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REVIEW

Thirty Years of Change in the Forests and Silviculture of the Southern Bottomland Hardwood Region, USA

Emile S. Gardiner[1] · **Wayne K. Clatterbuck**[2] · **Sonja N. Oswalt**[3] · **Krishna P. Poudel**[4]

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Abstract

The Southern Bottomland Hardwood Region holds over 28 million acres of deciduous bottomland and wetland forests (BHFs) that occupy the many river floodplains, creek bottoms, lowland swamps, and loessial hills of the southern United States. About 82.6% of the resource is found within Southeastern Mixed Forests, 11.6% is within Lower Mississippi Riverine Forests, and 5.8% is within Brown Loam Bluffs Forests. Over the last 30 years, the high rate of forest loss historically observed in the Region tapered to 1% concurrent with federally supported conservation-driven afforestation and a 66% rise in forestland ownership by federal, state, and local governments. Evolving ownership dynamics are shifting management objectives away from timber and fiber production towards ecological restoration, conservation, and recreation. Yet, BHFs continue to incur ever-increasing degradation from several fronts (e.g., invasive trees, pests and pathogens, climate-related impacts, and mismanagement) impacting forest structure—importance values of key species including several bottomland oaks (*Quercus* spp.), red bay (*Persea borbonia*), pondcypress (*Taxodium ascendens*), water tupelo (*Nyssa aquatica*), and swamp tupelo (*Nyssa biflora*) declined over the last 3 decades. Also, losses to milling capacity that shrank hardwood markets combined with slow progress in developing open access, comprehensive growth and yield models decreased opportunities for efficient implementation of silviculture and management. Still, a range of advances improved silvicultural practices and created applied tools that support bettering bottomland oak sustainability in mixed BHFs, improve decision making and techniques for regenerating baldcypress-water tupelo stands, and enhance mixed species stand establishment and intermediate stand management for restoring and enhancing ecosystem services on afforested bottomlands.

Keywords Hardwood silviculture · Bottomland forest · River bottoms · Lower Mississippi Alluvial Valley · Loess hills

Extended author information available on the last page of the article

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Introduction

In 1995, John D. Hodges, who was highly respected as a preeminent silviculturist working in southern bottomland and wetland forests (BHFs), contributed a comprehensive chapter on the "Southern Bottomland Hardwood Region and Brown Loam Bluffs Subregion" to the Third Edition of *Regional Silviculture of the United States* (Hodges 1995). The chapter written by Hodges marked a significant progression in the coverage of silviculture practiced in these forests and published in the Second Edition of *Regional Silviculture of the United States*. In the earlier edition, the Southern Bottomland Hardwood Region and the Southern Appalachian Hardwood Region were presented as subregions comprising a larger Southern Hardwood Region (Smith and Linnartz 1980; Barrett 1995). Though the contribution by Hodges provided much-needed focus on the resource and expanded upon the ecology and silviculture presented in earlier editions of the text, the Editor, John W. Barrett, correctly asserted that our knowledge base would evolve and the emphasis of silviculture would change (Barrett 1995). Thus, the purpose of this manuscript is to quantify change in the southern BHFs resource, summarize advancements in tools available for informing silviculture for these forests, and highlight changes to the practice of silviculture that occurred since Hodges published his seminal work over three decades ago. Because this manuscript is intended as an update rather than a revision and expansion of Hodges (1995), we cannot revisit in detail much of the information he presented on silvics of important tree species, the physiography, climate, geology and soils of the Region, and historical forest use within the Region. Given this constraint, the chapter published by Hodges remains foundational to our understanding of the ecology and silviculture of southern BHFs ecosystems and it should be referenced for a more complete understanding of updates provided in this manuscript.

Brief Overview of the Region and Forest

The Southern Bottomland Hardwood Region largely aligns within three ecological provinces delineated by Bailey et al. (1994): the Southeastern Mixed Forest Province (231), the Outer Coastal Plain Mixed Forest Province (232), and the Lower Mississippi Riverine Forest Province (234). The Region extends southerly from Delaware along the Atlantic seaboard into Florida, westerly from Florida along the Gulf Coast into eastern Texas, and northward through the Lower Mississippi Alluvial Valley (LMAV) to southern Illinois (Fig. 1) (Hodges 1995). It is known for its deciduous BHFs occupying the numerous river floodplains, creek bottoms, lowland swamps, and hammocks that are found among the more prevalent pine (*Pinus*) uplands and lowlands of the noted ecological provinces (Putnam et al. 1960). The Brown Loam Bluffs Subregion is a narrow band of loess-covered upland occurring mostly within the Southeastern Mixed Forest Province roughly corresponding to Bailey's ecological subsection 231H, Deep Loess Hills and Bluffs (Bailey et al. 1994; Hodges 1995). It is situated along the eastern margin of the LMAV where it extends northward

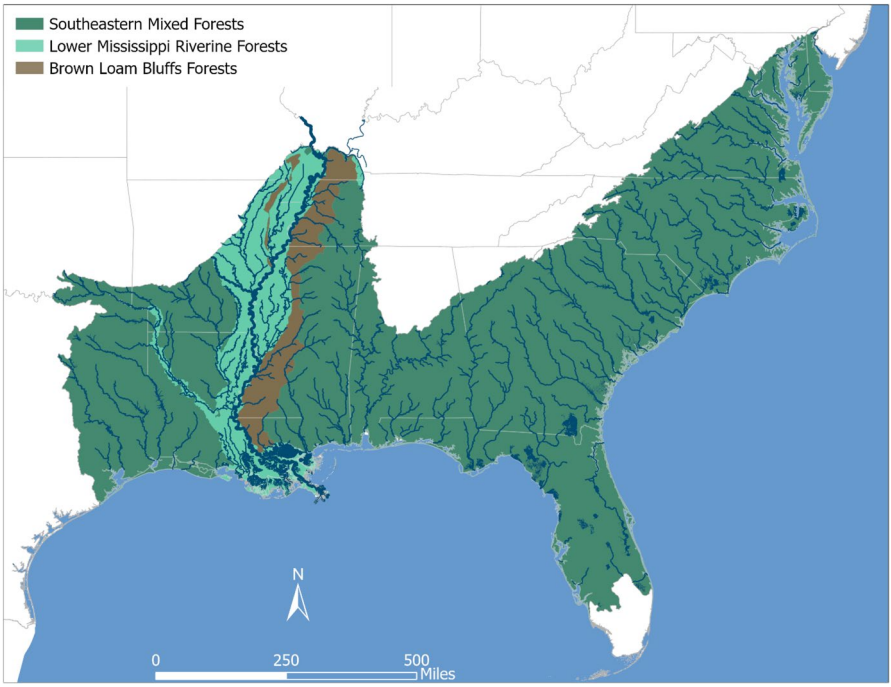


Fig. 1 Illustration of the Southern Bottomland Hardwoods Region of the southern United States

from Baton Rouge, Louisiana to near Cairo, Illinois (Fig. 1) (Hodges 1995). The upland forests of the Subregion are primarily mixed deciduous hardwoods but can develop a moderate component of pine, particularly where sites are relatively dry. For purposes of this manuscript, the Region and Subregion are partitioned into three "forest areas:" the Lower Mississippi Riverine Forests (LMRF), the Brown Loam Bluffs Forests (BLBF), and the Southeastern Mixed Forests (SEMF). The LMRF encompasses forests of the Lower Mississippi Riverine Forest Province, the BLBF encompasses forests of the Brown Loam Bluffs Subregion which cover the Deep Loess Hills and Bluffs ecological subsection for purposes of this manuscript, and the SEMF encompasses forests of the Southeastern Mixed Forest Province (minus those of the BLBF) and the Outer Coastal Plain Mixed Forest Province of Bailey et al. (1994).

Tree species richness is notably high throughout the Southern Bottomland Hardwood Region with early authors often citing a conservative estimate of as many as 70 species found across its bottomland, wetland, and upland forests (Putnam et al. 1960). Several genera are ubiquitous including *Quercus* (oak), *Carya* (hickory), *Fraxinus* (ash), *Nyssa* (gum), *Celtis* (hackberry), *Ulmus* (elm), *Acer* (maple), *Taxodium* (cypress), *Populus* (cottonwood), and *Salix* (willow). Species not represented in these genera that are often found in forests of the Region include sweetgum (see Table S1 in Online Resource 1 for scientific names of tree species), American sycamore, common persimmon, river birch, American hornbeam, and loblolly

pine. Because of the regularity of certain species occurring on specific sites, several recognized species-site associations add some organization to tree communities of BHFs (Hodges 1997). Still, spatial variation in tree species compositions within most forests of the Region, other than swamp forests, is characteristically varied because the fluvial processes that shape floodplain geomorphology impose shifts in topography and site conditions over short distances. Additionally, complexity in species compositions is added through temporal variation because the various species associations of BHFs respond differently to disturbance, and they follow differing successional trajectories based on drainage properties and rate of alluviation at the site (Hodges 1995).

Along with high species richness, forests of the Region show some of the highest productivity in the eastern US. For reference, site index values for the highest quality bottomland and loessial upland sites can range between 90–110 ft for bottomland oaks (base age 50), 100–120 ft for sweetgum (base age 50), and 110–130 ft for eastern cottonwood (base age 30) (Broadfoot 1976). The high productivity is supported in part by a humid, subtropical climate (Muller and Grymes 1998) that brings relatively high precipitation (45 to 64 in. annually), warm air temperatures (54 to 74 °F annual average), and a lengthy frost-free period (200 to > 300 days annual average) to the Region (NOAA 2023). High productivities are also supported by the rich soils inherent to the Region. Soil parent materials vary from alluvial sands, silts and clays on floodplains and terraces, decomposed organic materials over mineral deposits in basin and muck swamps of the coastal plain, and eolian silts in the loessial uplands (Stanturf and Schoenholtz 1998). These parent materials give rise to soils representative of many orders including Alfisols, Entisols, Histosols, Inceptisols, Mollisols, Ultisols and Vertisols in bottomlands and swamps, and Alfisols in the loessial uplands (Broadfoot 1976; Stanturf and Schoenholtz 1998).

Historically, BHFs across the Region experienced a substantial decline in area and currently cover a fraction of their precolonial extent (Kellison and Young 1997). Estimates of loss are speculative but range between 40 to 60% (Clark and Benforado 1981; US Epa 2025). Deforestation for agriculture is the main cause of forest loss in the Region; farming was widespread in eastern bottomlands by the mid-1700s and expanded rapidly across the Region through the mid-1800s (Kellison et al. 1998; Saikku 1996). The largest concentration of forest loss within the Region occurred in the 25-million-acre LMAV where agricultural use currently prevails on about 62% of the land base (Turner et al. 1981; Gardiner 2014). This area sustained an estimated 50% loss in forest cover by the 1930s, and an estimated 75% loss in forest cover by the 1970s (MacDonald et al. 1979). However, there were episodes of forest regrowth in the Region, particularly with farm abandonment during the Civil War (1861–1865) and the Great Depression (1930s) (Winters et al. 1938), and more recently with conservation policies supporting active afforestation of economically marginal agricultural land written into the Food Security Act of 1985 and subsequent Farm Bills (Gardiner and Oliver 2005).

In addition to the loss in forest acreage, BHFs experienced significant degradation from a range of sources. Hodges (1995) noted the widescale degradation of BHFs that resulted from commercial logging practices initiated in the early 1900s and commented that the "high-grading" practices of that time have remained a systemic

source of degradation to species composition and quality of stands. Kellison and Young (1997) likewise stressed the detrimental impacts of such degenerative logging practices. BHFs across the Region also experienced extensive degradation related to landscape or watershed-level alteration that impacts various hydrologic factors. Activities such as river channelization, levee construction, dam construction, and ditching and drainage projects usher long-term degradation of BHFs through modification of floodplain geomorphology, alteration of natural hydrologic regimes, changes to floodplain sediment and nutrient storage patterns, saltwater intrusion, and other factors (Oswalt and King 2005; Hupp et al. 2009; Krauss et al. 2009; Kroes and Hupp 2010; Pierce and King 2017). Additionally, numerous invasive plants, pests, and pathogens impart considerable degradation to forests of the Region by impacting regeneration processes and causing mortality that alters stand compositions and contributes to lost productivity (Oswalt 2010).

The Current Forest

Southern BHFs occur on about 28.13 million acres across the Region (Table 1) (See analysis methods and a synthesis of forest area, forest composition, forest size structure, forest volumes, and invasive trees, pests, and pathogens in Online Resource 1; data will be available in the U.S. Department of Agriculture, Forest Service, Research Data Archive). About 82.6% of the resource is found within the SEMF, 11.6% is found within the LMRF, and 5.8% is found within the BLBF. Current acreages represent a net total loss in BHF cover of about 1% over the past 30 years (Table 1). During the 1990s, stands cataloged under the oak/gum/cypress forest type group occupied 23.14 million acres, and those catalogued under the elm/ash/cottonwood group occupied 5.29 million acres (Table 2). By the 2020s, the oak/gum/cypress group declined 6.3% to 21.7 million acres, whereas the elm/ash/cottonwood group expanded 22.1% to 6.4 million acres (Table 2). Size distribution of trees shifted towards larger diameter classes (Online Resource 1, Tables S4, S5, S6), while the estimated volume of live trees in forestland across the Region grew about 13.8% since the 1990s to 54.2 billion ft^3 (Table 3). In aggregate, oak importance

Table 1 Forestland acreage within regional areas of the Southern Bottomland Hardwoods Region by survey period

Forest Area	1990s (acres)	2020s (acres)	Change (acres)
Lower Mississippi Riverine Forests[a]	2,740,028	3,256,498	516,470
Brown Loam Bluffs Forests[b]	1,480,378	1,642,261	161,883
Southeastern Mixed Forests[c]	24,205,930	23,233,903	−972,027
Total	28,426,337	28,132,662	−293,674

[a]Corresponds to the Lower Mississippi Riverine Forest Province (234) (Bailey 1994)

[b]These forests represent Sect. 231H of the Southeastern Mixed Forest Province (231) (McNab et al. 2007)

[c]Corresponds to the Southeastern Mixed Forest Province (231, except for 231H) and the Outer Coastal Plain Mixed forest Province (232) (Bailey 1994)

Table 2 Forestland acreage for primary forest type groups within the Southern Bottomland Hardwoods Region by survey period

Forest Type Group	1990s (acres)	2020s (acres)	Change (acres)
Elm/Ash/Cottonwood	5,287,554	6,453,487	1,165,933
Oak/Gum/Cypress	23,138,783	21,679,175	−1,459,608

Table 3 Volume, growth, removals, and mortality within timberland of the Southern Bottomland Hardwoods Region by survey period

Forest Area	Volume[a] (Bft^3)		Growth[b] ($MMft^3\ y^{-1}$)		Removals ($MMft^3\ y^{-1}$)		Mortality ($MMft^3\ y^{-1}$)	
	1990s	2020s	1990s	2020s	1990s	2020s	1990s	2020s
Lower Mississippi Riverine Forests	4.40	5.97	129.7	151.6	69.6	32.7	55.9	101.6
Brown Loam Bluffs Forests	2.23	3.36	70.8	91.9	57.9	29.9	32.3	75.1
Southeastern Mixed Forests	41.03	44.92	951.4	1014.2	922.8	460.1	597.4	888.5
Total	47.67	54.25	1151.9	1257.7	1050.3	522.7	685.6	1,065.2

[a]Volume of all trees

[b]Average annual net volume increment of all trees, mortality has been subtracted

exceeds that of all other genera occurring in the Region (Online Resource 1, Tables S2, S3). Assessment of 10 common bottomland oaks (overcup oak, swamp chestnut oak, white oak, water oak, swamp laurel oak, willow oak, cherrybark oak, Nuttall oak, Shumard oak, and pin oak) indicates their collective importance across the Region trended upward (3% increase) over the past 30 years (Online Resource 1, Table S3), but the trend was driven by only 3 species (Nuttall oak, cherrybark oak, and water oak). Importance of Chinese tallowtree, the most prevalent invasive tree in the Region, is now ranked among the top 30 trees in BHFs. Extensive redbay mortality resulting from laurel wilt disease, which is caused by the fungal pathogen *Harringtonia lauricola*, led to a 58% decline in importance of this tree in coastal forests throughout the Region. Though the emerald ash borer (*Agrilus planipennis*) now occurs in all states of the Southern Bottomland Hardwood Region except Florida (USDA Aphis 2026), declines in ash stocking have yet to register in the data set analyzed for this manuscript.

Forest Landowners and Their Objectives

The majority (81%) of BHF acreage in the Region is privately owned (Table 4). However, the privately-owned share is substantially less than it was in the 1990s having declined by about 7 percentage points from 88%. During this time, state and local government ownership nearly doubled—from 1.56 million to 3.01 million acres—and federal lands increased 52% from 1.25 million to 1.89 million acres (Table 4). The change in shares between private and public ownership is partly

Table 4 Forestland acreage for broad ownership groups within the Southern Bottomland Hardwoods Region by survey period

Ownership	1990 s (acres)	2020 s (acres)	Change (acres)
Private[a]	25,130,652	22,661,141	−2,469,511
State & Local Government	1,561,208	3,015,170	1,453,962
Federal[b]	1,247,149	1,898,656	651,507
U.S. Department of Agriculture, Forest Service[c]	487,327	557,695	70,367

[a]Nonindustrial and corporate owners

[b]Does not include the U.S. Department of Agriculture, Forest Service, National Forest System

[c]National Forest System

attributable to movement of acreage from private corporations to public ownership through widescale timberland divestitures by vertically integrated forest products companies during the 1990s and 2000s. Conservation interests played a strong role in facilitating this ownership transfer throughout the Region (Bliss 2010). For example, the State of Alabama, through partnerships with several conservation organizations, acquired more than 47,000 acres of BHFs in the Mobile-Tensaw River Delta after Kimberly-Clark divested of this timberland in 1999 (BEN 1999). Also, increased shares in ownership among public entities is partly attributable to land use change associated with forest restoration on former agricultural land acquired for public mitigation banks and habitat restoration projects (Stanturf et al. 2000). For example, the Lake George Wetland and Wildlife Restoration Project, a US Army Corps of Engineers mitigation project located in the Mississippi portion of the LMAV, restored BHFs on 8,892 acres of privately held agricultural land brought into public ownership in 1990 (Williams et al. 1997). Despite the observed 7-point shift towards public ownership, non-industrial private owners continue to dominate forest ownership, underscoring the importance of private land incentives and technical assistance for promoting and achieving quality silviculture.

Understandably, objectives for owning and managing BHFs shifted with the ownership dynamics noted above and other developments in policy and market factors influencing silviculture. In general, the shifts resulted in an apparent lessening of intensity for silviculture practiced in these forests, i.e., fewer entries per stand, longer periods between entries, and smaller treatment units (Meadows and Hodges 1997). A few factors contributed to this trend. Primarily, opportunities for landowners to pursue objectives focused on management for hardwood fiber and timber production have been limited by a loss of milling capacity across the Region (Brandeis and Guo 2016). This decline, particularly in the hardwood pulp market, was unforeseen by Hodges (1995), who commented on the strong hardwood pulp market of 30 years ago as being essential for implementation of sound silviculture in bottomlands.

Concurrently, objectives focused on ecological restoration, conservation, and recreation increased in popularity with the rise in public ownership and acreage enrolled in conservation easement programs (King and Keeland 1999; Stanturf et al. 2000). Conservation easements are important for ensuring that BHFs are not

converted to other land uses, but their contractual terms can limit opportunities for silvicultural interventions and move management towards passive approaches. For example, where afforestation was supported through governmental conservation programs such as the USDA Agricultural Conservation Easement Program, program objectives targeting environmental or ecological benefits provide context to the type, timing, and intensity of silvicultural practices approved for use (Gutierrez-Castillo et al. 2022). Thus, it is noteworthy that silvicultural activity on much of the recently gained forest acreage established on former agricultural land in the LMRF is encumbered through federal conservation easements. Exceptions to the silvicultural restrictions associated with federal easement programs occur where forestland is protected through a working forest conservation easement—this instrument type typically holds few silvicultural restrictions other than those specified under most state forestry best management practices (BMPs), e.g., exclusion of streamside management zones (SMZs) from management (Reeves et al. 2020). Along with conservation easements, the carbon market has been a welcome source of income for some owners of BHFs. Afforestation of former agricultural land provides high potential for restoring forest carbon uptake and storage functions that support global climate mitigation efforts, and revenue generated from carbon can, in the least, offset taxes, annual management costs, or supplement other non-timber income (Aryal and McConnell 2025). As with conservation easements, silvicultural activities in forests managed for climate mitigation are generally limited by terms established in the carbon contract (Sharma and Kreye 2022).

Though opportunities to practice silviculture in BHFs apparently declined over the past three decades, a growing wood pellet market replenished some milling capacity thereby providing opportunity for management involving harvest of small-diameter stems (Conrad and Blinn 2024). The export market for wood pellets grew substantially since the 1990s and today the US South is the greatest exporter of pellets globally (Thrän et al. 2019). However, most wood pellet facilities in the Region primarily procure pine that is not sourced from BHFs (Kittler et al. 2020), and the wood pellet industry has had little impact on the hardwood pulpwood feedstock market (Parajuli et al. 2024), so this market has yet to create opportunities to sell small-diameter hardwoods other than on some local bases.

Changes in Silviculture and Management of Bottomland Hardwoods

Hodges (1995) detailed the silviculture of three different BHF assemblages within the Southern Bottomland Hardwood Region, these were the broad Mixed Bottomland Hardwoods forests, the Baldcypress-Tupelo type, and the Cottonwood-Willow type. He also detailed silviculture of the Brown Loam Bluffs subregion. We address silvicultural change for Mixed Bottomland Hardwoods forests, Baldcypress and Water Tupelo forests, and Afforested Bottomlands. Discussion of silviculture for the mixed species forests of the BLBF was pooled into the Mixed Bottomland Hardwoods assemblage because of similarities in species compositions and common objectives focused on oak silviculture. The Cottonwood-Willow type covered by Hodges (1995) was omitted from our review because silviculture

of this type changed little over the past few decades. The assemblage, Afforested Bottomlands, was included in this overview because of the sharp rise in forest restoration practiced within the Region over the previous 30 years and developments to the silviculture used to establish and manage these artificial stands.

Mixed Bottomland Hardwoods Forests

Mixed BHFs, found on floodplains, terraces, and loessial uplands across the SEMF, LMRF, and BLBF (Fig. 2), represent the largest forest assemblage within the Southern Bottomland Hardwood Region. These forests are extremely complex with an array of species, each with varying site requirements, tolerances to light and flooding, and differing growth habits (Hodges 1997). Structure of this forest resource across the landscape is continually being modified by social and ecological changes that occurred in the last 30 years. With the previously noted decline of wood markets, active forest management, formerly conducted by wood products companies and private landowners, is now supplanted by more passive management by public and private ownerships interested in retaining forest cover for conservation, hunting enterprises, and carbon credits. This shift was recognized in the resource statistics presented in Online Materials 1 (Table S4) as it promotes maintenance of stands with larger size classes, i.e., older trees, and often with closed canopies.

Undesirable Stand Conditions

Irrespective of the decline in industrial ownership over recent decades, relatively few mixed BHFs have been professionally managed (Clatterbuck and Meadows 1993). Presently, two adverse stand conditions prevail in this forest assemblage, both are considered detrimental risks to sustaining desired species compositions and preserving future management options. The first condition results from maintaining a closed overstory canopy that limits sunlight penetrating to the forest floor. Aging stands of this condition are difficult to regenerate and represent increased health risks due to their greater susceptibility to pests and pathogens and less resilience to site perturbances such as flooding, wind, and ice (Fig. 3). The second condition arises within stands that are repeatedly cutover, mismanaged, or unmanaged without thought for regeneration (Clatterbuck and Meadows 1993). Often referred to as high-grading, selective cutting, or diameter limit cutting, these logging practices result in degraded stands of poorly formed, inferior tree species and shade-tolerant reproduction (Kellison and Young 1997). Both conditions encourage dense midstories and understories of undesirable, shade-tolerant trees that will eventually replace the preferred overstory species composition of the future forest. Reversing these stand conditions and procuring desirable regeneration through restoration activities takes considerable time, effort, and expense to control unwanted vegetation while advancing species such as the bottomland oaks that are favored for providing recreational and cultural

Fig. 2 **a**) A mature mixed bottomland hardwood stand of Nuttall oak, American elm, green ash, and sugarberry, Washington County, USA; **b**) A mature mixed hardwood stand of cherrybark oak, water oak, and sweetgum in the Brown Loam Bluffs, Warren County, MS USA ▶

benefits, supporting quality wildlife habitat, contributing to carbon storage, producing fiber and wood products, and provisioning other ecosystem services.

Oaks—the Keystone Genus in Mixed Bottomland Hardwoods Forests

For mixed BHFs, oaks are a keystone and focus genus for wildlife and wood products with various species occurring on most bottomland sites contingent on the landform and soil substrate (Gardiner 2001). Although the social (ownership, markets, management objectives) and ecological (invasive species, hydrologic regimes, species compositions, age structures) environments are repeatedly modified, oak sustainability continues as a constant thread important to stewardship of mixed BHFs. Progress in application of sound silvicultural systems for regenerating mixed bottomland oak stands peaked in the 1990s as researchers built knowledge to support even-aged regeneration methods and discredit earlier uneven-age methods that failed to account for stand development patterns of mixed bottomland hardwoods and were too involved for practical large-scale application (Johnson and Krinard 1989; Clatterbuck and Meadows 1993; Kellison and Young 1997). Yet, the shifting values and objectives accompanying ownership changes across the Region are increasingly moving the resource towards continuous cover forests and the same approaches that previously failed to sustain bottomland oaks, i.e., approaches that disregard recruitment dynamics of mixed species stands or promote closed canopy conditions. The challenge of maintaining oaks in future stands is presented as an example of the changing environment associated with mixed BHFs.

Identifying Challenges

As previously mentioned, evidence is mounting that the composition of BHFs is slowly shifting from oaks to other species (Fei et al. 2011). Though they may comprise a majority of the overstory in some stands, oaks are often infrequent in the mid- and understories (Online Materials 1, Table S6). Many forests predominated by oaks do not regenerate to a similar proportion of oak after harvest. Shade tolerance of bottomland oak reproduction is generally considered intermediate, ranging between intolerant (e.g., cherrybark oak, Nuttall oak) and tolerant (e.g., white oak) depending on species (Gardiner and Stanturf 2025); reproduction of most species will prosper under moderate light environments given sufficient soil moisture availability (Dey et al. 2012). If the stand canopy is too open, relatively high sunlight will favor more shade-intolerant species such as yellow-poplar, American sycamore, and sweetgum over bottomland oaks. If the stand canopy is closed, relatively low light conditions will favor more shade-tolerant species such as maples, elms, sugarberry, and American beech rather than oak (Clatterbuck and Meadows 1993).

a)



b)



a)



b)



Fig. 3 **a**) A mature mixed bottomland oak stand damaged by ice, Issaquena County, MS USA; **b**) Partial cutting in a mature mixed bottomland oak (Nuttall oak, green ash, sugarberry) stand, Issaquena County, MS USA

Also of importance, bottomland oaks are "advance growth dependent." This means reproduction must be established and of sufficient size to be in a competitive position before the regeneration harvest (Clatterbuck and Meadows 1993). Small oak seedlings and those that establish at the time of disturbance typically grow too slowly to be competitive, but well-established oak reproduction of larger size classes has a much greater probability of contending with fast-growing competitors (Belli et al. 1999).

Landowner Perspective

In stands lacking oak advance reproduction, seedling cohorts potentially establish after masting years (bumper acorn crops) when acorn production exceeds predation—masting can occur as frequently as every year (e.g., willow oak, swamp laurel oak) or as infrequently as every 4 to 10 years (e.g. white oak) depending on species (Gardiner and Stanturf 2025). Given a favorable understory environment, the new seedling cohort may need 5 to 7 years to build vigor and grow to a competitive size. Assuming a 3- to 5-year masting frequency, securing viable advance oak reproduction could take 8 to 12 years under the best of circumstances. Ideally, the regeneration pool would have multiple cohorts of advance reproduction prior to regeneration harvesting.

Where understory conditions are not favorable for reproduction to develop to competitive size classes, seedling mortality is high due to herbivory, flooding, moisture deficit, and other factors. Frequent disturbances to establish and maintain a moderate light environment are necessary to facilitate oak seedling survival and growth and to discourage growth of shade tolerant species as well as faster-growing competitors (Dey et al. 2012). Most stands are disturbed too infrequently to sustain cohorts of oak reproduction. Thus, when those stands receive a regeneration harvest, the future species composition shifts away from bottomland oaks (Oliver et al. 2005). The primary obstacle to successful stand regeneration is the unwillingness of owners and managers, whether public or private, to allow sufficient time (years) and incur the necessary expense to obtain adequate advance oak reproduction by maintaining favorable light conditions and controlling competing species before the regeneration harvest. Additionally, most landowners are not willing to pay for artificial regeneration practices that could mitigate identified deficits in the regeneration potential of the stand (Clatterbuck and Peairs 2024).

Finding Solutions

Over the last 3 decades, researchers approached the oak regeneration problem by studying practices that promote establishment and development of robust natural oak reproduction and practices to enrich oak regeneration pools with artificial reproduction. Measures to initiate and develop natural or artificial oak advance reproduction to a competitive size take several years with considerable expense and effort (Gardiner and Yeiser 2006; Lockhart et al. 2000). Because oaks respond slowly to release, faster-growing vegetation, including shade tolerant and shade intolerant species, must be controlled before they exceed growth of the oak reproduction

(Meadows and Stanturf 1997). The required time and expense of regenerating bottomland oaks often discourage property owners who wish to harvest their timber without delay. Although the process of obtaining and developing advance oak reproduction is lengthy and burdensome, maintaining open forests that have moderate understory light conditions throughout the rotation can alleviate the delay associated with procuring advance reproduction at the end of the rotation. Alongside maintaining a light environment favorable to oak seedling growth, managers should also address other vegetation released by the stand entry and likely to compete with oak reproduction, e.g., midstory tree stump sprouts (Dey et al. 2012). Stand entries too infrequent to maintain open conditions and failing to address competing species across all diameter classes, regardless of the regeneration method, invariably result in the two undesirable stand conditions presented above.

Silvicultural Options

The key to establishing and developing advance oak reproduction is in the regulation and maintenance of sunlight reaching the forest floor through frequent disturbances. Too much or too little light promotes more shade intolerant and shade-tolerant vegetation, respectively, and discourages oak advance reproduction. Bottomland oaks generally exhibit increased growth as light availability rises, but understory light availability in the 20 to 50% range of full sunlight is suitable for growth of advance reproduction (Lorimer et al. 1994; Gardiner and Hodges 1998; Dillaway and Stringer 2007; Gottschalk 1987; Lhotka and Lowenstein 2009; Dey et al. 2012). These same light levels are not as suitable for growth of more intolerant and tolerant species associated with oaks. Regardless, the light environment beneath a partial canopy is heterogeneous, so managers should monitor development of oak reproduction relative to competing vegetation.

Several silvicultural operations promote more open-canopy stands with partial light conditions that favor oak—many of these are suitable for establishing oak advance reproduction during the rotation and maintaining appropriate light conditions for enhancing growth of the reproduction (Fig. 3). Applicable regeneration harvests and intermediate stand management practices include shelterwood cuts, creation of small gaps (0.1–0.5 acres), various thinning methods, crop tree release, midstory removal, and timber stand improvement (Clatterbuck and Peairs 2024). Stocking guides enable the manager to index a consistent and targeted amount of growing space across stands in a forest (Goelz 1995a, b), the C-10 line referenced in Goelz (1997), for example, would create relatively open conditions of moderate light availability in the understory for about 10 years. It is important to note that the practices listed above do not create stand conditions that allow oaks to recruit into the overstory. Recruitment would generally require release of the advance reproduction through nearly complete overstory removal (Oliver et al. 2005).

Solution – Maintaining Open Forests Through Active Management

Hodges (1989) states the following: "*the answer to the question of how to ensure adequate oak regeneration … is not the development of some radically new method*

of cutting, but recognition that all cutting operations in the stand, from the very first, should have as some of their objectives creation of an environment, largely light conditions, favorable for oak regeneration … and furthermore … ensure that cuttings occur frequently enough to maintain the growth of oak regeneration." Bottomland oaks are advance growth dependent. The slow initial growth of oak reproduction necessitates that they are well established before the harvest to be able to compete with faster-growing species after the disturbance. Bottomland oaks are also disturbance dependent. Establishment and retention of advance reproduction in mixed hardwood stands requires that forest overstories are opened through frequent disturbances. Regenerating oak is a process that should begin early in the rotation rather than an event that occurs after the harvest or disturbance. Stands actively managed during the rotation for open forest conditions should not require actions beyond competition control to recruit and culture advance oak reproduction.

Baldcypress and Water Tupelo Forests

Baldcypress and water tupelo are among the most flood tolerant tree species occurring in the Southern Bottomland Hardwood Region (Hook 1984). Stands are found throughout the Region in floodplain sloughs and swamps, coastal swamps, and along the margins of rivers and lakes where sites remain flooded for much of the year (Putnam and Bull 1932) (Fig. 4). These species typically form even-aged stands that range in composition from exclusively baldcypress or water tupelo to mixtures of the two species. Black willow is also found growing ephemerally in mixture with these species after significant canopy disturbance (Hodges 1995). Baldcypress and water tupelo will typically persist on a given site until natural or anthropogenic factors alter edaphic or hydrologic stability. For example, shifts in hydroperiod and soil drainage associated with alluviation can allow for recruitment of less flood tolerant and more shade tolerant species such as red maple, common persimmon, overcup oak and water hickory, which will eventually replace the cypress-tupelo stand (Hodges 1995). Likewise, factors that alter the natural flooding dynamics of riverine or coastal swamps by increasing depth or duration of inundation can lead to significant tree mortality and shift cypress-tupelo stands to open-water environments (Harms et al. 1980; Conner and Brody 1989).

Baldcypress and water tupelo stands regenerate naturally after canopy disturbance through stump sprouting, release of advance reproduction (primarily baldcypress), and germination of seed in the seedbank given a sufficient period of soil drainage (Johnson 1990; Wilhite and Toliver 1990). Johnson (1981) indicated that even-aged or uneven-aged (group selection method) silvicultural systems could be applied to successfully regenerate and manage baldcypress and water tupelo stands. However, regeneration harvests traditionally involved clear-felling of stands partly because repeated entries necessary for uneven-aged management are costly and the uncertainty of inundation-free site access imposes limitations on harvesting frequency (Hodges 1995; Slye et al. 2020). Thus, harvesting practices employed to regenerate baldcypress and water tupelo stands for timber or fiber production objectives will

a)



b)



Fig. 4 **a**) A baldcypress and water tupelo swamp forest, Humphries County, MS USA; **b**) A coastal pondcypress and slash pine stand impacted by saltwater intrusion, Jackson County, MS USA

usually result in an even-aged cohort comprised of reproduction sources of varying size and vigor (Gardiner et al. 2000; Slye et al. 2020).

Concerns over timber production affecting ecosystem function of wetlands prompted study of harvesting impacts to swamp forests over the past three decades (Shepard 1994). Stand and soil disturbance from harvesting certainly imposes functional change in swamp forests, but evidence indicates that use of modern harvesting operations and adherence to BMPs limits the level and duration of adverse effects within healthy riverine and coastal swamp forests (Shepard 1994; Aust et al. 2006, 2020; Every et al. 2023). Various practices are employed to facilitate access and minimize site impacts when felling and conveying timber and poles from swamps. Felling is now predominately performed with tracked felling machinery operating on portable mats or temporary trails fashioned from felled trees (shovel-mats), while trees are conveyed to the landing with skidders operating on shovel-mats or, less commonly, with helicopter or cable yarding (Gardiner et al. 2000; Aust et al. 2020; Slye et al. 2020). Intermediate stand practices could often benefit growth of crop trees and/or establishment of advance reproduction in overstocked baldcypress and water tupelo stands (Williston et al. 1980; Meadows and Stanturf 1997). Stand stocking guides published by Goelz (1995a, b) and stand density indices published by Keim et al. (2010) deliver the first quantitative aids supporting intermediate stand management of these forests. But intermediate stand management is rarely employed in swamp forests due to the involvedness and costliness of harvesting practices. However, practices that do not require heavy machinery can be prescribed to improve stand composition or quality. For example, work by deGravelles et al. (2014) demonstrated the effectiveness of canopy gaps, created with a relatively inexpensive herbicide application, for improving growth of suppressed baldcypress in stands dominated by water tupelo in North Carolina.

Over the past 30 years, an impetus for change in management and use of baldcypress and water tupelo forests precipitated from the reality that many of these forests exist in a heightened state of degradation which prevents their regeneration and hastens their loss (Chambers et al. 2005; White et al. 2022). Watershed, river, and floodplain development altered the natural hydrological dynamics and sediment deposition patterns that sustain riverine and coastal swamps, plus development of coastal areas along with coastal subsidence are increasing susceptibility of coastal swamps to impacts of storms, climate-driven sea level rise, and associated saltwater intrusion (Fig. 4) (Phillips 2024; Conner et al. 2026). Recognition of this degradation initiated an objectives shift, away from production in forests where it is deemed unsustainable, towards conservation and restoration for broader ecological, economic, cultural and recreational values of these forests (Chambers et al. 2005). Accordingly, the mechanisms of riverine and coastal swamp forest degradation, approaches to mitigate the degradation, and restoration of these forests and their ecological functions steeply grew as research focal points over the last three decades (Chambers et al. 2005; Yeung et al. 2025; Conner et al. 2026).

Coastal baldcypress and water tupelo forest restoration is being approached through integrated mitigation of degradation at stand and landscape levels. Because the most pervasive forces of degradation affecting these forests, i.e., altered hydrologic regime and alluviation patterns, are marked by the inability of stands to

regenerate, the regeneration process has been a central emphasis of forest restoration research and landscape restoration planning. An example of a landscape-level effort promising to restore freshwater and sedimentation dynamics that support swamp forests is the combined endeavor of the West Shore Lake Pontchartrain Diversion Project led by the US Army Corps of Engineers and The River Reintroduction into Maurepas Swamp Project led by the State of Louisiana. This work will divert sediment laden water from the Mississippi River to a 45,000-acre area of the saltwater impacted Maurepas Swamp in Louisiana (CPRA 2017; US ACE 2025). A key innovation supporting landscape restoration initiatives is a conceptual model proposed by Chambers et al. (2005) for distinguishing the biological and physical condition of swamp forests and their potential to regenerate. Faulkner et al. (2009) applied the concept and demonstrated practicality of delineating condition classes and regeneration potential for forests across the Atchafalaya Basin, LA landscape, but also recognized application constraints at the stand level where long-term hydrological records do not exist. Regardless, the model forwarded by Chambers et al. (2005) provides a method for classing areas and stands experiencing degradation impacts, a framework for prioritizing mitigation and restoration activities, and a common purpose for establishing collaboration between landowners, managers, and policy makers pursuing restoration, conservation, and use of coastal swamp forests.

At the stand level, various advances that improve success in artificial regeneration of baldcypress and water tupelo forests arose to offset issues with securing natural regeneration. Artificial regeneration can be beneficial in situations where alteration of the hydroperiod prevents seed germination and seedling establishment, e.g., sites permanently flooded with shallow water. A stock and planting technique refinement that improved efficacy of outplanting in standing water over that of traditional bareroot seedlings involves burlap bagging topsoil and the root system of bareroot or containerized seedlings, placing the bagged root system on the surface of inundated soil, then staking to keep the bag in place and the seedling vertical (Conner et al. 1999). Still, Brantley and Conner (1997) more efficiently established baldcypress and water tupelo in standing water by pruning the lateral roots from large seedlings and planting the seedling by pushing the taproot into the inundated soil to the root collar (Conner et al. 1999)—these species readily generate adventitious roots to compensate for those pruned. In many situations, achieving acceptable survival and growth of artificial regeneration relies on protecting seedlings from herbivory. Double wall plastic or wire mesh tree shelters are effective in protecting planted seedlings from rabbit (*Sylvilagus* spp.), nutria (*Myocastor coypus*), beaver (*Castor canadensis*), and white-tailed deer (*Odocoileus virginianus*) herbivory but they must be removed from around established trees and plastic shelters can be lost to floodwater (Stanturf et al. 2004).

Apart from progress with stock types and establishment techniques, efforts to understand genetic variation in salt tolerance and identify salt tolerant genotypes in baldcypress show strong promise for developing improved planting material for initiating restoration of this species in coastal systems impacted by saltwater intrusion (Krauss et al. 2000; Conner and Inabinette 2005). Baldcypress can tolerate salinity to a greater extent than other swamp species (Krauss et al. 2007) and, importantly for advancement of tree improvement, appears to hold significant variation in salt

tolerance across its coastal range (Conner and Inabinette 2005). Though promising, the tree improvement effort has yet to advance beyond exploratory investigations. Significant effort in other phases of tree improvement, such as controlled breeding and genomic selection to accelerate genetic gain for salt tolerance, will be necessary before salt-tolerant stocks can be made available for large-scale deployment (Krauss et al. 2007). Notwithstanding the current limitations, regeneration of degraded sites through artificial means, in cases of moderate impact, could serve to buy additional time for implementation of landscape-level restoration projects necessary for addressing primary factors of degradation such as altered hydrologic regimes and deficiencies in alluviation.

Afforested Bottomlands

Planting deforested bottomland sites has traditionally been driven by two distinct purposes, either intensive management for fiber production or low intensity management for restoration and conservation. Industry supported research aimed at developing short rotation plantations for fiber production was well underway in bottomlands by the 1950s (Maisenhelder 1961). Eastern cottonwood was the primary species studied for entry into plantation management because it is the fastest growing bottomland tree, is easily reproduced vegetatively, has favorable fiber and wood quality, and other poplars were being successfully improved and cultivated in European forestry (Maisenhelder 1961). Later, work on other fast-growing species including American sycamore and sweetgum was launched across the Region to expand plantation forestry onto sites less suitable for eastern cottonwood productivity (Robison 2006). Still, advancement of genetically improved clonal material and development of plantation operations for eastern cottonwood led industry to begin establishing short rotation plantations and dedicated fiber farms in the early 1960s to buffer pulpwood supply to mills. Plantations and fiber farms of various fast-growing bottomland trees, particularly eastern cottonwood, persisted in the Region for several decades but did not endure the previously cited corporate timberland divestitures of the 1990s and 2000s. Currently, the potential for use of trees like eastern cottonwood in the growing bioeconomy and innovation in fields like functional genomics are bringing renewed interests and opportunities for short rotation plantation forestry to bottomlands (Gardiner et al. 2024; Gosselaar et al. 2025).

Research on planting bottomland hardwood species not traditionally used in short rotation systems expanded in the 1960s and supported early conservation efforts to restore forests on state and federal lands, e.g., the US Fish and Wildlife Service, National Wildlife Refuge System (Gardiner and Oliver 2005). At that time, cost-efficient establishment of bottomland oaks was the primary emphasis of research and application. Oaks were a highly desired component of these plantings because of their values to wildlife habitat and timber production and were the focus of artificial regeneration because of their limited acorn dispersal (Allen 1997; Dey et al. 2010). It was also thought that volunteer regeneration from wind, animal, or floodwater dispersed seeds would naturally lead to development of species rich stands (Allen 1997), but this strategy would prove ineffective where plantings were not

Fig. 5 **a**) A 15-year-old mixed bottomland oak stand established on former agricultural land, Washington County, MS USA; **b**) A 20-year-old stand of eastern cottonwood interplanted with mixed bottomland hardwoods on former agricultural land, St. Landry Parish, LA USA ▶

immediately adjacent mature forest (Allen 1990, 1997). Planting bareroot seedlings was the standard but methods to successfully direct seed bottomland oaks were developed and commonly practiced on larger afforestation tracts because of the relatively low cost of the approach (Johnson and Krinard 1987; Gardiner and Stanturf 2025). Importantly, the oak-centric afforestation originally applied on public lands served as the model for implementing wide-scale afforestation of private land initiated in the mid to late 1980s (Stanturf et al. 2000).

Most afforestation accomplished over the past 30 years, as previously mentioned, has been supported by Farm Bill programs that provide incentive for removing economically marginal cropland from production and establishing tree cover for conservation needs (Haynes 2004) (Fig. 5). Federal policy subsidizing afforestation has been popular within the Southern Bottomland Hardwood Region—programs administered by the USDA Natural Resources Conservation Service and the USDA Farm Service Agency facilitated land use change from agriculture to hardwood forest cover on the majority of about 500,000 acres planted in the LMAV between 1989 and 2003 (Haynes 2004). Since that time, forest restoration continued to expand across the Region but estimates of farmed bottomland acreage receiving afforestation are not available from the administering agencies. Too, U.S. Department of Agriculture, Forest Service (Forest Service) FIA data analyzed for this work are not collected or structured to generate highly accurate afforestation statistics, i.e., land use change statistics are presented in this report, not afforested acreages. Regardless, the transition from privately to publicly financed forest establishment: incentivized land use change across the Region from agriculture to forest cover; moved the primary establishment purpose from fiber production objectives of industrial landowners to program-based objectives encompassing a broader suit of ecosystem services; transitioned establishment and management operations from high intensity, short rotation silviculture to low intensity management for continuous cover; and raised demand for technical knowledge needed to improve establishment success and apply afforestation systems that restore ecological functions and deliver a range of values.

Practices currently employed for stand establishment in bottomland restoration settings have seen significant change from those used for early plantation forestry (Dey et al. 2010). Because most afforestation sites experienced decades of agricultural production, engineering approaches are sometimes necessary to ameliorate adverse soil or hydrologic conditions that hinder seedling establishment and reduce site productivity (Patterson and Adams 2003). Land forming is used to restore topographic relief and natural surface drainage where precision leveling practices were used to improve agricultural efficiencies (Smith 2001). Likewise, water control structures are frequently installed to manage aspects of the hydrologic regime on appropriate parts of the restoration site, e.g., where improving soil moisture or duration of surface water is important for enhancing wetland function (Smith 2001). Aligning topographic relief and more natural hydrologic regimes with soil map units

a)



b)



allows for improved species assignments and more predictable outcomes on the forest restoration site (Gardiner and Stanturf 2025). Still, it is important to understand that small-scale practices may be beneficial locally, but they typically do not recapture the natural dynamics of riverine, flow through hydrology (Lockaby and Stanturf 2002). Restoration of river-floodplain connectivity and flow through hydrology, particularly within the LMAV, would require landscape-level engineering efforts (DuBowy 2013), e.g., like those aimed at coastal baldcypress-water tupelo forest restoration mentioned above.

Site preparation and post-planting practices for hardwood plantings saw advances as afforestation of deforested bottomland expanded. Prescription options for chemical site preparation and post planting herbaceous weed control in hardwood plantings grew with progress in tank mix development and application practices (Cunningham et al. 2019). Accordingly, operational use of herbicides in afforestation settings has grown over the past 3 decades (Gardiner and Oliver 2005). However, applications for grass and sedge control remain considerably more effective than those available for controlling broadleaf weeds (Stanturf et al. 2004; Self et al. 2012). Cultivation, traditionally practiced for site preparation and to abate small mammal (herbivore) use of the planting area, is regularly used to prepare fallowed fields or those retaining heavy crop stubble (Gardiner et al. 2002). Additionally, subsoil ripping is critical for breaking traffic pans and creating planting rows on former agricultural sites that were cultivated for decades. Thus, ripping is regularly used in site preparation of most afforestation sites, except for a relatively few that will be machine planted. Experience indicates that subsoil implements fitted with coulters and winged shanks offer improved fracturing of hardpans and furrow closure in heavy clay alluvial soils versus conventional straight shank implements (Personal Communication: J. Mike Oliver, USDA NRCS, retired).

Regardless of advances in stand establishment practices, their application intensity in forest restoration settings remains low relative to industrial settings and this often results in poor hardwood seedling survival and widely variable establishment success (Stanturf et al. 1998, 2004). But modest gains in reducing poor seedling survival frequently observed in restoration plantings were realized through research on bareroot seedling quality and development of alternative planting stocks (Dey et al. 2010; Jacobs et al. 2012). Certain seedling morphological variables, such as root-collar diameter and height/diameter ratio, hold correlation to probabilities of shoot dieback and seedling mortality and thereby inform nursery culture and seedling grading for improved outplanting success (Gardiner et al. 2009; Jacobs et al. 2012). Likewise, development of alternative bareroot and container stocks with large, well-proportioned root systems can raise survival where heavy competition or herbivory typically impact conventionally sized bareroot seedlings (Dey et al. 2010). Too, refinements in the spacing of planted stands evolved over the past few decades, trending towards more densely spaced plantings given the uncertainty of seedling survival and especially the improbability of volunteer regeneration enriching the planting (Allen 1997; Battaglia et al. 2002). During the 1990s, managers routinely established hardwood plantings on a 12×12 ft spacing but stands today are often established on a 10×10 ft spacing in some areas of the Region.

Planting designs used for establishing BHFs on restoration sites represent another source of change over the past few decades. While the earliest large-scale efforts focused primarily on bottomland oaks, practitioners today recognize the importance of establishing species-rich plantings for improving stand development, increasing site productivity, sustaining forest health, or benefiting other ecological functions or ecosystem services (Gardiner et al. 2002). Mixed species plantings replaced pure oak plantings over the last three decades—current designs are arrangements of multiple species in either true mixtures or intercropping mixtures (Goelz 1995a, b). True mixtures, either systematic or random combinations of species with somewhat compatible silvics, comprise most plantings established today, and oaks still comprise up to 50% of most mixtures. Current designs for mixed oak plantings, though, are rooted in stand dynamics of natural bottomland oak stands. The ecological basis for planting schemes that promote favorable bottomland oak stand development was established by Clatterbuck and Hodges (1988), who illustrated the importance of interspecific competition for crown differentiation and canopy stratification within even-aged, mixed bottomland red oak stands. Later, Lockhart et al. (2008) developed a silvics-based guide for assigning species combinations compatible with stand development patterns in bottomlands. In practice, though, most mixed-species plantings are arbitrary arrangements of species chosen primarily for site suitability. Managers incorporate stand dynamics knowledge into the design of mixed species systems when they can contract planting crews able to implement detailed project plans with systematic arrangements of species mixes and variable spacings mapped across the afforestation site.

The use of intercropping mixtures, arrangements of fast-growing early successional species with slower growing mid- to late-succession species, has also arisen in the Region over the past 30 years. Establishment of intercropping mixtures typically requires more intensive site preparation and post-planting vegetation control than conventional afforestation, but the increased management intensity and cost can translate to quicker restoration of targeted ecosystem services (Stanturf et al. 2009; Zalesny et al. 2016). For example, an afforestation system involving eastern cottonwood and mixed bottomland hardwoods has been applied on tens of thousands of acres of former agricultural land in the LMAV because of its utility in rapidly establishing forest structure which accelerates early carbon sequestration, development of vertical structure that supports arboreal habitats, creation of favorable understory environments for natural regeneration, and initiation of other ecosystem services (Gardiner et al. 2004) (Fig. 5). Most privately-owned acreage afforested through this system is under federal easement and many participating landowners draw early income from their afforestation investment by partnering with a private company that brokers verifiable forestry carbon offsets to private investors (Van Voorhis 2012).

Additional to advancements in planting design and establishment, the expanded afforestation of farmed bottomland over that past 30 years precipitated change in intermediate management of mixed bottomland hardwoods stands. Stand entry options remain similar to those conventionally practiced in natural hardwood stands but the primary purpose, timing, and method of their application shifted with the expansion of plantings established under federal conservation programs.

Intermediate stand management has traditionally been part of a prescription-based management plan written by the forester who applies stand dynamics principles to improve stand quality to meet stated objectives. More recently, entries into planted forests bound by a conservation easement are conducted as conservation practices written to administer program objectives established by the principal agency—stand entries in bottomland hardwood plantings are primarily granted for wildlife habitat objectives. Landowners typically apply for the opportunity to implement a defined conservation practice, and approval is usually determined in part by existing stand conditions relative to indicator variables that define stand conditions benefiting the specified objectives and the availability of program funding for implementation of practices that are precommercial. In practice, program policy usually determines the type of harvest that can be applied and sets limits on the percentage area of the stand that receives cutting (TCP 2016). Due to the great amount of afforested acreage supported by conservation easements and its developmental status (largely precommercial), first stand entries tend to be performed systematically, e.g., row thinning. This is because practices such as row thinning can be performed efficiently, can be completed with disregard for stand development (i.e., timing of crown differentiation), and require minimal professional oversight relative to selective thinning. But Meadows et al. (2021) cautioned that indiscriminate tree removal in systematic fashion is a risky practice in hardwood stands that will be managed on long rotation because leave trees are selected based on their location in the stand rather than their suitability for achieving the defined management objectives. For young mixed bottomland oak plantings not bound by a conservation easement, Meadows et al. (2021) published a comprehensive guide that details when and how to select and implement various intermediate stand management options for addressing a range of objectives. Still, as mentioned above, weak or nonexistent markets for small diameter trees currently limits more widespread application of intermediate stand practices over much of the Region.

Advances in Tools Supporting Bottomland Hardwood Forestry

Quantitative methods have long played a critical role in forestry as decision support tools, informing choices related to species selection, planting density, silvicultural treatments, and harvest scheduling. Indeed, forest management decisions are made using information about current and future resource conditions often obtained from models (Amateis 2003; Poudel and Cao 2013). More specifically, forest growth and yield models (GYMs) are central to these quantitative approaches, having evolved from the earliest normal yield tables developed using graphical techniques into sophisticated spatially explicit individual tree models. Recent advances in forest modeling include data fusion techniques and the use of modern statistical, machine learning, and artificial intelligence methods that enhance predictive capacity and flexibility.

Considering these advances, the development and application of tools specifically designed for BHFs trailed progress focused on commercially managed pine plantations (McTague et al. 2008). In addition to the traditional industrial support of pine

forestry, this can be attributed to the previously mentioned ecological complexity of BHF systems which is difficult to capture through empirical modeling. Additionally, decision support tools for BHFs are increasingly expected to inform multiple objectives (e.g., wildlife habitat, carbon sequestration, water regulation, and other ecosystem services) and to represent the spatial and structural complexity of these forested floodplains. Concurrently, there has been a growing emphasis on landscape-scale modeling supported by advances in remote sensing technologies. Spaceborne, airborne, and terrestrial LiDAR, in combination with multispectral and hyperspectral imagery, have the potential to enhance characterization of canopy structure, vertical complexity, and fine elevation gradients critical to BHF dynamics. However, current application of such tools and technologies in BHFs remains fragmented, with studies focused mostly on dataset comparisons or their ability to predict a few stand attributes rather than on development of integrated applied tools.

Tools for Silviculture and Management

Decision-making tools in forestry have ranged from expert opinion to sophisticated computer models that vary by forest type, region, and organization (Ray 2022). As forest management objectives are achieved by controlling stand characteristics that influence growth and yield, a useful decision support tool should incorporate and be able to predict the relationships between those stand characteristics and the growth and yield of timber in the stand. Though relatively little effort has been devoted to developing comprehensive GYMs for BHFs (Iles 2008), key advances were made over the last 30 years. Rauscher et al. (2000) evaluated the accuracy of hardwood GYMs in the southern US but reported that no publicly available model applicable to bottomlands existed. Zhao et al. (2004) studied individual tree diameter growth and mortality models for the BHFs in the LMAV and extended their work (Zhao et al. 2005) to develop density-dependent matrix models for mixed species stands. However, these models were recommended by the authors to be applied for short term inventory updating only (Koirala 2022). Schultz et al. (2010) developed component models for stand level growth and yield prediction of red oak–sweetgum forests in minor stream bottoms of Mississippi and Alabama. Later, Jeffreys (2014) produced individual tree GYMs for these forests, and Banzhaf et al. (2016) further expanded this work by developing models to predict volume by log grade. Unfortunately, these models are not publicly available (Aryal et al. 2023). Most recently, Aryal et al. (2023) utilized the Forest Inventory and Analysis (FIA) dataset and developed variable density yield equations for the oak/gum/cypress forest type group and Ogana et al. (2025) used FIA data to develop GYMs for natural hardwood stands of the southern US.

Because most GYMs are proprietary, requiring purchase or membership to a cooperative, the Forest Vegetation Simulator (FVS) of the Forest Service (Dixon 2002), an individual tree distance-independent GYM, has been widely used in timber yield forecasting and carbon project development (Munro et al. 2025). It is one of the most used GYMs for hardwoods (Ogana et al. 2025). However, Parresol and Stedman (2005) found that accuracy of the southern variant of FVS height

predictions was lowest for the bottomland hardwoods and a comprehensive accuracy analysis of this data intensive individual tree GYM is warranted.

Site index is the most widely used predictor of productivity by forest managers. McTague et al. (2006) used data from 13 southern States collected between 1967 and 2004 by the Hardwood Research Cooperative at North Carolina State University from fully stocked even-aged southern hardwood forests to calculate site index curves. Schultz et al. (2010) developed anamorphic site index models for red oak–sweetgum stands on mid-south minor stream bottoms which were incorporated in their stand level GYMs. Lockhart (2013) reviewed several techniques for determining site index in bottomland hardwoods, including species trials, site index curves, soil–site methods, and expert systems. Although site index curves are the most widely used, Lockhart (2013) emphasized that many bottomland hardwood species still lack developed curves and that existing anamorphic curves should be evaluated against polymorphic alternatives. Anamorphic site index models for willow oak and cherrybark oak in east Texas were developed by Oswald et al. (2017). Most recently, VanderSchaaf (2024) developed dominant height and site index equations for the swamp chestnut oak–cherrybark oak forest type using FIA data. Predictions from these models closely matched those produced by the Schultz et al. (2010) models.

Stand density is another critical factor affecting growth and yield of bottomland hardwoods, and it can be more readily modified through management activities than site quality (Goelz and Meadows 1997). Meadows and Skojac (2008) advanced a tree classification system that improves stand inventory, planning, and marking for objectives-driven intermediate practices in southern hardwood forests. Coupled with tree classification, stocking guides released by Goelz and Meadows (1997) can be used to implement stand density management within BHFs. As an alternative to strict stand density management strategies, Meadows forwarded a stand quality management approach that prioritizes regulation of quality over density to improve stand health and value for timber production or other defined objectives (Meadows and Skojac 2008; Meadows et al. 2021).

Prior to the 1990s, managers lacked access to methods tested under operational conditions that could assess the regeneration potential of mixed bottomland oak stands. Belli et al. (1999) refined and published a simple tool, based on an empirical model proposed by Johnson and Deen (1993), that uses regeneration inventory data to estimate the probability that advance reproduction will attain free-to-grow status and contribute stocking to the regenerating stand. Application of this tool enables the manager to determine adequacy of advance reproduction, thereby it identifies deficiencies or confirms sufficiency of reproduction to proceed with regeneration harvesting.

Tools for Restoration

Selecting appropriate species for site-species matching is one of the first and most challenging tasks for the restoration practitioner because of the wide variety of

species and differences in their survival and growth characteristics (Stanturf et al. 2004; Self 2020). However, the only existing tool to assess site suitability that considers microsite variation in bottomlands is the Baker–Broadfoot method of site evaluation, which considers soil physical properties, moisture availability during the growing season, nutrition, and drainage (Baker and Broadfoot 1979). The method provides site index estimates for 14 common species and has been developed into a DOS based (Harrington and Casson 1986) and, most recently, as a web-based tool (Polinko 2025). While the Baker–Broadfoot site evaluation method is widely used by foresters (Stanturf et al. 2004), it is not calibrated on rigorous quantitative data. Still, Groninger et al. (2000) calibrated the Baker–Broadfoot site index predictions against USDA Natural Resources Conservation Service survey data for specific combinations of tree species and soil series commonly encountered on afforestation sites.

Many of the early restoration plantings across the southern US have now reached stem exclusion phase (Leite et al. 2016), creating a need for tools to evaluate restoration success and guide optimal management strategies. Detailed guidelines noted above are available to help make first-entry treatment decisions for bottomland hardwood plantings being managed under a range of objectives (TCP 2016; Meadows et al. 2021). However, comprehensive growth and yield analyses that integrate stand growth dynamics and assess economic potential of mixed species plantings considering both market and nonmarket products (ecosystem services) remain significantly understudied for these systems.

The complexity of BHF systems and lack of information about the economic tradeoffs among different management approaches are the main challenges for bottomland hardwood managers (Nepal et al. 2018). Nepal (2016) found that even-aged management generally outperformed uneven-aged management of BHFs in terms of end products and harvest timing, but the tradeoffs varied with stand conditions and required return rates. Jenkins et al. (2010) estimated the economic value of restoring wetlands in the LMAV through the Wetlands Reserve Program and showed that ecosystem services such as greenhouse gas mitigation, nitrogen reduction, and waterfowl recreation generate social benefits that outweighed restoration costs and offer attractive returns for private landowners and the public. Though several independent studies estimated the economic value of BHFs, we still lack comprehensive tools to evaluate these ecosystem services across different management strategies. Notable exceptions are models built to assess economic viability of short rotation woody crop systems that utilize fast growing bottomland hardwoods, e.g., eastern cottonwood, for biomass feedstock production or other purposes that serve climate mitigation. Stanturf et al. (2017) calibrated the process-based model, 3PG, to predict yields and economic returns on eastern cottonwood and hybrid poplar biomass plantings for bioenergy project siting. Additionally, Ghezehei et al. (2019) developed the web-based tool, SRWC-PEAM, to allow for evaluation of species, landtype and management scheme factors on the economic feasibility of fast-growing species in the southeastern US.

Summary of Silvicultural Issues That Persist

Much of the change observed in the Southern Bottomland Hardwood Region during the previous 3 decades reflects positively upon the resource. Recognition of the unique and broad array of ecosystem services provided by BHFs increased appreciation of the many values associated with these systems and shifted a greater share of the resource to public ownership that broadens management objectives and safeguards it from deforestation. Because of significant land-use change due to conservation driven afforestation, the historic decline in forest area across the Region tapered to about 1% over the last 30 years. Importantly, advances in our knowledge of the ecology and silviculture of BHFs led to refinement of silvicultural practices and technologies that improved success in achieving management objectives. Yet, irrespective of the encouraging developments, there are prominent gaps in our knowledge, shortfalls in technological developments, and market-related issues that persist in stifling implementation of sound silviculture.

First, the disinclination or inability to regenerate stands of certain species associations are persistent issues plaguing BHF sustainability across the Region. These issues are most prevalent for oaks in mixed BHFs and baldcypress and water tupelo in coastal swamp forests. Next, selective cutting, high grading, and diameter limit cutting, perpetuated through uninformed loggers and foresters that misguide unaware landowners, continue as a commonplace source of forest degradation that contributes to the observed decline in several bottomland oaks throughout forests of the Region. Additionally, the prevailing lack of sound markets for the many ecosystem services provided by BHFs furthers proliferation of their mismanagement across the Region because landowners cannot invest in silviculture where markets do not exist. Finally, limited access to comprehensive GYMs for mixed BHFs remains a significant hindrance to application of progressive silvicultural prescriptions and forest management in the Southern Bottomland Hardwood Region relative to other ecological regions of the US.

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Authors and Affiliations

Emile S. Gardiner[1] · Wayne K. Clatterbuck[2] · Sonja N. Oswalt[3] · Krishna P. Poudel[4]

✉ Emile S. Gardiner
emile.gardiner@usda.gov

Wayne K. Clatterbuck
wclatter@utk.edu

Sonja N. Oswalt
sonja.n.oswalt@usda.gov

Krishna P. Poudel
krishna.poudel@msstate.edu

[1] U.S. Department of Agriculture, Forest Service, Southern Research Station, Center for Bottomland Hardwoods Research, Stoneville, MS 38776, USA

[2] School of Natural Resources, University of Tennessee, Knoxville, TN 37996, USA

[3] U.S. Department of Agriculture, Forest Service, Southern Research Station, Forest Inventory and Analysis, Knoxville, TN 37920, USA

[4] Department of Forestry, Mississippi State University, Starkville, MS 39762, USA