BOTTOMLAND HARDWOOD AFFORESTATION: STATE OF THE ART

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Abstract—Over the past decade, land managers have implemented large-scale afforestation operations across the Southern United States to rehabilitate agricultural land historically converted from bottomland hardwood forest cover types. These afforestation efforts were initially concentrated on public land managed by State or Federal Government agencies, but have later shifted towards private holdings that qualified for governmental assistance or cost-share programs. Traditional silvicultural practices dominate bottomland hardwood afforestation schemes in the South, with 1-0 bare-root oak (*Quercus* spp.) seedlings comprising the balance of planting stock mixtures. However, traditional methods do not always yield successful afforestation, especially when applied on an operational scale across a landscape of heterogeneous site types and ownership objectives. This manuscript summarizes bottomland hardwood afforestation techniques and compares the knowledge base with current practices. Additionally, this manuscript reviews new silvicultural systems to enhance establishment success on adverse sites, to enhance ecological benefits of afforestation, and to address multiple objectives of landowners. We identify four vital components of afforestation that are generally lacking in most regeneration activities in the Lower Mississippi River Alluvial Valley.

INTRODUCTION

Afforestation activities in the Lower Mississippi River Alluvial Valley (LMRAV) are currently peaking after the past four decades of extensive deforestation (Allen 1997, King and Keeland 1999, Stanturf and others 1998). Different forces drive the afforestation efforts of public resource agencies, conservation organizations, private corporations, and private landowners. Their interests include conversion of economically marginal agricultural land to forest cover for ecosystem rehabilitation, soil conservation, aesthetics, and recreation. They may want to establish intensively managed fiber farms and carbon sequestration banks, and to mitigate forested wetlands destroyed elsewhere in development projects.

Since 1992 on more than 250,000 ac in Louisiana, Mississippi, and Arkansas, governmental incentive programs have defrayed plantation establishment costs and/or purchased long-term conservation easements from private landowners (King and Keeland 1999, Stanturf and others 1998). Since program dollars largely support these afforestation activities, associated enrollment deadlines often create a sense of urgency about plantation establishment. The urgency with which managers have implemented recent afforestation activities leads some to question the validity of afforestation decisions and practices at the stand, forest, and landscape levels (Allen 1997; Stanturf and others, in press; Twedt and Portwood 1997; Wilson and others, in press).

A sustained, formal research initiative on bottomland hardwood plantation establishment in the LMRAV began as early as the 1960s (Kennedy 1993). This manuscript summarizes current afforestation techniques and compares the knowledge base with current practices to emphasize aspects of afforestation where existing knowledge is not incorporated into operational practice. This manuscript also reviews new silvicultural systems to enhance success on adverse sites and enhance ecological benefits, while addressing multiple objectives of landowners. In addition to available literature, a large portion of this manuscript is based on the authors' combined observations and experiences in the LMRAV.

REVIEW OF CURRENT AFFORESTATION TECHNIQUES

Management Objectives

Defining clear management objectives in terms of what outputs are to be achieved is prerequisite to directing successful establishment and future management of afforestation sites. Landowner objectives will ultimately influence or govern all system decisions involving stand establishment (species suitability, site preparation requirements, planting density, postplanting operations), intermediate stand management (precommercial thinning, timber stand improvement, stand health and sanitation practices, improvement cutting and thinning, control of fire, disease, insects, or other damaging agents), and regeneration harvesting (including regeneration methods) in order to regulate forest structure for the desired outputs (Daniel and others 1979). Management objectives can be simple or complex encompassing multiple aspects of watershed or wildlife management, wood, fiber or forage production, and aesthetics (Daniel and others 1979, Smith 1986). Rehabilitating functions and health of the bottomland hardwood forest ecosystem always underlies other management objectives.

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Government monetary incentives for landowners to establish forest cover drive objectives on the vast majority of afforestation sites in the LMRAV (Haines 1995, Kennedy 1990, Stanturf and others 1998). Although a multitude of cost-share programs are available to private landowners, most incentives target public environmental goals such as conservation of highly erodible or otherwise delicate soil (Haines 1995, Kennedy 1990). Even when program objectives allow for “creation of wildlife habitat,” “promotion of biodiversity,” or “production of sustainable timber harvest,” these objectives often offer insufficient focus to ensure optimal management of future stands for specific outputs (Wilson and others, in press). The landowner should clearly define singular or multiple objectives; for example, a management objective for carbon sequestration would describe the desired accumulated carbon or biomass output in tons per acre per year over the specified rotation. Without explicit objectives, the forester cannot properly determine planting density, species assignments, site preparation requirements, or postplanting cultural practices; nor can he or she evaluate success of the afforestation effort. The failure to specify management objectives has led to wholesale establishment of stands without clear description of future management pathways. Our observation suggests that some landowners may be making uninformed decisions. The current approach does not address sustainability issues and could prove costly if the future forest structure is not compatible with desired outputs.

Species–Site Selections

Alluvial floodplain forests exhibit high species richness and spatial diversity of vegetational communities (Kellison and others 1998, Meadows and Nowacki 1996). Bottomland hardwood forests are comprised of more than 70 endemic tree species along with numerous vines, shrubs, and herbaceous species (Carter 1978, Putnam and others 1960, Tanner 1986). A wide array of edaphic and hydrologic conditions sculpted by the erosional and depositional processes of rivers provide the foundation for vegetational diversity in alluvial floodplains. Site types range from permanently inundated sloughs with very poorly drained, heavy clay soils to rarely inundated ridges of well-drained, sandy loams (Stanturf and Schoenholtz 1998). Since the early 1900s, studies have associated tree species with various site types (Meadows and Nowacki 1996, Putnam and others 1960, Tanner 1986). It follows that the suitability of the species assigned to a given site will largely determine initial and long-term afforestation success, the trajectory of stand development, site productivity, future management opportunities, and costs. Some of these relationships appear in reports by Baker (1977), Dicke and Toliver (1987), Krinard and Johnson (1985), Stine and others (1995), and Williams and others (1993).

Afforestation information is available to assist the forester with species-site prescriptions. Useful sources include “A Practical Field Method of Site Evaluation for Commercially Important Southern Hardwoods” by Baker and Broadfoot (1979), “Hardwood Suitability for and Properties of Important Midsouth Soils” by Broadfoot (1976), and county soil series manuals published by the Natural Resource Conservation Service. In addition, basic information characterizing physical and chemical soil properties can identify soil texture and drainage classes, plow pan development, nutrient deficiencies or factors such as pH that regulate nutrient uptake. Surveys of adjacent forested stands to determine local abundance of desirable species can inform decisions on species assignments (Groninger and others 1999). In practice, though, market availability of planting stock is probably the most prevalent factor-driving species assignments on afforestation sites. Fewer than 25 of the 70-plus native bottomland hardwood species are available through established commercial nurseries on a yearly basis [(Personal communication. 2000. Sam Campbell, Nursery Manager, Molpus Timberlands Mgmt. L.L.C., 29650 Comstock, Elberta, AL 36530); (Personal communication. 2000. David McCain, Nursery Manager, Delta View Nursery, Route 1 Box 28, Old Highway 61 South, Leland, MS 38756); (Personal communication. 2000. Randy Rentz, Nursery Manager, Columbia Nursery, P.O. Box 647, Columbia, LA 71418); (Personal communication. 2000. Gary Schaefer, Nursery Manager, Winona Nursery, Route 3, Box 83, Winona, MS 38967)]. However, some nursery managers will raise custom seedlings of other species if contracted.

Site Preparation

Site preparation can be vital to afforestation of former agricultural land. Treatments can condition the seed or seedling bed; decrease competing or undesirable vegetation, such as exotic pests; reduce herbivore habitat; improve nutrient availability; and improve access on the site for the planting operation (Baker and Blackmon 1978; Kennedy 1981a, 1993). Benefits are typically realized though increased survival and improved early growth of hardwood planting stock (Baker and Blackmon 1978, Ezell and Catchot 1998, Russell and others 1998). The wide array of conditions on former agricultural fields precludes wholesale prescription of site preparation practices. Rather, the landowner’s objectives and the condition of the field determine the appropriate level of site preparation for a given tract. For fields immediately out of crop production, site preparation is generally not necessary unless objectives and site conditions make it desirable to break up a hard pan or compacted soil, broadcast a pre-emergent herbicide application for weed control, or incorporate fertilizer into the planting site. Fertilization, for example, can consistently boost growth of hardwood reproduction on former agricultural sites, because long-term agricultural production significantly depletes soil organic matter and associated nutrients (Francis 1985, Houston and Buckner 1989). Such practices are common if fiber production, timber production, or biomass production are identified as primary management objectives (Joslin and Schoenholtz 1998, Kennedy 1981a, Thornton and others 1998, Yeiser 1999), but also have merit where other objectives target early stand growth and development.

Depending on the length of the uncultivated period and the rate of succession, fields removed from cultivation for more than a year prior to planting will present a range of herbaceous and woody vine, shrub, or tree competition. It may be desirable to control advance vegetation prior to planting, and site preparation practices for such fields can be accomplished with mechanical or chemical methods. In the LMRAV, multiple-pass disking has been effective to bust dense sod, improve soil aeration, and promote water infiltration (Baker and Blackman 1978, Kennedy 1990, McKnight 1970). Following years of cultivation, subsoil or deep plowing to 16 to 20 in. is effective in breaking plow pans that may develop. This practice, which is generally necessary for establishment of fast-growing species, such as eastern cottonwood (*Populus deltoids* Bartr. Ex Marsh) (McKnight 1970), improves aeration and allows the regeneration to exploit a greater soil volume.

Chemical site preparation and new dormant season weed control applications show promise for relatively inexpensive early control of herbaceous weeds for improved survival and growth in hardwood plantations (Ezell 1995, 1999; Ezell and Catchot 1998; Ezell and others 1999). Chemical methods of site preparation offer the forester an ability to apply weed control during periods when site conditions prevent use of mechanical practices. Prior to herbicide application, mowing or burning the field and allowing for a uniform regrowth of vegetation can improve efficacy (Miller 1993).

In the LMRAV, mowing is a common site preparation technique on afforestation projects sponsored by governmental cost-share programs. This practice improves planter access on afforestation sites that have not received cultivation for several years, but mowing probably does little to reduce weed competition or herbivory (Houston and Buckner 1989). In fact, empirical studies rarely demonstrate improved survival or growth of hardwood regeneration following mowing for site preparation and/or subsequent weed control (Houston and Buckner 1989, Kennedy 1981b, Schweitzer and others 1999). Kennedy (1981b) reasoned that mowing is not effective for improving growth or survival because it does not reduce competition for soil water or nutrients. Prescribed burning, a more economical practice than mowing, can also be used to improve planter access on afforestation sites. However, the use of prescribed fire requires training, and liability related to smoke management may limit the use of burning in some regions.

In the LMRAV, it is common to omit site preparation on some sites to accommodate use of heavy equipment in machine planting. To reduce site damage on saturated soil, competing vegetation and the increased risk of herbivory are accepted in a tradeoff with improved trafficability and planting machine function.

Planting Stock Types, Size, and Procurement

Planting stocks used for afforestation in the LMRAV include seed, bare-root seedlings, containerized seedlings, and cuttings. Hard mast species, which can be successfully established with seed on an operational scale include several of the red oak species (*Quercus nigra* Linnaeus, *Q. phellos* Linnaeus, *Q. shumardii* Buckley, *Q. pagoda* Rafinesque, *Q. nuttallii* Palmer); white oak species (*Q. lyrata* Walter, *Q. michauxii* Nuttall); common persimmon (*Diospyros virginiana* Linnaeus); and sweet pecan [*Carya illinoensis* (Wang.) K. Koch] (Johnson and Krinard 1985, Stanturf and others 1998). Bottomland species that can be established vegetatively with cuttings include eastern cottonwood, American sycamore (*Platanus occidentalis* Linnaeus), green ash (*Fraxinus pennsylvanica* Marshall), and black willow (*Salix nigra* Marshall) (Kennedy 1977, McKnight 1970, Stanturf and others 1998). The species listed above and others not listed can be established as bare-root or containerized seedlings. Choice of stock type should be determined by management objectives, site preparation practices, species decisions, planting window, and market availability. King and Keeland (1999) estimated that over 67 percent of the public land and cost-share plantings in the LMRAV have been established with 1-0, bare-root seedlings.

Size and quality of bare-root planting stock can be of major importance in determining establishment success and early growth of tree seedlings (Land 1983, Thompson and Schultz 1995). Because of differing growth rates, growth habits, i.e. indeterminate, semi-determinate, or determinate, and biomass accumulation patterns (Dickson 1994; Hodges and Gardiner 1993; Long and Jones 1993, 1996), bottomland hardwoods exhibit a wide range of interspecific seedling morphologies. Early researchers working on bottomland hardwood regeneration identified desirable seedlings as having a shoot length of 30 to 36 in. and a root-collar diameter of 1/4 to 3/8 in. or larger (Kennedy 1981a, McKnight and Johnson 1980). However, definitive guidelines defining optimal seedling dimensions for bottomland hardwood species, particularly concerning factors that reduce survival and growth such as competing vegetation and flooding, have not been developed or published.

Research on quality seedling production in nursery beds has revealed that certain practices can improve outplanting performance, especially on harsh sites. In his review of existing literature, South (1998) concluded that proper top pruning of hardwood seedlings can significantly boost outplanting survival (range 3 to 42 percent). Top pruning may benefit the seedling by improving its root-weight ratio, while it also helps the planter because top-pruned seedlings are easier to handle. In addition to potential gains in survival, stimulated height growth of seedlings from moderate top pruning quickly compensates for the lost height from pruning (Adams 1985, Meadows and Toliver 1987). Moderate root pruning can also facilitate planting without significantly reducing survival or growth (Toliver and others 1980). Yet, root pruning should be approached cautiously because excessive pruning will negatively alter root-weight ratio and reduce carbohydrate reserves needed by the seedling to survive lifting and transplanting. Kennedy (1993) suggested that root systems of oak seedlings should be pruned to no shorter than 8 in.

In addition to seedling size and handling practices, morphological traits including the number of first-order lateral roots can have a profound effect on early survival and growth of hardwood seedlings (Thompson and Schultz 1995). Research conducted by Kormanic and colleagues provides clear evidence linking seedling out-planting performance and the inherited expression of first-order lateral root proliferation (Kormanik 1986, 1989; Kormanik and Ruehle 1987; Kormanik and others 1998; Thompson and Schultz 1995). Based on their observations, Clark and others (2000), Kormanik and Ruehle (1987), and Johnson (1984) suggested that fewer than 40 percent of oak seedlings lifted from nursery beds are suitable planting stock based on lateral root development. Although first-order lateral roots are strongly controlled by genetics, research has demonstrated that their development can be increased by growing seedlings at relatively low nursery bed densities (Dey and Buchanan 1995). Most planting operations in the LMRAV do not consider seedling morphology. Operational programs generally target a shoot length of 18 to 24 in. and a root-collar diameter of 3/8 in. as the minimal seedling size. Clearly, managers need empirical data defining optimal seedling dimensions and morphological traits to support efficient planting of a diverse array of bottomland hardwood species.

Few studies have examined the transfer of seed within the southern hardwood region, but available evidence has revealed provenance and family-within-provenance differences for survival and growth of common species, including cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.), American sycamore, and eastern cottonwood (Greene and others 1991, Jokela and Mohn 1976, Land 1983). These studies suggest that survival and growth can be increased through provenance selections, but they also illustrate the hazards of indiscriminate seed transfer. For example, Dicke and Toliver (1987) observed a 30-percent range in survival within cherrybark oak families at age 5. Transfer of seed to different regions may be a concern, as well as establishing upland ecotypes on bottomland soils. For example, Keeley (1979) demonstrated that blackgum (*Nyssa sylvatica* Marsh.) ecotypes selected along a flooding gradient exhibited differing physiology, biomass accumulation patterns, and survival rates. On the other hand, short-term data presented by Yuceer and others (1998) revealed no distinct differences in survival or growth of upland versus bottomland sources of cherrybark oak. In practice, few foresters in the LMRAV specify seed source constraints in purchasing agreements. This lack of quality control or use of certified seed in afforestation projects could potentially reduce establishment success, productivity, and forest health. Ideally, foresters should avoid transfer of seed collected from other regions and site types until adequate protocols for seed transfer are established. Morgenstern (1996) provides conceptual details for establishing seed transfer protocols for forest tree species. Interestingly, most other developed countries and large companies have in place transfer protocols and seed-certification programs for the forests they manage.

Seed and Seedling Storage

Because seedlings are the predominant stock type currently used in afforestation projects of the LMRAV, the remainder of this manuscript will concentrate on practices and techniques appropriate for them. Bonner and Vozzo (1987), Bonner and others (1994), and Schopmeyer (1974) have thoroughly discussed suitable techniques for collecting and storing seed of bottomland hardwood species. Allen and Kennedy (1989) and Stanturf and others (1998) describe direct seeding techniques.

Bare-root seedlings should be lifted when dormant and directly transferred to storage under refrigeration at 34 to 38 ^{o}F. To maintain seedling viability in cold storage, seedling bags should receive ample ventilation and moisture-content monitoring. Mobile cold-storage facilities are readily available for lease and most large-scale contractors maintain on-site cold storage facilities during active planting. Such practices enable operators to maintain seedling dormancy and viability until time of planting.

Planting Seedlings

To establish reproduction on afforestation sites, contractors operating in the LMRAV utilize crews of hand and machine planters. Few studies have directly compared establishment success rates between hand planting and machine planting (Russell and others 1998). However, the authors have observed that either method can be sufficiently effective if experienced, conscientious personnel oversee the planting job. We discuss techniques, advantages, and disadvantages of each method below.

Hand planting—Hand-planting techniques originally employed to establish large-scale hardwood plantations were generally borrowed from conifer plantations. These practices were generally not applicable to hardwood plantation establishment in the LMRAV because of the relatively large root system characteristic of most hardwood seedlings and the often saturated, heavy clay alluvial soils. Hardwood seedlings should be planted such that the apparent root collar is at least 1 to 2 in. below the soil surface. This practice helps ensure that all lateral roots are sufficiently covered, and it can improve the sprouting potential of seedlings, primarily oaks, that herbivores have clipped. Hardwood seedlings typically have the taproot pruned to about 8 in. and the laterals to 4 to 6 in. A planting tool is needed with a blade at least 10- to 12-in. long by 6- to 8-in. wide. The type of dibble or planting shovel varies among contractors, and often the same tool will not work well on all sites due to soil and/or moisture conditions. Because of the time and care required to plant large seedlings properly in saturated soil, some contractors pay their planters by the hour rather than by the number of seedlings planted. A hand-planting crew of 20 people can usually plant over 130 ac per day (about 2,000 seedlings per planter at 300 seedlings per acre). This rate is quicker than a machine-planting crew with one tractor. However, because hand planting is labor intensive and requires more administrative supervision and logistical planning to keep planting crews active, it can be more expensive than machine planting.

Machine planting—Machine planters for hardwoods are largely similar to conifer planters, with modified packing wheels and coulters to allow for planting of larger seedlings. In addition, most operators modify stock planters to accommodate their specific planting needs. Planting machines are normally pulled by four-wheel drive, rubber-tired tractors with a minimum rating of 175 horsepower. If soil conditions are favorable, machine planting can be more consistent for large seedlings with well-developed root systems, and machine planting is generally not as expensive as hand planting based on cost per seedling. A single-machine planter crew can plant about 15 to 20 ac per day if soil conditions are ideal. However, water saturated, heavy clay soil typical of some alluvial floodplain sites can hamper progress of machine planting, and the heavy equipment required for machine planting can damage afforestation sites by creating ruts. Furthermore, if soil conditions are not ideal, the slit created by the planting machine is often never closed near the lower reaches of the foot or coulter blade and may serve as a site of cracking under dry conditions in the smectitic soils of the LMRAV. Machine planting also increases the minimal distance between rows, and may damage growing stock if seedlings are being planted supplemental to partial failures or volunteer regeneration.

Planting Job Inspections

Ongoing inspection is necessary to ensure proper seedling handling, planting, and spacing. Viability problems from improper handling or storage are near impossible to detect after planting. Inspections also allow for real-time correction of planting and spacing mistakes. Walk-through inspections enable the forester to verify seedling condition and appropriate root pruning. Establishing fixed-radius plots behind the planting crew, the forester can monitor planting density, seedling size, planting depth, and general quality. Some choose to routinely sample one 0.02-ac plot for every 10 ac planted. However, seedling spacing should be considered when determining the size of fixed-radius plots, while sampling intensity will depend on the project area, site heterogeneity, and the consistency of the planting crew.

Postplanting Cultural and Protection Practices

Postplanting cultural and protection practices improve seedling survival, early growth, and plantation integrity. Postplanting cultural practices primarily target competition control as a means of boosting survival and improving seedling growth, but irrigation and fertilization practices may increase as future demands for hardwood fiber increase (Francis 1985; Houston and Buckner 1989; Kennedy 1981a, 1981b, 1993; Schweitzer and others 1999; Yeiser 1999). In spite of the demonstrated biological benefits, cost-benefit analyses of postplanting operations have not been conducted to project their financial benefits. However, the additional costs of the practices may be justified if they prevent plantation failure during drought or herbivore damage, or if they significantly decrease rotation length as in the case of disking operations in short-rotation woody crops. In practice, few afforestation foresters prescribe postplanting cultural treatments unless fiber or timber production is a primary management objective.

Competition control in hardwood plantations can be accomplished with mechanical or chemical methods, or with using mulch material. Mechanical methods of competition control primarily include mowing and disking. Because mowing does not reduce belowground competition for soil water and nutrients, hardwood reproduction generally does not respond (Houston and Buckner 1989, Kennedy 1981b, Schweitzer and others 1999). Mowing may only be practical where the forester wishes to slow down development of invasive woody species.

Although both share similar costs, disking is generally more effective than mowing for controlling competing vegetation. Several bottomland species including sweet pecan, Nuttall oak, green ash, American sycamore, eastern cottonwood, and sweetgum (*Liquidambar styraciflua* L.) respond favorably to disking (Houston and Buckner 1989, Kennedy 1981b, Schweitzer and Stanturf 1999). In addition to increasing aeration and moisture infiltration into soil, disking improves nutrient status and subsequently growth of hardwood reproduction (Kennedy 1981b). Gains in survival and growth derived from disking often come from early stand development, e.g., quicker advancement to canopy closure and self-pruning. However, excessive disking or disking too deep can prune roots excessively and reduce tree growth (Schweitzer and Stanturf 1999).

Recent research on plantation establishment has identified several herbicide tank mixes suitable for use with bottomland hardwood species (Ezell 1999, Ezell and Catchot 1998, Ezell and others 1999, Russell and others 1998). Vegetation control with herbicides can effectively increase growth of bottomland hardwood seedlings (Miller 1993, Russell and others 1998) and may provide the most cost-effective control of competing vegetation in relatively large, hardwood plantations. However, most tank mixes are best suited for controlling grass and some broadleaf herbaceous species, and chemical technology is not available for woody vines, shrubs, or trees in established plantations. Chemical control of undesirable woody species can only be attained with directed applications of suitable herbicides with appropriate measures taken to minimize spray drift and contact with crop species (Leininger and McCasland 1998, Miller 1993). Sites occupied by resilient vine species, such as ladies'-eardrops (*Brunnichia cirrhosa* Banks), trumpet creeper [*Campsis radicans* (L.) Seemann], and peppervine [*Ampelopsis arborea* (L.) Koehne], may require 2 or more years of treatment before afforestation.

Mulching is generally more expensive and more cumbersome than other methods of vegetation control, but it can provide long-term efficacy resulting in dramatic gains in survival and growth during the initial stages of stand development (Adams 1997, Windell and Haywood 1996). Limited research has demonstrated promising gains in early growth for mulched common persimmon, green ash, Nuttall oak, cherrybark oak, and water oak (Adams 1997, Schweitzer and others 1999). Various organic and synthetic mulch materials are commercially available, but a manager should consider ease of application, durability of the material, maintenance requirements, effectiveness, and cost (Haywood 1999, Windell and Haywood 1996). Mulch use may increase on wetland sites not amenable to mechanical or chemical control.

In addition to improving early survival and growth of seedlings, control of herbaceous vegetation can reduce herbivory by modifying herbivore use of old field habitats (Paul B. Hamel. 1995. Files/Sharkey/mammals. On file with: U.S. Department of Agriculture, Forest Service, Southern Research Station, Southern Hardwoods Laboratory, P.O. Box 227, Stoneville, MS 38776). White-tailed deer (*Odocoileus virginianus* Zimmerman), rodents (including *Sigmodon hispidus* Say and Ord), rabbits (*Sylvilagus* spp.), beaver (*Castor canadensis* Kuhl), and nutria (*Myocastor coypus* Molina) can be primary damaging agents in bottomland hardwood plantations (Burkett and Williams 1998, Conner and Toliver 1990, Conner and others 1999, King and Keeland 1999, McKnight 1970). Animal damage can range from mild, with little effect on planted seedlings, to severe, in which high densities of herbivores decimate young tree plantations (Conner and Toliver 1990). Aside from modification of habitat, which is effective on rodents, seedling protection or herbivore eradication practices may discourage herbivory.

Shelters can increase seedling survival where herbivory limits establishment (Conner and others 1999, Graveline and others 1998, Strange and Shea 1998). Several different styles of seedling shelters are available commercially, and selection of style and size will depend on the size of seedlings, expected herbivory type, costs, and assembly and installation requirements (Windell 1991). Some tree shelters also provide a favorable microclimate for improved early tree growth (Schweitzer and others 1999, Tuley 1985). Shelters can facilitate growth by moderating the light environment, reducing seedling transpiration rates, increasing temperature, and increasing carbon dioxide (Tuley 1985, Windell 1991). However, early gains in height growth are often due to temporary shifts in biomass accumulation and are not always maintained after seedlings grow above the shelters (Clatterbuck 1999, Mullins and others 1998). Besides their high costs, shelters are easily knocked down or swept away by floodwaters. These drawbacks limit the use of shelters to sites of severe herbivory. Perpetual eradication practices may most effectively curtail severe herbivory by beaver and nutria.

Other protection in established plantations involves control of insect or disease pests, fire prevention and suppression, and floodwater management. Insects and diseases can reduce plantation health and can render planted stock vulnerable to other stress. For example, young plantations of eastern cottonwood cultured for rapid biomass production may require control of several pests including the cottonwood leaf beetle (*Chrysomela scripta* Fabricius) and the cottonwood borer [*Plectrodera scalator* (Fabricius)] (Solomon 1985). Preventative practices such as selection of resistant seed sources or clones may reduce damage by insects and disease (Cooper and others 1977, Kellison 1994, Nebeker and others 1985); direct cultural, chemical, or microbial techniques may also eradicate pests (Solomon 1985, Solomon and others 1997). In several useful handbooks, Solomon and his colleagues describe major insect pests and diseases of common bottomland tree species including cottonwood, green ash, sycamore, and the oak species (Leininger and others 1999; Morris and others 1975; Solomon 1995; Solomon and others 1993, 1997).

Wildfire can destroy young hardwood plantations and reduce stem quality on stump spouts. As a precautionary measure against wildfire, Kennedy (1993) suggested maintenance of fire lanes around all plantations. If fire sweeps though a hardwood plantation, a site inventory must determine the extent of damage and the necessary management.

Although most bottomland hardwood species exhibit some level of tolerance to anaerobic soil, long-term inundation during the growing season can harm all but the most flood-tolerant species (Baker 1977, Hook 1984). Monitoring and control of floodwater depth and duration are necessary if survival of young hardwood seedlings is at stake. Where flooding is desirable for waterfowl habitat, floodwater removal before the active growing season will usually reduce stress on seedlings. Additionally, by increasing soil moisture availability during the potentially dry summer months, well-managed impoundments may improve seedling survival or growth (Broadfoot 1967).

Postplanting Survival and Growth Monitoring

Comparing seedling survival and growth to the *A Priori* definition of success can determine success of the planting effort. The landowner's management objectives, the type of plantation, e.g., pure versus mixed species, availability of preexisting data, and the costs of acquiring new data will help determine sampling interval, timing, and measurement intervals (Curtis 1983). However, prior to postplanting assessments, baseline information on plantation establishment will be vitally important to the afforestation forester. Information such as seed source, seedling size and condition, seedling lifting, shipment and storage history, soil and atmospheric conditions during planting, planting methods, planting contractor, site preparation activities, and planting date can identify the source of problems or successes. Postplanting assessment and monitoring techniques vary widely among landowners and public agencies, but they may often include sample transects, permanent sample plots, photodocumentation, and periodic aerial photography.

PLANTATION DESIGN

Hardwood plantations on former agricultural fields in the LMRAV range from single-species to mixed-species plantings. The afforestation forester should select a particular plantation type based on the desired outputs defined by management objectives (Daniel and others 1979). Single-species plantations, or monocultures, are often the most efficient plantation type for optimizing a single output, e.g., fiber production or soil amelioration. Single-species stands allow efficient cultural practices, more predictable stand-development patterns, and more predictable yields (Smith 1986). In the LMRAV, the native soft broadleaf species that exhibit indeterminate growth patterns are well suited for single-species stands. Perhaps eastern cottonwood plantations, cultivated for high-quality printing fiber, are the most extensive single-species plantations in the LMRAV (Krinard and Johnson 1980). In recent years, scientists in other regions have demonstrated the value of fast-growing, single-species plantations as catalysts for rehabilitating degraded forest ecosystems (Parrotta and others 1997). In this role, rapidly grown above- and belowground biomass stabilize soil, increase soil organic matter, nutrient or water-holding capacity, develop an understory microclimate that promotes establishment of native species, and develop habitat for native fauna (Fisher 1995; Lugo 1997; Mapa 1995; Parrotta 1992, 1999). Single-species plantations often do not produce high-quality sawtimber because most valuable species such as the oaks generally develop their highest vigor and quality in stands providing interspecific competition (Lockhart and Hodges 1998). Some managers may assume that single-species stands provide poor wildlife habitat, but homogeneous stands of eastern cottonwood, black willow, sandbar willow (*S. exigua* Nutt.), and baldcypress [*Taxodium distichum* (L.) Rich] occurring naturally along the Mississippi River contribute to landscape diversity and provide critical habitat for various wildlife species.

Mixed-species plantations can include various arrangements of multiple species in true mixtures or intercropping mixtures (Goelz 1995a). Potential benefits of mixed-species stands versus single-species stands can increase pest resistance, productivity in a vertically stratified stand, product diversity, crop tree quality, and canopy species diversity (Goelz 1995b, Smith 1986). True mixtures generally consist of randomly or systematically assigned species combinations established at the same time. Some mixed plantations are established with species of similar growth rates and developmental patterns (Goelz 1995a), but most successful mixtures require species that will stratify within the forest canopy (Smith 1986). Stressing these points for bottomland hardwood plantations, Lockhart and Hodges (1998) cited work on mixed-species stand development by Clatterbuck and Hodges (1988) and Clatterbuck and others (1987). Lockhart and others (1999) also indicated that stand development processes in well-designed species mixtures will be similar to developmental tracts observed in natural patterns. Most current afforestation practices under governmental cost-share programs attempt to establish true species mixtures to provide stand-level species diversity. Unfortunately, many plantations are established without consideration for the developmental trajectories and competitive interactions of individual species comprising the mixed plantation (Lockhart and Hodges 1998).

Establishing species that exhibit very different growth rates can create intercropping mixtures. Such mixtures may provide different products such as a commercial timber species intercropped with a nitrogen-fixing species (Goelz 1995a). In the LMRAV, scientists and land managers have developed an intercropping scheme using the early-successional eastern cottonwood as a nurse species for the slower growing, disturbance-dependent Nuttall oak (Schweitzer and others 1997, Twedt and Portwood 1997). Its very fast early growth, sparse crown architecture, and its suitability to intensive culture make eastern cottonwood a viable candidate as a nurse species. Potential benefits of the eastern cottonwood-Nuttall oak intercropping could include rapid rehabilitation of soil quality, rapid development of vertical structure for faunal habitat, early financial return on the rehabilitation investment, and development of an understory favorable for oak seedlings and other native woody species. Intercropping systems show potential for providing multiple ecological and landowner benefits in the LMRAV. Future research scheduled by the lead author and cooperators will examine development of other intercropping systems to extend application on a variety of bottomland site types, e.g., use of black willow as a nurse for other species on hydric sites.

MANAGEMENT CONSIDERATIONS

The LMRAV is currently experiencing extensive afforestation of former agricultural fields on sites that historically supported bottomland hardwood forests. Projections indicate that the current pace may be maintained through the next decade, resulting in hundreds of thousands of acres in bottomland hardwood plantations. In summarizing our review of literature, techniques, and practices, it became apparent that several fundamental components of afforestation were generally lacking in most regeneration practices currently performed in the LMRAV. Developing some of these missing components will require additional research, but others will require only an extension of current knowledge or application of conservation principles. Four fundamentally vital components should be more deeply incorporated into 21st century, state-of-the-art afforestation activities in the LMRAV:

(1) definition of specific landowner management objectives,
(2) establishment of stock size and quality guidelines,
(3) development of protocols for transfer of genetic material, and
(4) application of silvicultural and ecological principles in plantation establishment.

Incorporating these basic components will enable landowners, natural resource managers, and the general public a method of evaluating success of these afforestation activities and should improve afforestation efficiency, ecosystem health, and resource sustainability in the LMRAV.

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