern USA, bottomland forests were dominated by a diversity of hardwood species, and maximum tree diversity occurred in the LMAV where more than 60 species are endemic to the floodplains. Although the bottomlands were inherently rich in species diversity, native bottomland oaks (*Quercus* L.), and species such as pecan [*Carya illinoensis* (Wangenh.) K. Koch] and black walnut (*Juglans nigra* L.) were the initial focus of plantings to restore forests because of their value for timber and mast production for wildlife, and because of the difficulty in natural regeneration of these species (King & Keeland, 1999). These genera generally occurred naturally on the higher elevations in floodplains, where site inundation was less frequent and with shorter duration. Historically, these were the first areas cleared for crop production, resulting in long-term loss of seed production from the site as remnant mature oak, black walnut and pecan trees are rare in these big river floodplains. Natural regeneration of these genera is non-existent because of a lack of local seed-producing trees and a limited dispersal of the heavy nuts from adjacent uplands.

Bottomland oaks still comprise a large component of the outplanted species, and methods for establishing bottomland oaks are available (e.g. Allen et al., 2004). However, regeneration results on these degraded bottomland sites are inconsistent owing to a number of factors including intense vegetation competition, poor seedling quality, flooding and poor soil drainage (improper species-site selection), wildlife herbivory, inadequate soil management and landowner failure to apply recommended practices at the proper time (King & Keeland, 1999; Stanturf et al., 2000, 2004). Current afforestation research is poised to address many of these persistent issues. This manuscript provides an outline of focal points from current research and a synthesis of practical findings and afforestation innovations advancing forest restoration on previously farmed bottomlands in the USA.

Seedling quality and competitiveness

Planting high-quality hardwood seedlings may help to overcome some of the challenges to afforestation of agricultural bottomlands. The use of large, vigorous seedlings capable of rapid early growth reduces the time they are vulnerable to competing vegetation, subject to growing season inundation by flooding and within the reach of herbivores (Stanturf et al., 2004). This is problematic when working with oak species that are known for their slow juvenile growth (Johnson et al., 2002).

Seedling quality can be assessed using seedling physiological condition and morphological traits (Wilson & Jacobs, 2006; Dey et al., 2008). Physiological indicators for hardwood seedlings are under development (e.g. Garriou et al., 2000; Goodman et al., 2009). However, reliable physiological indices are not available yet for commonly planted species. Morphological indicators such as shoot length, basal stem diameter and number of first order lateral roots (FOLRs; roots >1 mm in diameter) are still the primary means of assessing hardwood seedling quality.

Whether planted in the field or forest of uplands or floodplains, the competitiveness of oak seedlings is strongly related to their root system size at the time of planting (Ward et al., 2000; Dey et al., 2004; Gardiner et al., 2009). Kormanik et al. (1995) reported increased survival and probability of being free to grow with increasing numbers of FOLRs for northern red oak (*Quercus rubra* L.) and white oak (*Q. alba* L.) bareroot seedlings planted in a North Carolina, USA, clear-cut. Those seedlings that had more than 11 FOLRs were most likely to be competitive. Dey and Parker (1997) also found that the initial number of FOLRs in northern red oak bareroot seedlings was positively and significantly correlated with future seedling size when they were underplanted in Ontario, Canada, shelterwoods.

Relationships among initial shoot size and future survival and growth are similar to those found with the initial size of the root system because stem size, especially root collar diameter, is highly correlated to root mass, area and volume in oaks (Kormanik et al., 1995; Dey & Parker, 1997). Consequently, shoot growth in oak seedlings increases with increasing initial basal diameter of the stem (Jacobs et al., 2005*a*, *b*; Dey et al., 2009). Gardiner et al. (2009) noted increases in seedling survival in 1-0 bareroot seedlings of pecan and Nuttall oak (*Quercus nuttallii* Palm.) planted in fields being afforested in the LMAV of Mississippi and Arkansas, USA. In contrast, they did not see any relation to survival of 1-0 green ash (*Fraxinus pennsylvanica* Marsh.) seedlings and initial basal stem diameter because survival was very high (95%) regardless of seedling size (range in diameter: 2–18 mm). Spetich et al. (2002) observed that the long-term probability of being dominant for planted northern red oak increased significantly with increasing initial basal diameter when seedlings were underplanted in upland shelterwoods in the Boston Mountains of Arkansas, USA. The growth performance of oak is also improved by planting seedlings with larger initial shoot lengths and volumes (Dey & Parker, 1997).

Nursery seedling types: large container and bareroot

Typically, 1-0 bareroot seedlings, which average 0.5–0.7 m in height and 6–8 mm in basal diameter, are planted in afforesting bottomland fields. More recently, nurseries are producing larger hardwood seedlings by intensive bareroot (e.g. Kormanik et al., 1994) or container production methods (e.g. Dey et al., 2004). Large oak seedlings have been produced by these methods that reach average heights of 1.0–1.5 m and root collar diameters of 10–20 mm after 1 year, depending on the species.

The early development of a large root system is key to oak regeneration competitiveness (Johnson et al., 2002). The intensive nursery cultural methods noted above are able to produce large root systems in oak in just 1 year (Figure 1). For example, Shaw et al. (2003) reported significant increases in root volume and root dry mass for 1-year-old container seedlings of pin oak (*Q. palustris* Muenchh.) and swamp white oak (*Q. bicolor* Willd.) grown by the Root Production Method (RPM®) compared with traditionally grown 1-0 bareroot seedlings.

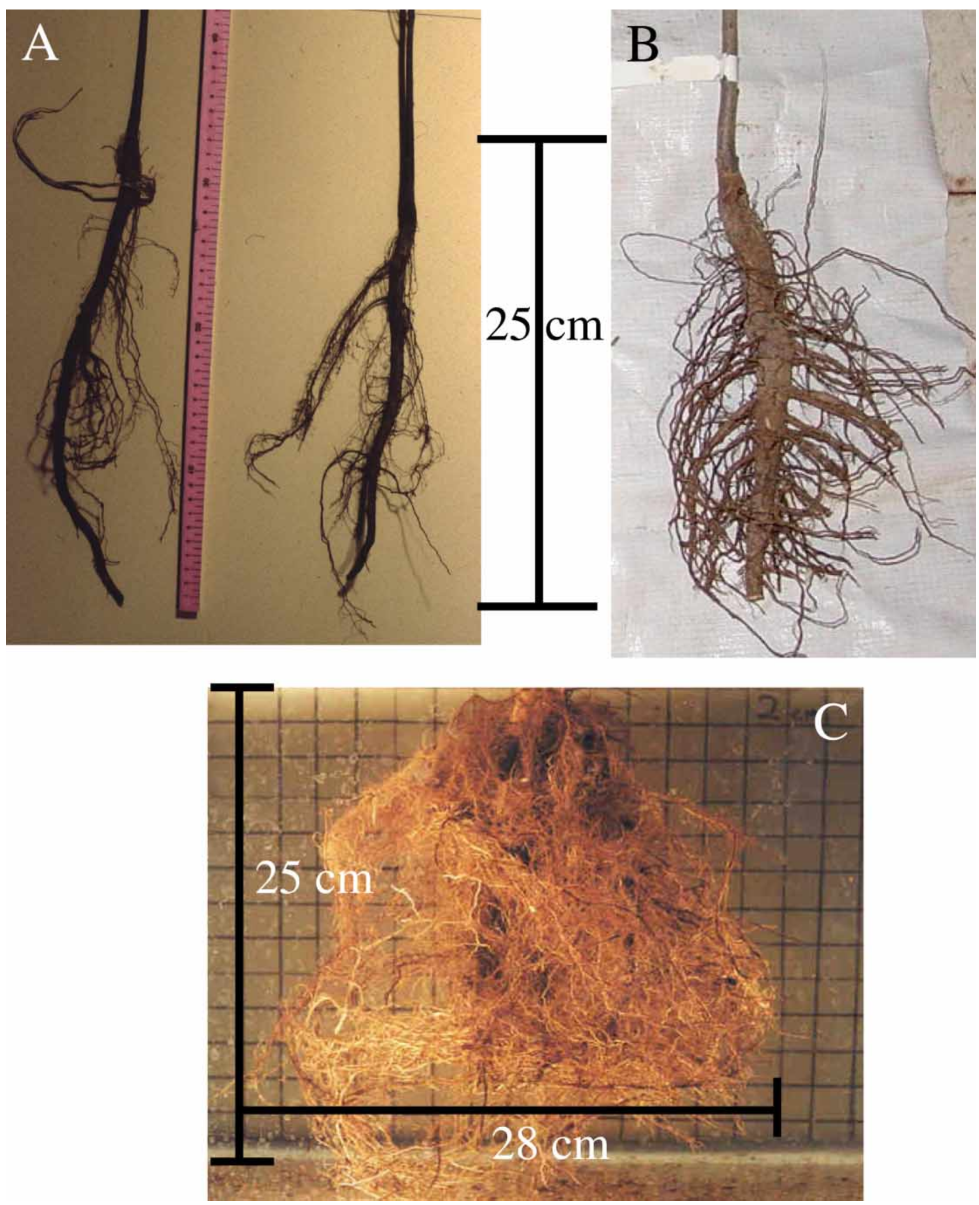

Figure 1. Comparison of 1-year-old swamp white oak (*Quercus bicolor* Willd.) root systems grown by different nursery production systems: (A) following conventional bareroot nursery culture, (B) produced by intensive bareroot culture at low density and with high resource inputs (Kormanik et al., 1994), and (C) grown in 11 liter containers by air root pruning and intensive culture (Dey et al., 2004).

In field trials of large container-grown oak, Dey et al. (2004) reported that third year survival was significantly greater (>94%) for pin oak and swamp white oak RPM® seedlings (grown in 11 and 19 liter containers) than 1-0 bareroot seedlings (<76%) in afforestion plantings in the Lower Missouri River Valley, USA. They also noted that basal diameter increment was significantly greater for RPM® seedlings than for bareroot stock, regardless of species. Similarly, Kormanik et al. (1995) assessed the field performance of 1-0 bareroot seedlings of northern red oak grown by their improved nursery protocol and found that seedlings with more than 12 FOLRs outperformed substantially smaller seedlings that had fewer than seven FOLRs in clear-cuts on high-quality sites in North Carolina, USA. Of the seedlings with the largest root systems, 52% were free to grow after 5 years, whereas only 6% of seedlings in the smaller size class were still in a competitive position.

An unusual ability of large oak seedlings grown by either the RPM® or intensive bareroot culture method is that they are able to produce viable acorns at an early age. Naturally established oak trees begin producing acorns between 15 and 35 years of age depending on species, stand density and other factors that influence flowering and seed development (Schopmeyer, 1974). In afforestation plantings in the Lower Missouri River Valley, Grossman et al. (2003) observed production of sound acorns in swamp white oak RPM® seedlings during the first year of establishment when the trees were 2–3 years old. The probability of producing sound acorns was significantly and positively related to the initial size of RPM® seedlings. The first trees to bear acorns continued mast production in subsequent years, and more trees have come into production each year following plantation establishment (Dey et al., 2004). Early acorn production (8 years) in northern red oak planted as large 1-0 seedlings (more than six FOLRs) has also been observed by Kormanik et al. (2004). Early acorn production is of considerable value to managers desiring hard mast production for wildlife. Use of RPM® or very large and robust bareroot seedlings with large root systems helps to restore bottomland forests and accelerates natural regeneration capability for oaks on sites where it was eliminated at the time of conversion to agricultural production.

Benefits of a cover crop to tree establishment

It is widely recognized and recommended that competing vegetation must be controlled during the first 2–5 years of hardwood establishment in afforestation (Allen et al., 2004). Herbicides applied while seedlings are dormant are effective and much research has been done on the best application of a number of chemicals for control of a variety of competitive species (Stanturf et al., 2004). Competing vegetation can also be controlled mechanically by disking or tilling. Repeated, annual application of chemical or mechanical vegetation control is expensive and costs must be carried over the rotation. For some land ownerships, herbicide use is not desired by the landowner or by the public. In these cases, the control of competing vegetation by a living cover crop may be a good alternative (Van Sambeek & Garrett, 2004). Cover crops that are self-sustaining eliminate the annual cost of vegetation management and may provide economic benefits to the landowner who can harvest the seed crop, make hay or graze the alleyways. Typically, legumes or grasses have been used as cover crops. A new area for future study is in assessing the potential of native bottomland herbaceous species as cover crops.

Current work on cover crops has focused on the use of naturalized species, whose seed is readily available and affordable, and which land owners are accustomed to managing. For example, Dey et al. (2004) showed that a redtop grass (*Agrostis gigantea* Roth) cover crop reduced mortality of pin oak and swamp white oak planted as 1-0 bareroot or RPM® seedlings in former agricultural fields in the Lower Missouri River floodplain compared with fields where oak seedlings competed with vegetation that naturally colonized abandoned crop fields (Figure 2).

Large fields (16.0 ha) of redtop grass benefited oak survival and growth also by controlling the extent and severity of herbivory damage by eastern cottontail rabbits (*Sylvilagus floridanus* Allen) (Dey et al., 2004). Fields of redtop grass, which exhibit a low growing stature, provided minimal winter security cover for rabbits compared with fields dominated by coarse-stemmed forbs, which formed a canopy of cover that permitted rabbits to move freely across the plantation. Rabbit densities in redtop grass fields were one-third those in natural vegetation, and rabbit activity was restricted to edges in the redtop grass fields (Dugger et al., 2004).

Songbird conservation is an important part of land management plans and objectives. An additional ecological benefit of planting oaks in a redtop grass cover was that it prolonged the time the area exhibited a grassland community structure, which provided valued habitat for birds of conservation concern such as the Henslow's sparrow (*Ammodramus henslowii* Audubon) (D. Burhans, US Forest Service, Northern Research Station, personal communication).

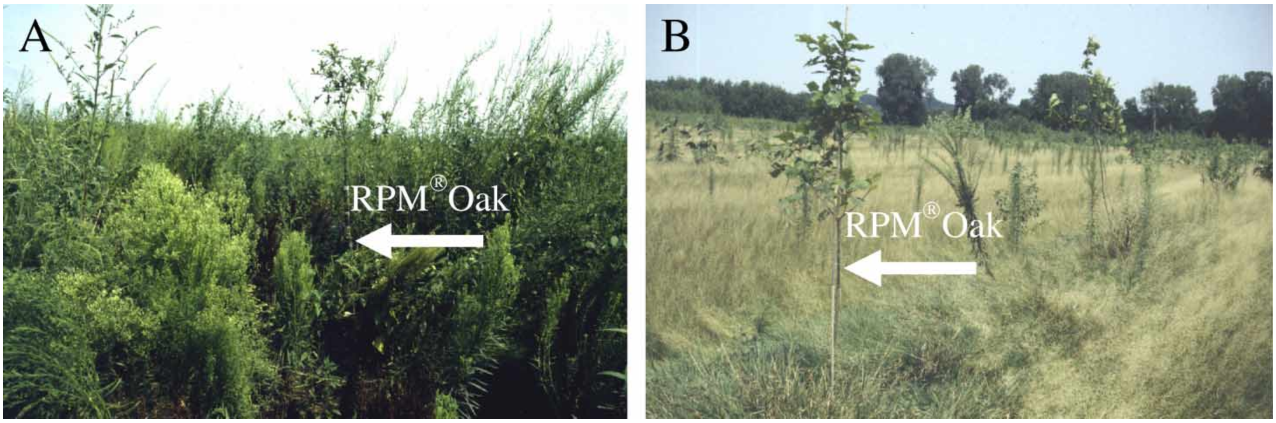

Figure 2. Planting oaks with a cover crop of redtop grass (*Agrostis gigantea* Roth) significantly improved the survival of pin oak (*Quercus palustris* Muenchh.) and swamp white oak (*Quercus bicolor* Willd.) seedlings 3 years after afforesting fields in the Lower Missouri River Valley: oaks in competition with (A) natural vegetation, or (B) a cover crop of redtop grass. Photographs represent the condition of competing vegetation in the first summer of plantation establishment. RPM® = Root Production Method.

Mixed species afforestation

Strategic approaches to tree establishment

Initially, large-scale plantings on bottomland sites were primarily eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) plantations established by the forest industry. Short-rotation intensive plantation culture of eastern cottonwood is done for fiber, biomass or pulpwood production. Silvicultural prescriptions and specific practices for short-rotation intensive culture of eastern cottonwood are well established (Stanturf et al., 2001). Regeneration and establishment of this forest production system is usually successful because the industrial landowner is committed to proper implementation of good silvicultural practices and motivated by the expectation of economic profit. In addition, they normally have the expertise, equipment and finances to implement best management practices. Early returns from harvests that occur within 10 years of establishment promote the profitability of these systems (Stanturf & Portwood, 1999). This fosters early investment in intensive culture that ensures regeneration establishment and good growth.

Until recently, the primary strategy to afforestation on non-industrial private and public lands has been to plant a single species or limited mixtures of bottomland oaks (Lockhart et al., 2006, 2008). The nut-producing species are valued not only for their fine-quality timber but also for mast production, which is important to many wildlife species. This strategy favors the slower growing, shade-intolerant oak species and relies on natural regeneration of light-seeded pioneering species such as eastern cottonwood, black willow (*Salix nigra* Marsh.), silver maple (*Acer saccharinum* L.) and boxelder (*Acer negundo* L.) to diversify the forests. This approach works well in small fields bordered by mature, mixed-species forests. However, reliance on natural regeneration to provide tree diversity by the addition of wind-disseminated species fails in large fields when adjacent forest edges are further than 100 m away (Allen, 1990, 1997; McCoy et al., 2002; Twedt, 2004). Poorly stocked forests result, and oaks growing in open conditions develop low-quality stems.

With an increase in landowner awareness, management goals have become more diverse and complex to include wildlife management, recreational hunting, timber production, conservation and restoration of more diverse, native forests. This shift, however, is problematic from an economic and ecological standpoint. Longer rotations to final harvest (e.g. 60–80 years), emphasis on slower growing species, regeneration of more complex species mixtures and management for indirect or intangible benefits all act to lower the economic feasibility and increase the management complexity of these systems. Management becomes extensive to keep the costs of establishment minimal because those costs must be carried for decades until harvest revenues are earned. Managers have less experience and knowledge of managing the multitude of species mixtures possible, and research on regenerating compatible species mixes is scarce (Lockhart et al., 2006, 2008). Limited financial and staff resources restrict landowner ability to control competing vegetation or protect trees from herbivores at critical times during regeneration. Lack of resources also makes it difficult to monitor regeneration, which is important for identifying problems early, so that corrective action can be taken. Consequently, regeneration results are less certain and failures are common (Schweitzer & Stanturf, 1997).

Afforestation and wildlife conservation

The great loss of bottomland forests in North America and the highly fragmented forest remnants make forest restoration a priority wildlife conservation goal (King & Keeland, 1999). Pure oak plantings, while they have been the dominant activity in bottomland afforestation in the south for the past 20–30 years, are not ideal when wildlife or timber is the primary objective. Oak plantations develop a vertical woody structure much more slowly than species such as eastern cottonwood. In LMAV afforestation stands, Twedt et al. (2002) observed that young (<10 years) cottonwood plantations had a greater abundance of high-priority forest bird species, as well as a significantly greater overall conservation value than young oak plantations, largely as a result of the rapid development of woody structure. Hamel (2003) attributed wintering bird species richness in 7-year-old bottomland hardwood plantations to accretion of vertical structure, noting that species richness in cottonwood plantings was twice that observed in oak plantings.

Another factor contributing to slow development of structure in oak plantings is that they are less intensively managed than eastern cottonwood plantations and thus are more susceptible to growth reductions owing to vegetation competition and herbivory, which is encouraged by dense herbaceous vegetation. Competing vegetation and herbivory by hispid cotton rats (*Sigmodon hispidus* Say and Ord), eastern cottontail rabbits and white-tailed deer (*Odocoileus virginianus* Boddaert) can retard oak height growth and forest development for 15 years or more, suppressing succession and maintaining an open grassland structure (Twedt, 2004). This delays the benefits of restoration for songbirds and other species dependent on the development of woody structure and large-diameter trees in a forested environment. In contrast, eastern cottonwood plantings can attain canopy closure and provide a complex structure within 3 years, and by the age of 5–7 years they can support four times the avian species with breeding territories compared with similarly aged oak plantings (Twedt & Portwood, 1997).

Twedt et al. (1999) observed increases in breeding bird populations in short-rotation (6–9-year-old) plantation monocultures of eastern cottonwood over those found in agricultural fields in the LMAV, but more mature bottomland forests (>30 years old) of mixed species were twice as valuable for bird conservation compared with the plantations. Avian species richness, diversity and territory density were significantly greater in diverse bottomland hardwood stands than in intensively managed eastern cottonwood plantations.

Afforestation and timber production

Pure oak plantings develop uniform canopies, lack complex vertical structure, and limit natural regeneration and recruitment of other species into the single-layered oak canopy (Twedt & Wilson, 2002) (Figure 3A). Plantations of a single oak species tend to stagnate, show little crown differentiation, have lowered diameter growth, develop epicormic branching and retain lower dead branches (Lockhart et al., 2006). Poor stem quality results from intraspecific competition among the oaks (Twedt & Wilson, 2002; Lockhart et al., 2008). Southern bottomland oaks can develop tall, straight, clear boles when growing with a mixture of "compatible" species, for example when cherrybark oak (*Quercus pagoda* Raf.) is grown with sweetgum (*Liquidambar styraciflua* L.) in natural stands or plantations (Clatterbuck & Hodges, 1988; Johnson & Krinard, 1988; Lockhart et al., 2006) (Figure 3B). Oak height growth is promoted with moderate levels of competition from companion species that do not overtop the oak. Early self-pruning of small-diameter branches in the lower crown occurs when oaks are competing with the right species. For these reasons, Lockhart et al. (2006, 2008), Twedt and Portwood (1997) and Twedt and Wilson (2002) have recommended planting oaks with other compatible species.

Selecting the right species mixtures

Lockhart et al. (2008) developed a system for identifying species that are good companions in bottomland oak plantings. Species are numerically scored according to key characteristics important in interspecific competition, including tree form, pattern of early height growth, branching pattern, relative twig diameter and durability, and shoot type. Their system is specifically calibrated for southern bottomland oak forests but can be adapted to other ecosystems.

They evaluated 24 species that naturally occur with oak in the LMAV and identified sweetgum, river birch (*Betula nigra* L.) and green ash as some of the most companionable species to be grown with oak, whereas American sycamore (*Platanus occidentalis* L.), eastern cottonwood and black willow were found to be less desirable for single-cohort stands. Eastern cottonwood scored low largely because of its rapid early height growth (>5 m in 2 years) (Twedt, 2004) and ability to overtop oaks. Despite its low score, eastern cottonwood is often recommended as a species to plant with oak (Twedt & Portwood, 1997; Stanturf et al., 2000, 2009). It can be useful in oak mixtures if wider spacings are used to lessen the competition with the oak, or if eastern cottonwood

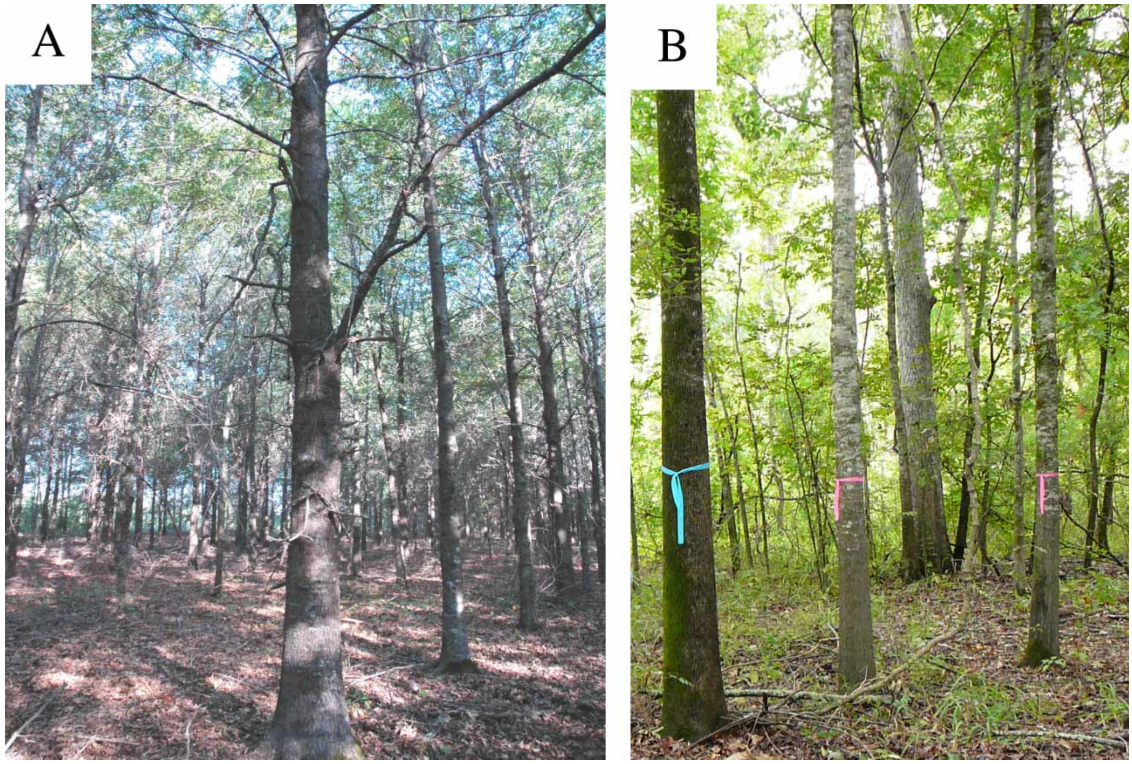

Figure 3. Stand development in (A) pure plantings of oak (*Quercus* L.) species results in intense intraspecific competition that promotes poor stem quality and produces relatively low-quality habitat for songbirds (Twedt, 2004; Lockhart et al., 2008). In contrast, (B) oaks have rapid height growth and develop quality stems when they compete with species such as sweetgum (*Liquidambar styraciflua* L.) in the example of afforestation of bottomland fields in the Lower Mississippi Alluvial Valley, USA.

competition is controlled by early silvicultural treatments such as thinning, or biomass or fiber harvesting. Eastern cottonwood is commonly managed for fiber on a 10 year rotation, which makes it ideal for growing with oak because the revenue-generating act of removing it releases the oak without a cost to the landowner.

Interplanting eastern cottonwood with oak

The concept of interplanting species is not new, but operational or research applications are few in the eastern USA. In the early 1990s, bottomland managers and scientists began establishing mixed-species plantations to restore forests in former agricultural fields (Gardiner et al., 2008), including the interplanting of established eastern cottonwood stands with oak seedlings as recommended by Twedt and Portwood (1997). By the late 1990s, more than 1000 ha of operational plantings of eastern cottonwood and oak had been established and research was underway to evaluate these systems for afforestation of agricultural bottomlands.

In a region where most of the floodplain is privately owned, an afforestation approach is needed that is simple in concept, provides multiple benefits to the landowner, returns early income to make operations profitable and is self-regulating to minimize the need for active intervention by the landowner. The perceived benefits of the eastern cottonwood–oak afforestation system are: (1) early development of vertical woody structure and accelerated development of complex vertical structure that benefits many wildlife species, especially songbirds of conservation concern; (2) early production of biomass, biofuels and fiber that provide early financial returns; (3) natural control of competing vegetation by the eastern cottonwood "nurse crop" and creation of an environment suitable for oak and other mid to late seral species regeneration; (4) flexibility to retain some of the eastern cottonwood to develop into large-diameter trees; (5) more rapid increase in forest diversity; (6) greater ecological buffering against environmental and biotic stresses and disturbances; and (7) possible reductions in costs to establish the overall system by using natural forest succession concepts and relationships to favor the desired species and promote forest structure (Gardiner et al., 2008; Stanturf et al., 2009).

Stanturf and colleagues initiated a study in 1995 to assess the suitability of using eastern cottonwood as a companion species, a nurse crop, with Nuttall oak in the afforestation of agricultural bottomlands in the LMAV (Gardiner et al., 2008; Stanturf et al., 2009).

Eastern cottonwood was chosen to promote the establishment of Nuttall oak because it provides early economic returns (harvest in 10 years) and is suitable, with cultivation, for growing with oak on soils common to afforestation sites in the LMAV. This afforestation system simulates natural secondary succession where the pioneer eastern cottonwood colonizes bare ground, forming dense stands under which other species are able to establish provided there is sufficient light to meet their physiological needs.

In their study, eastern cottonwood was established following the procedures used for operational plantation establishment (Stanturf et al., 2001) modified for interplanting the oak seedlings as described by Gardiner et al. (2001), Schweitzer et al. (1997) and Stanturf et al. (2009) (Figure 4). Cuttings were planted (3.7×3.7 m spacing) in the spring following site preparation by disking. For 2 years, competing vegetation was controlled with herbicides and cross-disking, and cottonwood defoliating insects were controlled with a broadcast insecticide. After the second growing season, 1-0 bareroot Nuttall oak seedlings were interplanted between every other eastern cottonwood row (3.7×7.3 m spacing for oak). As a control, Nuttall oak was also planted as a monoculture nearby (Gardiner et al., 2001).

The system design called for harvest of the eastern cottonwood at year 10, cutting trees in the winter to maximize coppicing and taking care to protect interplanted oaks. The second growth of eastern cottonwood is to be harvested 10 years later, providing a final release of the interplanted oaks. The design could be modified to retain individual eastern cottonwood trees for added diversity in forest structure and to provide a large-diameter tree component for wildlife that use dens and cavities. It is unclear, however, whether Nuttall oak would develop adequately under the eastern cottonwood canopy to be competitive after release from the eastern cottonwood (Gardiner et al., 2001, 2004). Harvesting can be done with minimal damage to interplanted seedlings if sufficient room for harvesting equipment operation is provided between rows, i.e. >5 m (Gardiner, 2006) and if directional felling is practiced.

After 3 years, the density of eastern cottonwood was 716 stems ha^{-1} and 8.3 m^2 ha^{-1} of basal area, maximum leaf area index developed and light in the understory was about 30% of that in the open (Gardiner et al., 2004). These light levels are expected to be maintained throughout the length of the eastern cottonwood rotation. In addition, the shade of the eastern cottonwood canopy reduced the biomass of competing herbaceous vegetation by $>65\%$ compared with that growing in the open. Thus, the nurse crop was an effective natural control of competing vegetation.

Light in the understory was sufficient for Nuttall oak seedlings to develop a photosynthetic mechanism with a capacity for carbon assimilation similar to open-grown oak seedlings receiving full sunlight (Gardiner et al., 2001). Although Nuttall oak is considered shade intolerant, the leaves of the oak seedlings under eastern cottonwood showed only minor reductions in mass per unit area, and had similar leaf areas to Nuttall oaks grown in the open.

The height growth of Nuttall oak seedlings under eastern cottonwood was similar to that of oaks grown in the open, but the basal diameter of the stem was 20% less for oaks in the understory (Gardiner et al., 2004). Total biomass was significantly reduced in oaks growing in the understory; however, the proportion of biomass allocated to stems, leaves and roots was similar between oaks in the understory and in the open. Overall, Nuttall oak seedlings growing beneath eastern cottonwood were able to show respectable biomass accumulation and stem diameter growth, and good height growth (Stanturf et al., 2009). Early height growth is important to survival and the increased competitiveness of oaks by placing the oak crown above competing vegetation, above growing season flood waters and out of the reach of browsing white-tailed deer (a height of ≥ 1.5 m protects the terminal leader from most deer). Species of similar physiology and silvical characteristics to Nuttall oak should do well being interplanted beneath eastern cottonwood that is managed on a short rotation.

Conclusions

Successful afforestation requires a commitment to implementing general principles and practices that are well known and available in local management guides. Failures in regeneration are common because of neglect to follow recommendations, including planting species that are ill-suited to the soils and hydrological regime of the site, planting seedlings of low quality, inadequate vegetation management, lack of natural regeneration in large fields, planting mixtures of incompatible species and failure to protect against wildlife herbivory.

Recent innovations in afforestation of bottomland hardwoods include: (1) the recognition and quantification of the superior survival and growth benefits of high-quality, large seedlings with well-developed root systems; (2) the understanding that cover crops can be effective in vegetation management and control wildlife herbivory, help to reduce the cost of tree establishment and provide additional income

Figure 4. Progression of interplanting Nuttall oak (*Quercus nuttallii* Palm.) in eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) plantations followed by Gardiner et al. (2001, 2004). (A) Eastern cottonwood cuttings are planted after site preparation. Herbicides and disking are used to control competing vegetation for 2 years. (B) One-year-old eastern cottonwood cuttings. (C) After two growing seasons, 1-0 bareroot Nuttall oak seedlings are interplanted in between every other eastern cottonwood row. (D) Nuttall oak grows well in the eastern cottonwood understory. (E) Nuttall oak attains large sapling sizes after 7 years in the understory. (F) After 10 years, the eastern cottonwood is harvested for pulpwood, releasing the Nuttall oak.

to the landowner; (3) the realization that planting companionable species mixtures that provide a diversity of economic and ecological benefits makes afforestation more affordable and potentially profitable; and (4) the recognition that greater ecological benefits can be obtained by interplanting oaks with fast-growing species such as eastern cottonwood that develop vertical structure quickly, and by planting large-container and bareroot seedlings that have the ability to produce seed at very early ages.

Landowners can minimize their costs when designing afforestation systems by ensuring that practices and regeneration sources are environmentally compatible, based on ecological principles and natural forest processes, include positively synergistic species interactions and, therefore, are as self-sustaining and regulating as possible. Revenues can also be enhanced by choosing the mix of plant species and management regimes that maximize the type and diversity of forest products and services, and minimizes time to harvest and revenue generation. There is a great need for operational demonstrations and experimental research to identify compatible species mixes, planting designs and management systems.

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