Seeding bottomland oaks (*Quercus* spp.) in the southern United States

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ARTICLE INFO

Citation:
Gardiner E, Stanturf J (2026) Seeding bottomland oaks (*Quercus* spp.) in the southern United States. Reforesta 21: 166-189.
DOI: https://dx.doi.org/10.21750/REFOR.21.09.139

Editor: Vladan Ivetić
Received: 15.11.2025
Accepted: 15.12.2025
Published: 20.01.2026

Abstract

Temperate broadleaf forests occupying river floodplains of the southern United States are rich in tree species diversity, with various species of bottomland oaks (*Quercus* spp. L.) often comprising a primary overstory component in these forests across the region. Comprehensive research to support development of seeding as a method for artificially regenerating bottomland oaks began in the early 1980s and quickly advanced to produce reliable practices for establishing oak-dominated stands. Large-scale forest restoration was initiated across the region during the late 1980s at which time bottomland oak seeding practices were adapted for broad scale use due to their relatively low costs. This manuscript presents a synthesis of basic bottomland oak ecology, factors leading to degradation of bottomland oak sites and stands, favored techniques and practices for restoring bottomland oak forests through seeding, factors that limit success and impose risks upon seeding projects, and silvicultural principles for seeding bottomland oaks in the southern United States.

Keywords

forest restoration, afforestation, direct seeding, *Quercus*

Note
This paper is a part of a Special issue on International Practices for Regenerating and Restoring Forest Trees by Seeding, edited by Emile S Gardiner and John A Stanturf

Contents

1 The forest

Bottomland forests of the southern United States occur on floodplains and terraces of the numerous major and minor river systems that dissect the Atlantic and Gulf Coastal Plain of the region (Figure 1). Today, these deciduous broadleaf forests are recognized for providing a multitude of ecosystem services including wood products, water quality, recreation, floodwater abatement, carbon sequestration, fish and wildlife habitat, and many others that sustain livelihoods in the southern US and beyond. Historically, though, bottomlands were recognized for their fertile soils, and incentives for growing the agricultural economy of the southern US led to incremental and wide-scale deforestation of these systems. In the case of the greatest expanse of bottomland forest, i.e., the Lower Mississippi Alluvial Valley (LMAV) (Figure 1), deforestation resulted in loss of more than 70% of this 10-million ha resource, beginning in the 1800s and continuing through the 1980s (Sternitzke 1976; MacDonald et al. 1979). Yet, the last three decades have witnessed a growing awareness of the ecological and economic value of these forested systems, and this has fostered federal government policy encouraging conservation of existing bottomland forests and funding wide-scale restoration of deforested or otherwise degraded bottomlands.

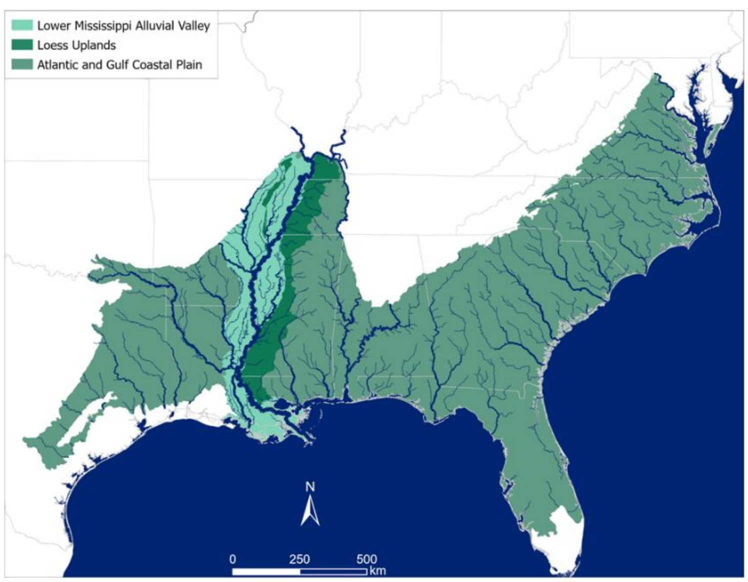

Figure 1. Map of the southern United States that outlines the Atlantic and Gulf Coastal Plain, the Lower Mississippi Alluvial Valley, and the numerous river systems that give rise to bottomlands in the region.

Prior to the wide-scale afforestation effort of the past three decades, US Forest Service scientists located in Stoneville, MS initiated comprehensive research to support development of seeding as a practice for artificial regeneration of bottomland oaks

(Johnson and Krinard 1985). Their success in advancing seeding as a viable practice for establishing bottomland oaks on former agricultural land led to its early use on many state and federal wildlife management areas and refuges where restoration of bottomland forests first received wide-scale adoption (Allen 1990). At that time, the nursery capacity to produce bottomland oak seedlings was low and seeding provided a relatively inexpensive and low intensity approach for large-scale establishment of bottomland oak stands. With the advancement of forest restoration and improved knowledge of bottomland oak stand development, restoration managers now promote establishment of mixed, bottomland oak stands, i.e., stands comprised of 25–50% bottomland oak with the remainder being other native tree species. Most of the trees naturally occurring with bottomland oaks are light seeded and proper techniques for seeding them have not been developed, so seeding to establish stands of bottomland oak has fallen out of favor. Nevertheless, there are particular restoration settings in which seeding remains a low-cost, viable practice for establishing bottomland oaks on deforested agricultural land, and work on acorn biology and storage, estimating soil productivity, site preparation requirements, and sowing practices conducted by those early scientists serves as the foundation for many of the techniques and practices that will be presented later in this manuscript.

1.1 Bottomland environments

Structure and productivity of bottomland forests are inextricably coupled to the site factors that prevail on floodplains. Although seemingly homogeneously flat to the casual observer, scouring and deposition of alluvium associated with annual overbank flooding and meandering of the river channel create significant topographic relief giving rise to landforms or “sites” and development of their associated soils (Figure 2). About six general sites characteristic of floodplains and terraces of the southern US are distinguished by topography, soil physical and chemical properties, and hydrologic regime (Hodges 1997). Soil development for a site progresses relative to the physical and chemical properties of its alluvium, time since deposition, position on the landscape, and other factors of environment and climate including vegetation and hydrologic regime. Entisols, Inceptisols, Alfisols, and Vertisols prevail on floodplains, partly because of the recency of alluvial deposition; Alfisols, Ultisols, and Vertisols prevail on terraces where deposition no longer occurs, and soil development has advanced (Stanturf and Schoenholtz 1998; NRCS 2020).

A temperate climate prevails over the bottomlands of the southern US—it is primarily humid, sub-tropical with cool winters and warm to hot summers (Muller and Grymes 1998). Precipitation is generally high, ranging between 1059 and 1609 mm annually, while the average daily temperature ranges from 0 to 12.4 °C in January to 22.0 to 28.8 °C in July (NOAA 2023). Although forecasts are plagued with uncertainty, temperature and rainfall patterns are expected to differ in the future across the southern US. Estimates through 2060 indicate that average annual temperatures could rise by 1 to 2.9 °C across the Coastal Plain and LMAV portions of the region, with greatest increases generally farthest from coastlines of the Atlantic Ocean and the Gulf of America. Precipitation forecasts through 2060 are variable and range between a 5% increase to an 18% decrease, annually, for the focal area. Increasing precipitation is most likely near the coastlines while decreasing precipitation is most likely interior from the coastlines (McNulty et al. 2013).

Figure 2. Image of the Pearl River and an area of its floodplain in Mississippi, USA illustrating erosion on the outer edge of bends, deposition on the inside of bends, and older meander scars which give rise to and are indicative of the various sites that are characteristic of floodplains and terraces of bottomlands in the southern US.

1.2 Native forests and bottomland oak ecology

In respect to temperate forests, the deciduous broadleaf forests of bottomlands are notably rich in tree species diversity with over 75 indigenous species occurring in these riverine habitats across the southern US. Species that are widespread in bottomlands throughout the region include sweetgum (*Liquidambar styraciflua* L.), green ash (*Fraxinus pennsylvanica* Marshall), boxelder (*Acer negundo* L.), sugarberry (*Celtis laevigata* Willd.), American elm (*Ulmus americana* L.), eastern cottonwood (*Populus deltoides* Bartram ex Marshall), black willow (*Salix nigra* Marshall), American sycamore (*Platanus occidentalis* L.), baldcypress (*Taxodium distichum* (L.) Rich.), water tupelo (*Nyssa aquatica* L.), hickories (*Carya* spp. Nutt.), and oaks (*Quercus* spp. L.). Midstory and understory strata naturally develop in some bottomland forest associations: small trees regularly found in midstories include American hornbeam (*Carpinus caroliniana* Walter), maples (*Acer* spp. L.), hollies (*Ilex* spp. L.), and hawthorns (*Crataegus* spp. Tourn. ex L.); common understory woody shrubs include northern spicebush (*Lindera benzoin* L.), common sweetleaf (*Symplocos tinctoria* (L.) L'Her.), snowbells (*Styrax* spp. L.), and American beautyberry (*Callicarpa americana* L.); and large, perennial monocots of frequent occurrence in understories include giant cane (*Arundinaria gigantea* (Walter) Muhl.) and palmetto (*Sabal minor* (Jacq.) Pers.). Also, with more than 25 indigenous species, bottomland forests are rich in woody vines; ubiquitous species include poison ivy (*Toxicodendron radicans* (L.) Kuntze), Virginia creeper (*Parthenocissus quinquefolia* (L.) Planch.), Alabama supplejack (*Berchemia scandens* (Hill) K. Koch), crossvine (*Bignonia capreolata* L.), grapes (*Vitis* spp. L.), and greenbriers (*Smilax* spp. L.).

Collectively, the oaks often comprise a primary overstory component in bottomland forests—as many as 17 species can be found in bottomlands, 10 of which are common to these forests across the region (Table 1). Seven of the species common to bottomlands are in the section Lobatae, the red oaks, and three are in the section Quercus, the white oaks. In bottomlands, oaks grow in association with other canopy species and these associations are found segregated among different site types (Hodges 1997) (Table 1). Thus, the occurrence of the various oak species in bottomland forests, and their primary co-occurring species, is largely predicated upon the area occupied by the various site types. Driving species-site associations in bottomlands are soil and hydrologic factors inherent to the scope of bottomland sites, e.g., soil flooding and soil pH, along with physiological tolerances and functional plasticities inherent to the various tree species. Distinctly, the range in flood tolerance among bottomland oaks plays a central role in distribution and stratification of the various species on the floodplain.

Table 1. Silvical characteristics of 10 oak species common to bottomlands of the southern US.

Species	Soil and Site Occurrence[1]	Seedling Flood Tolerance[2]	Seedling Shade Tolerance[3]	Seedling Growth Rate[4] (cm per year)
Section Quercus				
Overcup oak (*Q. lyrata* Walter)	Poorly drained, clayey soils of low flats, sloughs, and other depressions on floodplains and terraces	Tolerant	Moderately Tolerant	15–25
Swamp chestnut oak (*Q. michauxii* Walter)	Well drained, loamy soils of low ridges on terraces, less common on floodplains	Moderately Intolerant	Moderately Intolerant	15–25
White oak (*Q. alba* L.)	Well drained, loamy soils of ridges, principally on terraces	Intolerant	Tolerant	15–25
Section Lobatae				
Cherrybark oak (*Q. pagoda* Raf.)	Well drained, loamy soils of ridges and high flats on floodplains and terraces	Moderately Intolerant	Intolerant	15–25
Nuttall oak (*Q. texana* Buckley)	Poorly drained, clayey soils of flats and low ridges on floodplains and less commonly terraces	Moderately Tolerant	Intolerant	20–30
Pin oak (*Q. palustris* Münchh.)	Poorly drained, clayey soils of flats and low ridges on floodplains and terraces	Moderately Tolerant	Moderately Intolerant	15–25
Water oak (*Q. nigra* L.)	Poorly drained, clayey soils of low flats to well drained, loamy soils of ridges and high flats on floodplains and terraces	Moderately Intolerant	Moderately Intolerant	10–20
Willow oak (*Q. phellos* L.)	Poorly drained, silty or clayey soils of low flats to well drained, loamy soils of ridges and high flats on floodplains and terraces	Moderately Tolerant	Moderately Intolerant	15–25

Shumard oak (*Q. shumardii* Buckley)	Well drained, loamy soils of ridges on terraces and less commonly floodplains	Intolerant	Intolerant	15–25
Swamp laurel oak (*Q. laurifolia* Michaux)	Poorly drained, clayey soils of low flats and borders of sloughs on floodplains	Moderately Tolerant	Moderately Tolerant	10–20

[1] Putnam and Bull (1932).
[2] Seedling flood tolerance rankings are based on unpublished observations of the authors and are relative to the bottomland oaks.
[3] Based on shade tolerance rankings of mature trees presented in Burns and Honkala (1990) that were modified for seedlings relative to unpublished observations of the authors.
[4] Based on seedling growth information presented in Burns and Honkala (1990), Miwa et al. (1993) and Gardiner et al. (2004) that was modified by the authors to bracket seedling growth during the first 5 years after germination for afforestation sites that receive no post-sowing competition control.

The occurrence of bottomland oaks on the floodplain is also predicated upon the disturbance regime of a given site. As bottomland oaks are largely shade intolerant (Table 1), development of oak associations on favorable sites is facilitated where major canopy disturbance (stand replacing) has occurred (Oliver et al. 2005). Floodwater inundation and significant wind events are among the most common natural disturbance factors impacting bottomland forests. Seasonal flooding of bottomlands rarely impacts the overstory and midstory of mature forests but can affect understory vegetation including the oak regeneration pool. Long-term inundation from impoundment of water by beaver (*Castor canadensis*) or deposition of sediment and debris that blocks the flow of floodwater through return channels more commonly create major canopy disturbance attributable to flooding in bottomlands. High winds from hurricanes regularly impact bottomland forests near coastlines, and tornados impose stand-replacing impacts locally across the region (Cannon et al. 2023; Stanturf et al. 2007).

Bottomland oak stands tend to occur in mid-successional seres that follow major canopy disturbance to stands dominated by early successional species like eastern cottonwood, black willow, river birch, boxelder, American sycamore, American elm, and green ash (Hodges 1995). But it is not uncommon for stands of bottomland oak and sweetgum to occur in an early-successional sere in situations of old field abandonment, or for stands of bottomland oak and hickories to occur in a late-successional sere on sites that no longer receive flooding. Bottomland oak stands typically "mature" in 45 to 60 years, and their canopies begin to break up around years 100 to 150 (Kennedy and Nowacki 1997). Depending on species composition and site productivity, basal area of mature stands will range from 20 to 43 m^2 ha^{-1} and canopy height will range from 26 to 38 m (Meadows and Nowacki 1996; Kennedy and Nowacki 1997).

1.3 Deforestation and afforestation of bottomlands

Deforestation of bottomlands in the southern US began in earnest after substantial settlement of the region in the 1700s and increased incrementally through the 1980s. Estimates indicate that forest area of the LMAV, which has experienced the most widespread deforestation of bottomland in the region, was reduced to 50% of its original 11-million-ha extent by the 1930s, and to more than 75% of its original extent by the 1970s (MacDonald et al. 1979). Most of the historical deforestation was driven by expansion of the agricultural sector in the region which was supported by federal drainage and flood control projects. In recent decades, clearing for agriculture has been somewhat limited by US government "Swampbuster" legislation enacted in 1985, particularly on sites classified as wetlands (Stanturf et al. 2000). During this time, incentives established through additional US government legislation have promoted the afforestation of economically marginal and highly erodible agricultural land. Forest restoration in the LMAV, for example, has afforested well beyond 400,000 ha of former agricultural land since the 1990s (Gardiner 2014). Nevertheless, deforestation of bottomlands continues to persist across the region as development of rural areas and urban expansion progress with a growing population (Gardiner 2014).

2 Impacts of deforestation to bottomland sites

2.1 Site and soil degradation

Restoration in alluvial bottomlands of the southern US is practiced almost exclusively on former agricultural land. Deforestation and conversion to farming land use impose significant soil disturbance, alter natural hydrologic regimes, and affect species composition of colonizing vegetation at bottomland restoration sites. Major impacts of cultivation on bottomland soils include heightened erosion, the loss of organic matter, development of traffic pans, impairment of soil drainage (surface and internal), reduced soil fertility, and shifts in the soil microbial community (Groninger et al. 2000; Stanturf et al. 2004; Strickland et al. 2017). Too, the hydrologic regime of farmed bottomlands is significantly altered from the natural state. Depending on the setting of the restoration area on the landscape and occurrence of bottomland site types on the area, common impacts to the hydrologic regime will involve shifts in timing, duration, and depth of soil flooding, change in soil water retention, and an increased depth to the water table (Stanturf et al. 2004; Ouyang et al. 2019). Further, changes in colonizing plants typically reveal communities that are characteristic of old fields rather than bottomland forests, often with a preponderance of invasive weeds like Johnsongrass (*Sorghum halepense* (L.) Pers.), Brazilian vervain (*Verbena brasiliensis* Vell.), and Wright's morning-glory (*Ipomea wrightii* Sweet) that flourish in agricultural settings (Battaglia 2002; DeSteven et al. 2015). Collectively, the degradation of edaphic, hydrologic, and vegetative factors disrupts nutrient, carbon, and water cycling functions of the site, leading to reduced productivity and curtailment of many other ecosystem functions attributed to bottomland systems.

Because site and soil degradation impair forest establishment, reduce site productivity, and ultimately jeopardize restoration success of bottomland forests, it is helpful for the manager to accurately assess the extent of degradation to inform the restoration prescription. This will reveal issues that should be mitigated to facilitate recovery of the site and soil functions. An evaluation of the relative extent of site degradation can be approached by compiling information on key variables from the restoration site and adjacent properties. Important observations to collect include those that index the extent of constructed drainage and dikes, leveling of topography through land-forming, recent history of flooding, length of time in agriculture, and occurrence of invasive or otherwise problematic weeds. Likewise, the relative extent of soil degradation should be characterized through measurement of key variables that index the status of soil organic matter content, soil compaction, soil nutrient pools, and soil aeration. Baker and Broadfoot (1979) provide a simple field tool for assessing site productivity of bottomland soils—their tool relies on quantification of variables descriptive of soil physical condition, moisture availability, nutrient availability, and aeration (Table 2). Groninger et al. (2000) provide updated recommendations for application of the Baker and Broadfoot guide to sites degraded by cultivation.

2.2 Damaging agents

Several biotic and abiotic factors, which act through depredating sown acorns, impairing acorn viability, suppressing early seedling growth, or causing seedling mortality, can threaten success of bottomland oak seeding on former agricultural land. Insect pests and pathogenic diseases generally pose minimal impact to establishment and early growth of bottomland oaks on restoration sites. Mammals, especially feral pigs (*Sus* spp.), racoons (*Procyon lotor*), and rodents (Order Rodentia) like mice, rats (Suborder Myomorpha), and squirrels (Suborder Sciuromorpha), relish acorns and are known to systematically search for and depredate those sown on restoration sites. Rodents and rabbits (*Sylvilagus* spp.) commonly feed on young oak seedlings—their girdling of bark or stem clipping is often not lethal because bottomland oak seedlings possess the ability to resprout if the root collar remains intact (Figure 3). This feeding activity does, however, reduce seedling vigor and delays seedling recruitment into a larger size class, both of which hold the reproduction in a size class vulnerable to repeated herbivory and other threats. Herbivory by voles (*Microtus* spp.) will often kill seedlings because of their belowground feeding on the root system. White-tailed deer (*Odocoileus virginianus*) do not pose a widespread browsing issue on restoration sites of southern bottomlands, but they may present local issues where restoration is sited proximally to urban greenspace.

Table 2. List of diagnostic variables for four major site and soil factors employed by Baker and Broadfoot (1979) to assess productivity of bottomland soils.

Site and soil Factor	Diagnostic Variables
Soil Physical condition	Soil depth, presence of pans (artificial or inherent), soil texture, soil compaction, soil structure, past land use
Moisture availability	Water table depth, presence of pans (artificial or inherent), position on the landscape, microsite topography, soil structure, soil texture, occurrence of flooding, past land use
Nutrient availability	Geologic source of parent material, past land use, % soil organic matter, topsoil depth, soil age, soil pH
Aeration	Soil structure, swampiness, soil color, presence of mottling

Figure 3. Water oak (*Q. nigra* L.) seedling that has resprouted after being clipped multiple times by a rabbit (*Sylvilagus* spp.). Clipping reduces seedling vigor and delays stem development, which increases seedling vulnerability to additional clipping, competing vegetation, and floodwater inundation (Photo credits: Emile Gardiner).

Dense and vigorous old field vegetation that typically develops on afforestation sites can pose challenging risks to establishment and early growth of seeded bottomland oaks. Invasive grasses like Johnsongrass, and itchgrass (*Rottboelllia cochinchinensis* (Lour.) Clayton), herbaceous broadleaves like Brazilian vervain, asters (*Aster* spp. L.), and goldenrods (*Solidago* spp. L.), and aggressive vines like trumpet creeper (*Campsis radicans* (L.) Bureau), red vine (*Brunnichia ovata* (Walter) Shinners), and blackberry (*Rubus* spp. L.) quickly capture growing space then overtop and out-compete the characteristically slower-growing oak seedlings. Competition from dense vegetation during the establishment period will directly reduce seedling survival and it also delays oak seedling development, which increases vulnerability to herbivory and overtopping by floodwater.

Seasonal flooding drives ecological function of natural bottomland systems, and the acorns and seedlings of bottomland oaks are adapted to tolerate some soil flooding. Still, site inundation and soil waterlogging can adversely impact the afforestation effort when timing is unseasonable, duration is prolonged, or floodwater is too deep. Acorns, especially of the section Lobatae, sown during the dormant season will typically remain dormant for several months in waterlogged soil. In this situation, acorn viability remains intact, and germination will proceed when floodwater recedes, and aerobic conditions prevail in the soil. However, if soil waterlogging persists into warmer months, the acorns of some bottomland oaks will rot under the warm, anaerobic soil conditions. An exception to this occurrence is observed in overcup oak (*Q. lyrata* Walter), a species with acorns well-adapted for hydrochory. Acorn viability for this species has been observed to persist on inundated sites into the late summer or early fall. In natural bottomland systems, this phenomenon appears partly tied to the fact that overcup oak acorns float and thus may avoid anerobic conditions beneath floodwater. But observation of late-season germination by acorns buried under debris or sediment indicates other mechanisms may contribute to viability maintenance in this species.

The ability of bottomland oak seedlings to survive soil waterlogging or inundation varies by species and is also affected by seedling phenology, age, and size (Table 1). Flood tolerance rankings assigned to bottomland oaks generally refer to the ability of a species to tolerate soil waterlogging rather than inundation. As noted in Table 1, seedling tolerance to soil waterlogging ranges considerably by species. Oaks that regularly occur on lower elevation sites of heavier soils tend to exhibit greater tolerance to soil waterlogging than those regularly found on higher elevation sites of loamier soils. However, tolerance to soil waterlogging is also conditioned by seedling phenology, timing, and duration of anaerobic soil conditions.

For all bottomland oaks, flooding that overtops recent germinants for more than a very brief period, perhaps no more than a few days, will almost always be lethal. Likewise, mortality can advance quickly for actively growing seedlings overtopped by unseasonable floodwater during the hot months of summer. In contrast, seedlings of some species will survive overtopping for up to two months if site inundation occurs during the dormant period of the cool winter months. In this situation, cool, flowing water reduces the impact of inundation on established seedlings.

3 Mitigating impacts for seeding

3.1 Preparing the site

As indicated above, forest restoration in alluvial bottomlands of the southern US is practiced almost exclusively on sites degraded by agriculture. The site preparation phase of the restoration process provides the first opportunity for managers to mitigate some of the site and soil degradation discussed above and facilitate initiation of recovery of bottomland forest functions. Land-forming, improving and/or removing water management structures, cultivation, sub-soil plowing, fertilization, and vegetation control represent the primary practices considered by managers developing site preparation prescriptions for bottomland sites.

Land-forming is an engineering practice that is used when it is necessary to return spatial heterogeneity of topographic relief to the degraded restoration site (Figure 4). Topographic relief is important for encouraging hydroperiods more naturally associated with the suite of soil series present on the area. For example, raising surface elevations to form ridge features over soil series that are loamy in texture or lowering surface elevations to form depressions in soil series that are clayey in texture would pair the site-soil combinations with respective hydrologic regimes. Land-forming is a very expensive practice and is usually not necessary unless natural topographic relief of the restoration site was precision leveled during the previous farming operation. Further, restoration projects that are financially sound enough to bear the expense of land-forming would probably plant seedlings rather than sow seed to restore vegetation.

Figure 4. Land-forming a former agricultural site to restore topographic relief that was removed when the site was under cultivation (Photo credits: USDA, NRCS).

Practices more commonly used to restore hydroperiods on bottomland restoration sites include plugging of ditches to reduce surface drainage and installation of water control structures to manage temporary retention and impounding of water on-site (Figure 5). Restoring a hydrologic regime of flowing floodwater characteristic of seasonally flooded floodplains is usually an unrealistic objective on most bottomland restoration areas because of the many flood control projects that have minimized connectivity of rivers with their floodplains by constructing retainment levees and floodwater abatement reservoirs. Locally, altering drainage in low-relief landscapes could adversely impact neighboring properties. Still, capturing local precipitation on the restoration area will replace elements of the natural hydroperiod that can restore some functions of bottomland soils (Hunter et al. 2008).

Figure 5. Water control structure installed to manage water retention and wetland functions within a shallow depression on an afforestation site. Notice the saplings established in the right background where the topography grades to a higher elevation (Photo credit USDA, NRCS).

Most former agricultural sites slated for seeding will require cultivation to reduce row crop stubble or weedy vegetation and prepare the seedbed for sowing. In practice, cultivation is conducted with either a single or double pass of a disking implement—single pass disking is performed where residual crop stubble comprises most of the vegetative matter on the area, and double pass disking is performed where fields recently have not received cultivation, and weedy vegetation has occupied the site. Soils that have developed traffic pans should receive subsoil ripping after cultivation (Figure 6). Either straight shank or winged-shank subsoil plows are recommended for breaking-up traffic pans to increase the potential rooting depth for tree growth. Because subsoil plowing creates temporary, linear furrows on the restoration site, it is also beneficial for establishing rows that are sometimes desired for seeding.

Figure 6. Subsoil ripping of an afforestation site to break-up a traffic pan and increase rooting depth (Photo credits: USDA, NRCS).

Although most farmed soils in the southern US are typically nutrient deficient, e.g., nitrogen deficient, fertilization is rarely used to amend soil nutrition prior to sowing in bottomlands. Control of competing vegetation can benefit oak seedlings competing for available soil nutrients, and broadcast applications of herbicide tank mixes are a common site preparation practice for oak establishment on former agricultural sites. Herbicides commonly used for site preparation and early season control of grasses and herbaceous broadleaves include sulfometuron methyl, glyphosate, oxyfluorfen, fluazifop-P-butyl, and clethodim (Cunningham et al. 2019). Depending on weed development and composition, a single application of an appropriate tank mix is either broadcast across the entire area or applied in rows the fall before sowing season or immediately after acorns are sown.

3.2 Limiting acorn depredation and seedling damage

Acorn depredation and damage to young seedlings by feral pigs, rodents, raccoons, and rabbits can be primary factors contributing to poor stocking and delayed development of seeded bottomland oak stands on former agricultural sites. Devices designed to protect seed and seedlings from pilfering or damage, e.g., seed and seedling shelters, are not conventionally used on bottomland restoration areas because of the large scale of most afforestation projects and costs involved with their deployment and removal from the area (Löf et al. 2019). Likewise, fencing large restoration areas is usually a cost prohibitive option for controlling acorn depredation by feral pigs. Managers preparing to seed bottomland oaks should assess the current extent of vegetative cover, i.e., old field vegetation and crop stubble, on or immediately adjacent to the area. Such cover typically provides quality habitat for mice and rats and should be removed with cultivation during site preparation. Additionally, wooded edges and fallow fields that border the restoration area usually harbor racoons, squirrels and other rodents that pilfer sown acorns, so cultivation should be used to temporarily minimize connectivity between these areas and the adjoining restoration area. Acorn depredation by feral pigs can be reduced through permitted trapping to control the population.

Controlling significant rodent and rabbit damage to young seedlings is also a matter of minimizing cover on the restoration area. While cultivation is effective in clearing the area of old field vegetation in preparation for sowing, the treatment is temporary, and it does not retard the rapid development of succeeding vegetation. Sowing acorns in rows allows for additional cultivation as needed to set-back heavy vegetative cover that holds mice, rats, and rabbits. As with cultivation, herbicide applications made for site preparation also show temporary efficacy. Early season herbicide applications can further delay development of weedy vegetation on bottomland restoration areas. Herbicides commonly used to control grasses and some broadleaf weeds after acorns have germinated and seedlings are actively growing include clethodim and clopyralid (Cunningham et al. 2019).

Rabbit damage to young bottomland oak plantations is also frequently curbed through legal hunting. Rabbit hunting with beagle hounds is deeply rooted in tradition of the southern US and is a lawful and effective means for controlling rabbit population size and damage to seedlings. Areas of forest restoration on state and federal lands are usually open to the public for rabbit hunting because these lands are generally managed by a wildlife agency of the respective owner. On private property, landowners noting significant rabbit damage on their restoration areas will often invite local hunting groups to assist with control of the population.

4 Seed procurement and preparation

Acorn procurement and preparation for sowing is a critically important, active process for ensuring successful initiation of the restoration project. Procuring quality bottomland oak acorns begins with locating reproductive-aged stands of the appropriate species local to the afforestation site because few orchards for seed production exist and seed movement protocols for the future climate have not been developed. Reproductively mature bottomland oaks hold the potential to flower and produce acorns every year. For species in the section Quercus, flowering occurs in the spring and acorns complete maturation in the fall. In contrast, acorn development is suspended after pollination in the section Lobatae*,* and maturation is completed during the fall of the succeeding year. Seed collecting occurs when mature acorns are shed from the tree during the fall and early winter months—shedding varies by species within this period, which will determine when acorns of a given species can be harvested (Table

3). Heavy masting varies considerably in frequency and occurrence among species (Table 3), and its unpredictable nature often leads to limited seed availability from local stands.

Table 3. Masting and shedding characteristics of 10 oak species common to bottomlands of the southern US.

Species	Masting frequency[1] (years between heavy masting)	Acorn shedding period[2] (month)				
		Sept.	Oct.	Nov.	Dec.	Jan.
Section Quercus						
Overcup oak (*Q. lyrata* Walter)	3–4	XXXX	XXXXXXXXX			
Swamp chestnut oak (*Q. michauxii* Walter)	3–5	XXX	XXXXXXXXX			
White oak (*Q. alba* L.)	4–10	XXX	XXXXXXXXX			
Section Lobatae						
Cherrybark oak (*Q. pagoda* Raf.)	1–2		XXXX	XXXXXXXXXX	XX	
Nuttall oak (*Q. texana* Buckley)	3–4			XXXXXX	XXXXXXXX	XX
Pin oak (*Q. palustris* Münchh.)	1–2		XXXX	XXXXXXXXXX	XX	
Water oak (*Q. nigra* L.)	1–2		XXXX	XXXXXXXXXX	XX	
Willow oak (*Q. phellos* L.)	1		XXXX	XXXXXXXXXX	XX	
Shumard oak (*Q. shumardii* Buckley)	2–3		XXXX	XXXXXXXXXX	XX	
Swamp laurel oak (*Q. laurifolia* Michaux)	1		XXXX	XXXXXXXXXX	XX	

[1] Bonner (2008).

[2] Based on masting information noted in Burns and Honkala (1990) and unpublished observations of the authors.

Acorns are usually collected beneath fecund trees in bottomland oak stands by raking the nuts into piles that can be easily bagged and transported. Before raking begins, the collector should, using a small knife, cut open a small (about 10) sample of acorns to check for general condition, insect damage, and apparent viability. If the acorns appear in good quality, leaf litter is removed from the immediate area with hand-held leaf blowers, and heavier branches and other debris are moved off site. After raking the nuts into small piles, winnowing the piles with a rake and leaf blower helps remove acorn caps and other small debris before bagging and transporting the acorns to the processing and storage facility.

Upon arrival at the processing facility, the freshly collected acorns should be "float-tested" or plunged in clean water. Float-testing provides a simple technique for: separating insect damaged and desiccated nuts from the lot, cleaning fine debris and soil from the lot, and hydrating the nuts for storage. Because bottomland oak acorns are recalcitrant (i.e., they do not survive drying and freezing), they must maintain a sufficient moisture content (about 45–50% for section Quercus and 30% for section Lobatae) to retain viability in storage (Bonner and Vozzo 1987). To ensure complete hydration, the nuts should remain submerged in cool water overnight. If collections are made under wet or muddy field conditions, occasional stirring and water changes help clean the nuts for storage. Float-testing is not useful for separating sound from unsound nuts of overcup oak. The acorn of this species has a persistent cap that nearly encases the entire nut, and a corky layer surrounding the kernel that gives the acorn buoyancy—this acorn buoyancy is an adaptation that facilitates hydrochory in bottomland habitats. Still, the storage moisture status of overcup oak acorns is benefited by soaking them in clean water overnight.

Cleaned and adequately hydrated acorns should be removed from water and kept in a cool area for enough time to allow surface water to evaporate from the nuts before placing into cold storage. Refrigerated storage (1 to 3 °C) in polyethylene bags (≤ 10-mil thickness) has proven best for moderating metabolism and providing adequate gas exchange for acorns of both sections (Bonner and Vozzo 1987). Due to their recalcitrance, bottomland oak acorns do not retain viability through extended storage. In practicality, acorns of most species in the section Quercus will store for no more than 6 months, while acorns of most species in the section Lobatae will store for up to a year without substantial loss in viability (but see Bonner and Vozzo 1987). Maintaining gas exchange and moisture content are critical for retaining acorn viability during storage, so additional soaking may be required to maintain moisture status during extended storage.

Acorns of bottomland oak species in the section Quercus exhibit weak to no dormancy, often initiating germination and showing radicle extension under favorable environmental conditions soon after they shed from the tree. Acorns of species in the section Lobatae typically show a weak dormancy that is broken with 4 to 8 weeks of cold storage (Bonner and Vozzo 1987). Germination during storage is common among acorns of both sections. This does not usually reduce seedling vigor so long as radicle extension is not too advanced, but progress of mechanical sowing activities is hindered when lengthy radicles obstruct sowing machinery. Lastly, overnight soaking in cool water is an important final preparation for sowing—it replaces moisture loss during storage ensuring acorns are fully hydrated for the field environment.

5 Plantation establishment

5.1 Plantation design

As previously mentioned, the various bottomland oaks show a stratified distribution among sites common to floodplains of the southern US (Table 1). Well-designed plantations are intended to target the natural occurrence of species characteristic of the floodplain sites represented at the restoration area. This usually includes other bottomland tree species occurring in association with bottomland oaks. In designing the plantation, the restoration manager would select the most site-appropriate species mixtures for the occurrence of site types and associated soils at the area. For example, if sites on the restoration area were sloughs, low flats, and ridges, the slough sites would receive overcup oak, low flats would receive Nuttall oak (*Q. texana* Buckley) and ridges would receive cherrybark oak (*Q. pagoda* Raf.), swamp chestnut oak (*Q. michauxii* Walter) and water oak (*Q. nigra* L.).

Sowing densities for regenerating bottomland oak stands are generally based on a targeted stem density weighted by the expected germination and early seedling survival for a given species and site. While germination and first-year survival for most bottomland oaks on their respective sites can exceed well over 50%, second year mortality is usually high, and the manager can expect about 15 to 20% survival and establishment after year 2 (Table 4). Nuttall oak is a notable exception, often averaging about 30% germination and seedling survival though year 2. Expected survival and establishment will be lower on unusually harsh sites, for example, those subject to atypical flooding in the growing season or those extremely degraded from past cultural practices.

Table 4. Acorn sowing characteristics for 10 oak species common to bottomlands of the southern US.

Species	Nut length[1] (mm)	Number per kg[2]	Sowing depth[3] (cm)	Sowing season[4] (month)	Expected year 2 establishment[5] (%)
			Section Quercus		
Overcup oak (*Q. lyrata* Walter)	12–25	285–340	5–10	October–June	10–20
Swamp chestnut oak (*Q. michauxii* Walter)	19–38	75–430	5–10	October–March	10–20
White oak (*Q. alba* L.)	19–25	155–465	5–10	October–March	10–20
			Section Lobatae		
Cherrybark oak (*Q. pagoda* Raf.)	10–15	925–1640	3–7.5	November–March	15–25
Nuttall oak (*Q. texana* Buckley)	19–31	125–315	5–10	November–June	25–35
Pin oak (*Q. palustris* Münchh.)	9–13	705–1190	3–7.5	November–June	15–25
Water oak (*Q. nigra* L.)	8–16	510–1545	3–7.5	November–April	15–25
Willow oak (*Q. phellos* L.)	10–15	600–1530	3–7.5	November–April	15–25
Shumard oak (*Q. shumardii* Buckley)	19–25	170–280	5–10	November–March	15–25
Swamp laurel oak (*Q. laurifolia* Michaux)	10–12	860–1520	3–7.5	November–June	15–25

[1] Information from Vines (1960) adapted to include unpublished observations of the authors.
[2] Information from Bonner (2008) adapted to include unpublished observations of the authors.
[3] The range in recommended sowing depth is based on seed size, Johnson (1981), Johnson (1983), Gardiner et al. (2004), and unpublished observations of the authors.
[4] Sowing for all bottomland oaks will usually occur between December and March but all species can be sown as early as November to avoid storing seed if soil on the area is sufficiently moist. If the restoration area is inundated by floodwater, sowing can be delayed into late spring or early summer depending on species and the floodplain site it naturally occupies, i.e. sowing date can be delayed greatest for species of lowest sites.
[5] Based on information in Johnson (1983), Miwa et al. (1993), Gardiner et al. (2004), and unpublished observations of the authors.

Afforestation of former agricultural land largely results in single cohort stands, i.e., seeding for a stand occurs at one time. On sites where establishment of multiple oak species is appropriate, acorns are mixed prior to sowing in proportion to the desired establishment density of each species. It should be noted that practices for seeding bottomland tree species other than the oaks are not well developed; exceptions include for the species sweet pecan (*Carya illinoensis* (Wangenh.) K.Koch) and common persimmon (*Diospyros virginiana* L.). This lack of applied knowledge often leads the restoration manager to rely on planting seedlings rather than seeding to restore tree cover because achieving the high species diversity characteristic of natural stands is usually an objective when restoring bottomland hardwood forests.

Interplanting a fast-growing pioneer species, eastern cottonwood, with bottomland oaks is an alternative plantation design that has gained use in the LMAV over the last two decades (Gardiner et al. 2004). Those using this approach on restoration sites typically interplant established eastern cottonwood with bottomland oak bareroot seedlings. However, seeding oaks could readily replace planting bareroot seedlings as a lower-cost approach, and this approach has been successfully demonstrated in Europe where oaks and beech (*Fagus sylvatica* L.) have been sown under established poplar (*Populus* spp. L.) cultivars.

5.2 Sowing practices

The acorn sowing season in the southern US is usually December through early March. Nevertheless, sowing species of the section Quercus can be initiated much earlier—storage can be avoided, and acorns sown as soon as they are collected if soil moisture availability on the restoration area is high. Seeding by hand and tractor-drawn seeding machines have demonstrated equal success in sowing acorns of bottomland oaks. Regardless of method, the targeted sowing depth ranges between 3 and 10 cm. Relatively small acorns are usually sown on the shallow end of the depth range and relatively large acorns are sown towards the deeper end (Table 4). Field crews sowing bottomland oak acorns by hand often use a 2 to 2.5 cm diameter rod sharpened to a blunt cone on one end for forming the seeding hole. An acorn is dropped into the hole and the crew member covers it by stomping around the hole with a boot heel. Despite the fact that it is labor intensive, hand sowing is advantageous on bottomland sites too wet to be trafficked by heavy machinery. Seeding with machines has traditionally been conducted with row crop seed planters modified to dispense seed as large as an acorn. When conditions are favorable in the restoration area, machine sowing can be quite fast, especially if multiple seed planters are attached to an implement tool bar to allow for sowing several rows with each pass of the tractor.

Practices to protect sown acorns from rodent depredation are typically not used on restoration sites in the southern US. Previously stated recommendations for site preparation and early season vegetation control are usually sufficient for temporarily reducing rodent habitat and minimizing seed losses due to depredation. An exception to this generality is where the restoration area borders existing forests or fallow fields. In such situations, the restoration manager will want to plan for protecting seed sown adjacent to the existing forest or fallow field edge, e.g., cultivating soil to temporarily reduce vegetative cover and animal movement between the restoration area and adjacent habitat.

6 Post-sowing practices and maintenance

Few post-sowing practices are used to improve establishment and early growth or protect bottomland oak plantations in the southern US. This is largely because plantation establishment and early maintenance are usually conducted as low intensity operations to minimize costs. However, competition control that targets herbaceous broadleaves and grasses during the first growing season can be beneficial to early growth and improve establishment of the recently sown plantation. Applications of a broad-spectrum tank mix of herbicides labeled for use in oak plantations can be used to reduce aggressive weeds that are ever present on former agricultural land, and such practices can also retard development of rodent habitat while seedlings are most vulnerable to damage (see previous discussion).

The restoration manager should consider a few practices to protect the young plantation from external threats, especially where the restoration area is adjacent to current agriculture. Conventional agricultural practices in the southern US typically include aerial application of broadleaf herbicides. It is prudent for the restoration manager to communicate details of the forest restoration project with adjacent farmers and local aerial applicators to ensure necessary precautions are taken to prevent herbicide drift onto the restoration area. Also, it is common practice in the southern US to burn agricultural fields in the fall following the harvest of crops. Former agricultural fields that have been afforested are ideal for supporting dense growth of grasses and herbaceous vegetation that is readily flammable in the dry months of fall. Thus, protecting plantations from fire during this season, by maintaining appropriately located firebreaks, can prevent damage or loss of young bottomland oak stands.

7 Successful seeding

7.1 Defining success

Because the financial driver of forest restoration in bottomlands has historically been the singular impetus of removing land from agricultural production, success with seeding of bottomland oaks on former agricultural fields has simply been defined in respect to stand establishment and early growth. In practice, managers usually schedule inventory of seedling establishment and growth late in the third growing season after sowing. Small circular plots or linear row plots established systematically across the restoration area and stratified by soil series or site type are conventionally used to sample the restoration area. Circular plots are used if the manager samples seeded oaks plus other volunteer reproduction, while row plots that straddle sown rows are used if the manager is only concerned with sampling seeded oaks. A minimum threshold stand density for success is often arbitrary and may or may not include density of volunteer reproduction. Likewise, a minimum threshold for seedling or sapling growth is also arbitrary but should factor expected site productivity and status of competing vegetation. On average, year 3 densities of about 500 to 550 oak seedlings per ha, of sufficient vigor to out-grow adjacent competing vegetation, and well distributed across the area will be sufficient to mark success for most bottomland oak seeding objectives. Threshold densities for bottomland oak establishment would be reduced where volunteer reproduction of other native tree species, e.g., sweetgum, green ash, eastern cottonwood, common persimmon, and red maple (*Acer rubrum* L.), has established (Figure 7).

Figure 7. Stand of Nuttall oak (*Q. texana* Buckley) showing establishment and development 10 years after seeding the restoration site in Sharkey County, Mississippi USA. Oaks are the prominent vegetation in the image but other tree and shrub species that seed in naturally can be seen in the foreground (Photo credits: Emile Gardiner).

Over time, landowners and restoration program managers have begun to assess other metrics of restoration success, particularly where restoration is applied for specific environmental technologies or ecosystem services. For example, afforestation is a key nature-based tool for mitigating CO_2 emissions, so many bottomland forest restoration projects are now motivated by carbon sequestration and storage (Shoch et al. 2009). In these situations, managers may assess the short-term success of stand establishment but also assess the success of carbon sequestration and storage through verification of carbon stocks development over decades.

7.2 Factors that limit success and impose risks

Numerous factors have been associated with poor success of seeding bottomland oaks on former agricultural land, all which challenge attainment of sufficient seedling stocking on the restoration area. Poor seedling stocking often stems from sowing inferior quality seed which includes seed that lacks viability and seed originating from an inappropriate genetic source. Viability may be compromised prior to collection if microsite conditions around the parent tree are deleterious to the shed acorns, e.g., insufficient moisture in the litter layer. Seed quality, or acorn viability, can also be compromised through poor storage and handling practices. During storage, desiccation, rotting, or excessive premature germination will decrease viability and vigor when acorns are stored too long, too dry, too wet, or too warm. Allowing acorns to dry excessively or overheat during transport to the field or in the field prior to sowing will also reduce viability. Seed from an inappropriate genetic source includes acorns sourced too distant from the restoration site or those sourced from upland ecotypes of bottomland oak species. Acorns collected too distant from the restoration site may potentially express a germination or seedling phenology that jeopardizes survival of the sprouting seed, e.g., increased risk of frost damage. Seedlings produced from acorns collected from upland ecotypes of bottomland oaks, especially cherrybark oak, water oak, and white oak (*Q. alba* L.), may lack an inherent ability to tolerate soil flooding in bottomlands. Unfortunately, the hazards of sourcing inappropriate seed may not be revealed through establishment success or early stand performance but through other chronic issues like poor root architecture that renders trees susceptible to wind throw, or canopy dieback that decreases tree vigor and increases susceptibility to pests and disease later in the life of the stand.

Experience indicates that quality seed will typically not mitigate the risks of a poor sowing job. Sowing quality seed off-site, which can result from misguided species assignments or erroneous implementation of the seeding plan, will limit seedling establishment and early growth due to poor adaptability of the seed to the site on which it was sown. Likewise, sowing acorns too deep or too shallow reduces the probability for high establishment success, as does sowing a site that has not received adequate site preparation or post-sowing vegetation control. Managers often report spatially heterogenous or "patchy" stocking of bottomland oaks on seeded sites—this establishment result may not be due to a single cause on all sites but likely stems from a combination of multiple issues mentioned above.

Factors imparting risks that are less predictable and difficult to moderate are associated with local weather patterns during the establishment year. These include heavy rainfall that inundates the restoration area or waterlogs soil at a vulnerable time for newly sprouted seedlings, and a lengthy period of droughty conditions during the establishment year. Such weather or climatic events that produce extremes on each end of the hydrologic gradient will increase seedling mortality and can potentially lead to complete failure in stand establishment. Such extreme events could increase in frequency under future climatic conditions (Cai et al. 2014).

7.3 Elements that contribute to success

Success with seeding bottomland oaks begins with sound formulation of the restoration plan (Figure 8). Because alluvial bottomlands inherently show great spatial heterogeneity of site and soil conditions, the plan should be founded on thorough evaluation and detailed mapping of the topographic features, soil series, soil degradation, flooding frequency, water holding and drainage structures, and vegetation occurring on the restoration area. Compiling, organizing, and mapping such comprehensive information on the area enables the manager to make appropriate species assignments, prescribe site preparation treatments, establish sowing densities, anticipate seed depredation and herbivory, and prepare for other situations that might arise from degraded conditions of the site.

Committed implementation of the restoration plan is equally important to the success of bottomland oak seeding as formulating the plan. Securing quality seed, adequate preparation of the area for sowing, use of sound seed handling and sowing procedures, effective application of post-sowing treatments and practices, and timely monitoring of stand establishment and environmental conditions at the restoration area all contribute to purposeful implementation of the restoration plan. The likelihood of achieving committed implementation of the restoration plan is high when it is entrusted to a competent and dedicated restoration manager.

Figure 8. Closed-canopy stand of Nuttall oak (*Q. texana* Buckley) showing development 29 years after seeding the restoration site in Sharkey County, Mississippi USA. Notice the significant component of vines that provide natural structure to the stand. This is the same stand pictured in Figure 7 nineteen years later (Photo credits: Emile Gardiner).

In addition to sound formulation and committed implementation of the restoration plan, certain conditions relative to the restoration area can also contribute to success in restoring bottomland oak forests through seeding. Seeding success is often best on restoration areas where there is a high probability that light seeded tree species will contribute volunteer reproduction. This is because bottomland oak stands tend to develop a healthy and resilient structure when the oaks comprise a fraction (≤ 50%) of the overstory composition. On restoration areas seeded exclusively with bottomland oaks, species rich overstories tend to develop if the area is relatively small, adjacent to natural forest, and has received site preparation that conditions the seedbed for capture and germination of light seeded species. Conversely, large restoration areas distant from seed sources for other tree species may be captured by herbaceous species and vines.

Similarly, assigning more than one oak species and section to sites or soils that are naturally suitable for multiple oaks is often important to success. Sowing multiple oaks on a site could buffer against risks associated with a single species, e.g., poor quality seed or inappropriate seed source that impacts germination and establishment. In this respect, seeding species of both bottomland oak sections (Lobatae and Quercus) adds diversity in factors like germination dynamics, rate of seedling growth, and shade tolerance which should ultimately benefit stand composition.

8 Conclusion

In summary, the rich forests native to river bottoms of the southern US have experienced persistent and wide-scale loss and degradation since the 1700s, due mostly to deforestation for agriculture. The most recent decades, however, have brought efficiencies in agriculture and a growing awareness of the environmental and ecological values of these systems, and this has prompted considerable forest restoration. Development of techniques and practices to seed bottomland oaks coalesced in the early 1980s prior to broad implementation of afforestation to restore bottomland oak forests across the region. While the early seeding techniques and practices have been refined for large-scale application to degraded sites, the biological and ecological foundations of seeding bottomland oaks have endured over time. These have given rise to several silvicultural principles for seeding bottomland oaks including matching oak species to appropriate sites, procuring quality seed, practicing sound seed handling and sowing, sowing multi-species mixtures where possible, and monitoring conditions and stand development across the restoration area. Adherence to these principles through development and implementation of the restoration plan reduces risks and bolsters success of seeding to restore bottomland oak forests of the southern US.

9 Acknowledgement

The article is an activity within the work of IUFRO Task Force "Transforming Forest Landscapes for Future Climates and Human Well-Being." We thank the editors and two anonymous reviewers for helpful suggestions.

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