RESTORATION OF BOREAL AND TEMPERATE FORESTS

Edited by

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CRC PRESS

Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Restoration of boreal and temperate forests / edited by John A. Stanturf, Palle Madsen.
p. cm. — (Integrative studies in water management & land development ; 3)
Includes bibliographical references and index.
ISBN 1-56670-635-1
1. Reforestation. 2. Afforestation. 3. Forest ecology. 4. Restoration ecology. I. Stanturf, John A. II. Madsen, Palle. III. Integrative studies in water management and land development ; 3.

SD409.R485 2004
634.9'56—dc22 2004055355

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International Standard Book Number 1-56670-635-1
Library of Congress Card Number 2004055355
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

chapter thirty-two

Restoring longleaf pine forest ecosystems in the southern U.S.

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32.1 Southern forest environment

Longleaf pine (*Pinus palustris*) ecosystems are native to nine states of the southern region of the U.S. Longleaf pine can grow on a variety of site types including wet flatwoods and savannas along the Atlantic and Gulf coastal plain, higher droughty sand deposits from the fall line sandhills to the central ridge of Florida (Stout and Marion 1993), and the montane slopes and ridges of Alabama and northwest Georgia up to 600 m elevation (Boyer 1990b). This region has a humid subtropical climate (Bailey 1995). Maximum July temperatures average 29°C to > 35°C while minima during January range from 0 to 13°C. The mean annual precipitation is 1,040 to 1,750 mm and is well distributed through the year. The growing season is comparatively long, ranging from 300+ days in Florida to 220 days along the northern limit of longleaf. During the late summer and fall, hurricanes can develop over the Atlantic Ocean, move westward, and impact coastal plain forests. Such tropical storms are one of the principal large-scale disturbance agents for longleaf pine forests growing near the seacoast.

Longleaf pine grows on soils derived from marine sediments ranging from deep, coarse, excessively drained sands to finer textured clays (Boyer 1990b). Entisols and Spodosols, two of the major orders occupied by longleaf, are generally sandy, acidic, low in organic matter, and relatively infertile. Quartzipsamments, the most prevalent Entisol on xeric sandhills, are deep sands with weak horizon development. Spodosols, principally Aquods, are found on lower coastal plain flatwoods. These are wet sandy soils with a shallow water table that is at or near the ground surface during the rainy season. Longleaf pine is also found on more fertile clay soils (Ultisols) such as the red hills region of southern Georgia. Typic Paleudults and Plinthic Paleudults are the Ultisols most frequently supporting longleaf pine.

32.2 Longleaf pine ecology

32.2.1 Longleaf pine ecosystems

Longleaf pine forests were once among the most extensive ecosystems in North America (Landers et al. 1995). Prior to European settlement, these forests occupied ~38 million ha in the southeastern U.S. (Frost 1993). Travelers in this region during the late 18th and early 19th centuries reported vast areas of longleaf pine that sometimes covered >90% of the landscape (Bartram 1791; Williams 1837). The native range of longleaf pine (Figure 32.1) encompasses an area along the Gulf and Atlantic Coastal Plains from Texas to Virginia, extending well into central Florida and the Piedmont and mountains of northern Alabama and northwest Georgia (Boyer 1990b; Stout and Marion 1993).

An open, park-like stand structure (Figure 32.2) is a distinguishing characteristic of longleaf pine ecosystems (Schwarz 1907; Wahlenberg 1946). Naturally occurring longleaf pine forests contain numerous embedded special habitats such as stream bottoms, wetlands, and seeps (Brockway and Outcalt 1998; Hilton 1999; Platt and Rathbun 1993). In the western Gulf Coastal Plain, bluestem grasses (*Schizachyrium scoparium* and *Andropogon* spp.) dominate longleaf pine understories. From Florida north and eastward, longleaf pine typically is associated with wiregrass (*Aristida stricta* and *Aristida beyrichiana*), also known as pineland threeawn. Fallen pine needles and understory grasses facilitate the ignition and spread of fire, which limits woody shrubs and hardwood trees (Landers 1991). While such woody plants may be more numerous on mesic sites, their stature is typically limited by frequent burning.

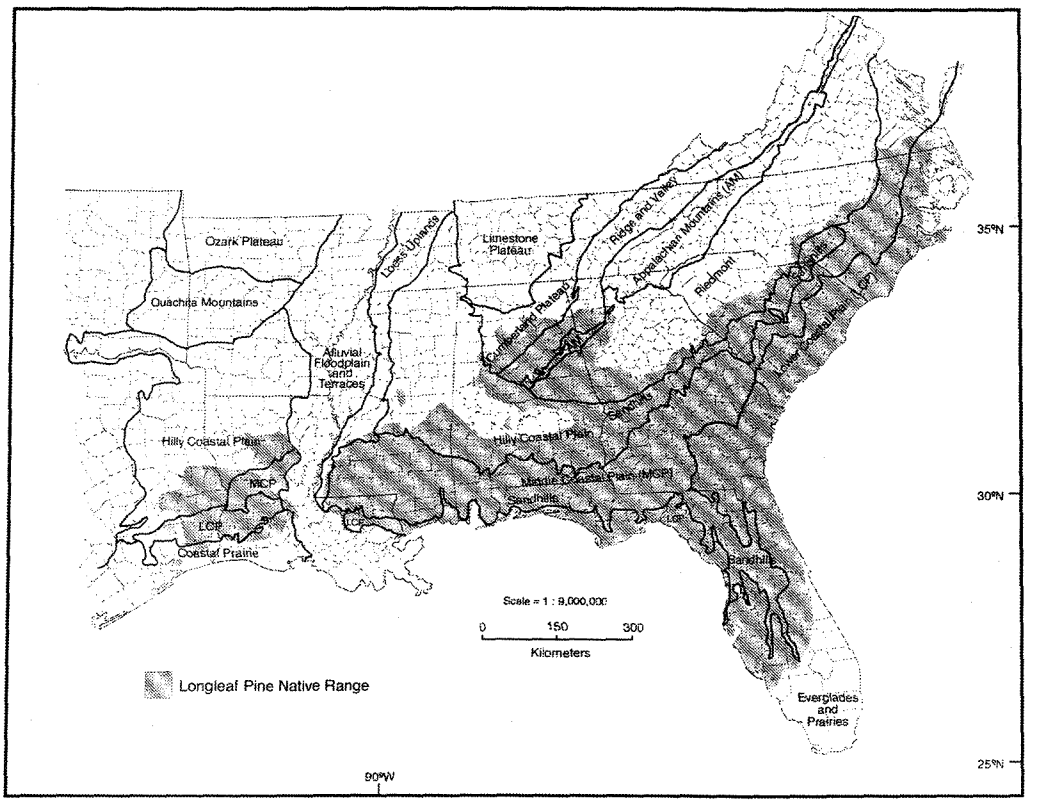

Figure 32.1 Native range of longleaf pine and physiographic provinces of the southeastern U.S. (Little 1971; Miller and Robinson 1995).

Figure 32.2 Longleaf pine bunchgrass ecosystem on xeric sandhills.

At various locations within the native range, *Quercus, Ilex,* and *Serenoa* may be common tree and shrub associates. Longleaf pine ecosystems support a great variety of herbaceous plant species. The high diversity of understory plants per unit area makes these ecosystems among the most species-rich plant communities outside the tropics (Peet and Allard 1993).

Longleaf pine is closely associated with frequent surface fires (Brockway and Lewis 1997; Garren 1943; Outcalt 2000). Longleaf pine and bunchgrasses function together as keystone species that facilitate but are resistant to fire (Noss 1989; Platt et al. 1988b). Their longevity and nutrient and water retention ability reinforce their site dominance and minimize change in the plant community following disturbance (Landers et al. 1995). The long and highly flammable needles of longleaf pine together with the living and dead leaves of bunchgrasses constitute a fine-fuel matrix that facilitates the rapid spread of fire (Abrahamson and Hartnett 1990; Landers 1991).

Prior to landscape fragmentation, natural fires occurred every 2 to 8 years throughout much of the region (Abrahamson and Hartnett 1990; Christensen 1981). Longleaf pine dominated this large expanse primarily because it tolerates frequent fire better than seedlings of thinner-barked competitors. Longleaf pine seedlings are susceptible to fire-caused mortality during the first year following germination, but they become increasingly resistant to fire in subsequent years. A unique adaptation of longleaf pine to a fire-prone environment is a seedling "grass stage," during which root growth is favored and the seedling top remains a tuft of needles surrounding and protecting a large terminal bud. The lack of a stem limits exposure to damage from surface fires. When sufficient root reserves have accumulated, grass stage longleaf pine seedlings "bolt" by rapidly growing 1 to 2 m in a short time period, putting their terminal bud beyond the lethal reach of most surface fires. Larger longleaf pine trees have a thick bark that protects cambial tissue from the lethal heating of surface fires (Wahlenberg 1946). Fires assist in the natural pruning of longleaf pine, creating a clear bole between the crown and any accumulated surface fuels. Surface fires are thereby prevented from easily moving into the canopy. Longleaf pine also tends to regenerate more successfully in forest openings than directly beneath mature trees (Brockway and Outcalt 1998), thus keeping ladder fuels away from the crowns of adult trees.

Longleaf pine evolved in an environment influenced by frequent disturbance, principally fire (Engstrom et al. 2001; Palik and Pederson 1996). Damaging tropical storms, such as hurricanes and associated tornadoes, may fell trees over an extensive area and open gaps in the canopy of longleaf pine forests (Croker 1987). Lightning is another important disturbance agent, typically killing individual trees but occasionally striking small groups of trees (Komarek 1968; Palik and Pederson 1996; Taylor 1974). Insect infestations are uncommon; however, annosus root rot (*Heterobasidion annosum*), pitch canker (*Fusarium moniliforme* var. *subglutinans*), and cone rust (*Cronartium strobilinum*) are among the pathogens that may infect longleaf pine (Boyer 1990b). Epidemics of brown-spot disease (*Mycosphaerella dearnessii*) occasionally occur in young longleaf pines; this pathogen is usually fatal unless a surface fire consumes infected needles and cleanses the stand of inoculum (Boyer 1990b).

Longleaf pine is a shade-intolerant tree species and regenerates naturally only in canopy gaps (Wahlenberg 1946). Seedlings developing in gaps at different times result in a network of forest patches at various stages of development dispersed across the landscape (Pickett and White 1985). Such gap-phase regeneration dynamics produce a forest structure commonly observed in natural longleaf pine ecosystems of even-aged patches distributed within an uneven-aged mosaic (Palik et al. 1997).

32.2.2 *Ecological significance*

The complex natural pattern and disturbance-mediated processes of longleaf pine forests cause extraordinarily high levels of biological diversity in these ecosystems, with as many as 140 species of vascular plants in a 1,000 m^2 area. Counts of more than 40 species per m^2 have

Figure 32.3 Former longleaf pine site invaded and occupied by oak.

been recorded in many longleaf pine communities (Peet and Allard 1993). A large number of these plant species are restricted to, or found principally in, longleaf pine habitats. Not surprisingly, many animal species also depend on longleaf pine ecosystems for much of their habitat, including two increasingly rare animals that are important primary excavators. Tree cavities created by red-cockaded woodpeckers (*Picoides borealis*) and ground burrows dug by gopher tortoises (*Gopherus polyphemus*) provide homes for a variety of secondary users such as insects, snakes, birds, and mammals (Engstrom 2001; Jackson and Milstrey 1989).

The longleaf pine forests and savannas of the southeastern coastal plain are among the most critically endangered natural ecosystems in the U.S., now occupying less than 3% of their original extent (Noss et al. 1995; Ware et al. 1993). Extreme habitat reduction is the primary cause for increasing rarity of 191 taxa of vascular plants and several terrestrial vertebrate species that are endemic to or exist largely in longleaf pine communities (Hardin and White 1989; Walker 1993). Habitat loss principally has resulted from conversion of longleaf pine forests to other land uses (i.e., agriculture, industrial pine plantations, and urban development), landscape fragmentation, and interruption of natural fire regimes (Landers et al. 1995; Wear and Greis 2002). Long-term suppression of fire typically depresses species diversity, and a substantial hardwood understory and midstory develops a thick layer of forest litter (Brockway and Lewis 1997; Kush and Meldahl 2000) (Figure 32.3). Such extraordinary buildup of forest fuel poses a serious wildfire hazard and, rather than naturally occurring surface fires, crown fires with potentially catastrophic effects on rare plants and animals are likely. Safe and effective reintroduction of fire into long-unburned forests remains the critical conservation challenge (Wear and Greis 2002).

Longleaf pine bunchgrass ecosystems are also vital to the maintenance of numerous biotic communities embedded within the southern forest landscape matrix (Landers et al. 1990). Many of these adjacent communities require periodic fire to maintain their ecological structure and health (Kirkman et al. 1998). Wildfires typically begin in longleaf pine forests and spread into adjoining habitats such as seepage slopes, canebrakes, treeless savannas, and sand pine scrub. Without periodic fire, these communities also change in ways that make them less suitable habitats for other fire-adapted plants and animals.

32.3 *History of longleaf pine ecosystems*

Longleaf pine, moving northward and eastward from its ice age refugia in southern Texas or northern Mexico (Schmidtling and Hipkins 1998), established in the lower coastal plain ~8,000 years ago (Watts et al. 1992) and during the ensuing 4,000 years spread throughout

the southeast (Delcourt and Delcourt 1987). Interestingly, this time period coincided with increased population levels of Native Americans throughout the region; their use of fire is thought to be related to the spread of longleaf pine forests (Landers and Boyer 1999; Pyne 1997; Schwartz 1994). Native Americans frequently used fire to manipulate their environment (Anderson 1996; Carroll et al. 2002; Robbins and Myers 1992; Stanturf et al. 2002). Recognizing the benefits of fire on the landscape, early European settlers adopted the practice of periodically burning nearby forests and woodlands to improve forage quality for cattle grazing and discouraged the encroachment of shrubby undergrowth.

European settlement had little impact on longleaf pine forests initially, with harvesting limited to areas near towns and villages for building log structures (Croker 1987). By the 1700s, water-powered sawmills became common, but log transportation was inefficient and remained confined to rivers (Frost 1993). After 1830, removal of the longleaf pine resource accelerated with the arrival of steam railroads, and was quickly followed by steam skidders. By 1880, most of the longleaf pine forests along streams and railroads had been harvested (Frost 1993). During the next 40 years, the great forests of longleaf and other southern pines were harvested, with temporary railroad spur lines laid down every quarter mile (Croker 1987). Timber extraction peaked in 1907, when 39 million m^3 were removed (Wahlenberg 1946). By 1930, nearly all old-growth longleaf pine was harvested and lumber companies migrated west.

Although well adapted to frequent disturbance from surface fires, longleaf pine was not well suited to disturbances brought by European settlement. As a result of cumulative impacts over three centuries of changing landuse, longleaf pine forests declined dramatically. By 1900, logging, extraction for naval stores, and agriculture had reduced the area dominated by longleaf pine by more than half (Frost 1993). Second-growth longleaf pine stands became established on only one third of the sites previously occupied (Wahlenberg 1946). Harvest of these second-growth stands, often followed by conversion to other southern pines or urban development, continued through 1985 (Kelly and Bechtold 1990) until longleaf pine was reduced to less than 5% of its original area (Outcalt and Sheffield 1996).

32.4 Social and political context

Longleaf pine ecosystems have provided raw materials for economic development in the southern U.S. Wild game, forage grasses, wood, and naval stores (chemicals derived from pine resin) were the principal products of these forests (Franklin 1997). During the early 20th century, affluent landowners recognized the value of longleaf pine forests as habitat for bobwhite quail (*Colinus virginianus*) and white-tailed deer (*Odocoileus virginianus*) and acquired large tracts for private hunting reserves. Many large areas of longleaf pine exist today only because of the opportunities they provided for hunting and timber harvest. Nevertheless, economic exploitation has played a major role in the decline of these forests. Recent developments provide hope that these negative trends may be reversed. Conversion of longleaf pine to other tree species has slowed, as numerous federal and state agencies have begun regenerating longleaf pine on their lands following harvest, and they rehabilitate degraded longleaf pine forests with fire and other appropriate techniques (Hilliard 1998; McMahon et al. 1998). Interest in longleaf pine reforestation and afforestation has increased on private lands because of incentives provided by the federal government; from 1998 to 2000, longleaf pine was planted on 68,240 ha across the region.

The southern forestry community has also gained an improved understanding of longleaf pine ecosystems and has come to appreciate the natural heritage that could be lost. No single entity dominates landownership in longleaf pine ecosystems but numerous groups share a sense of urgency, and partnerships have developed. The Nature

Conservancy, Tall Timbers Research Station, Joseph W. Jones Ecological Research Center, USDA Forest Service, USDI Fish and Wildlife Service, U.S. Department of Defense, Cooperative Extension Service, state agencies, private landowners, universities, and forest industry now work together to promote longleaf pine ecosystem restoration. In 1995, the Longleaf Alliance was formed to serve as a regional clearinghouse for a broad range of information on the regeneration, restoration, and management of longleaf pine ecosystems. The Alliance is housed at Auburn University in Alabama and facilitates communication among these groups and provides training for private landowners concerning successful longleaf pine regeneration.

32.5 Restoration perspectives

Longleaf pine still occurs over most of its natural range, albeit in isolated fragments; thus, restoration is feasible (Landers et al. 1995). Restoration to historical authenticity may not be desirable or even possible, but natural authenticity is a reasonable goal, meaning that compositional, structural, and functional components are present within an appropriate physical environment. Thus, ecological processes can be sustained in restored longleaf pine ecosystems, providing for native species perpetuation and evolution, ecosystem resiliency to disturbance and adaptation to long-term environmental change, goods and services for human societies, and safe harbors for rare and endangered species (Clewell 2000).

Because natural longleaf pine forest ecosystems are so variable, the range of conditions that fall within natural variability are correspondingly broad. Overall, full restoration would mean an overstory dominated by longleaf pine, occurring as uneven-aged stands or even-aged patches across an uneven-aged landscape mosaic. Depending on site type and location within the native range, a lesser component of other tree species may be present, such as slash pine (*Pinus elliottii*) or oaks, which may occur singly or in clusters. The midstory should generally be absent or mostly composed of ascending longleaf pines. Native grasses and forbs should dominate the understory, with lesser cover of shrubs and vines. Long-term ecosystem recovery and sustainability will be fostered by properly functioning ecological processes such as periodic surface fires, natural regeneration that leads to normal stand replacement dynamics, nutrient cycling that maintains primary productivity, and suitable habitat that facilitates life cycle completion by numerous native organisms. Augmenting existing longleaf pine fragments and creating new connecting habitat patches will achieve reductions in habitat fragmentation, population isolation, and species rarity.

32.6 Restoration methods

32.6.1 Restoration framework

Despite a wealth of knowledge and experience concerning longleaf pine restoration, much uncertainty still exists, fostering a healthy debate about the best approaches. Desirable changes in longleaf pine communities can be achieved by using a variety of methods, machines, and products, either singly or in combination. Prescribed fire may be used to reduce midstory, understory, and occasionally overstory layers and encourage fire-tolerant plants. Because frequent fire is crucial for ecosystem restoration, other treatments should be planned to facilitate the eventual application of prescribed fire. Physical or mechanical treatments include complete overstory harvest, selective thinning of overstory and midstory trees, and shredding or mowing midstory and understory plant layers. Chemical treatments, principally herbicide application, can be used to selectively induce mortality of undesirable plant groups. In highly degraded ecosystems, biological approaches such as reintroducing extirpated species will likely be required for full restoration.

32.6.2 Selecting techniques

Historical events and changing landuse provide an array of candidate sites in various conditions for restoration of longleaf pine ecosystems. While about 1.2 million ha currently have an overstory of longleaf pine (Outcalt and Sheffield 1996), only 0.5 to 0.8 million ha of these have intact native understories (Noss 1989). Other candidate areas with little overstory longleaf pine have understories that range from having most of the native species to highly altered understories with no native species (Outcalt 2000). This variety of existing vegetation exists across the range of sites that longleaf pine can occupy, from dry sandhills to wet savannas. Suitable restoration techniques depend on the site type and degree of ecosystem degradation (Table 32.1). The types of longleaf pine ecosystems discussed are based on the classification of Peet and Allard (1993), with sandhills corresponding to their xeric and subxeric series, flatwoods and wet lowlands to their seasonally wet series, and uplands to their mesic series. However, we include their Piedmont/upland subxeric woodland community in the uplands rather than sandhills.

32.6.3 Restoration prescriptions

32.6.3.1 Xeric and subxeric sandhills dominated by longleaf pine with native understory

In many existing xeric and subxeric sandhills longleaf pine forests, fire suppression allowed turkey oak (*Q. laevis*), bluejack oak (*Q. incana*), sand live oak (*Q. geminata*), and sand post oak (*Q. stellata* var. *margaretta*) to develop into a scrub oak midstory. Repeated applications of fire during the growing season are effective at restoring these sites, by gradually reducing the density of the midstory oaks (Glitzenstein et al. 1995). Fires stimulate grasses and forbs to produce flowers and seeds (Christensen 1981; Clewell 1989; Outcalt 1994; Platt et al. 1988a), which aid in colonization of newly exposed microsites.

Reintroducing growing-season fires into xeric longleaf pine forests that have not burned for a prolonged period may kill older trees over the 1 to 3-year interval following

Table 32.1 Prescriptions for Restoring Longleaf Pine (LLP) Ecosystems in Varying Stages of Degradation

	Moderately Degraded	Very Degraded	Highly Degraded
Overstory: Understory:	Longleaf pine Native Plants	Other trees Native Plants	Other trees Nonnative Plants
Xeric and subxeric sandhills:	Growing-season fire Dormant-season fire Mechanical removal and herbicide hardwoods	Mechanical harvest Growing-season fire Herbicide sprouts Plant LLP seedlings	Roller-chop twice and burn Herbicide if needed Plant LLP seedlings Sow native understory seed
Montane and mesic uplands:	Growing-season fire Dormant-season fire Mechanical removal and herbicide hardwoods	Growing-season fire Mechanical harvest to create canopy gaps Plant LLP seedlings	Growing-season fire Harvest, chop, harrow Herbicide if needed Plant LLP seedlings Sow native understory seed
Flatwoods and wet lowlands:	Growing-season fire Dormant-season fire at 2-year intervals	Growing-season fire Mechanical harvest Roller-chop once and burn Plant LLP seedlings	Roller-chop twice and burn Herbicide if needed Plant LLP seedlings Sow native understory seed

the initial burn. The precise cause for this is unknown, but seems to be related to excessive forest litter accumulation around the base of larger longleaf pines and damage to roots, cambium, or both from smoldering combustion of this litter. To decrease this mortality, several dormant-season fires should be applied to gradually reduce the accumulated litter before switching to growing-season burning. Duff moisture levels during burns must be high enough to prevent ignition of the lower litter layer at the base of larger longleaf pines.

Usually three or four growing-season fires are sufficient to control scrub oak on these sites, but supplemental treatments can accelerate the restoration process. Mechanical methods such as chainsaw felling, girdling, or chipping on-site can reduce midstory hardwoods (Provencher et al. 2001); following these treatments with prescribed burning will stimulate grasses and forbs and reduce the growth of hardwood sprouts. If woody material from the midstory is not chipped or removed from the site, it should be allowed to decay before introducing the first prescribed burn. Mechanical methods are expensive and are most appropriate for critical areas in need of rapid restoration, such as red-cockaded woodpecker colony sites or along the urban–wildland interface where it is difficult to schedule the series of prescribed fires required for restoration.

Hexazinone herbicide can be useful in accelerating the restoration process compared with burning alone (Brockway et al. 1998). Application rates of 1 to 2 kg active ingredient ha^{-1} liquid formulation in a 2×2 m grid pattern will produce 80 to 90% oak mortality without long-term damage to herbaceous understory species (Brockway and Outcalt 2000). Because hexazinone does impact woody species, desirable nontarget species, such as gopher apple (*Licania michauxii*), may be reduced for a time. During dry periods, liquid hexazinone may photodegrade before sufficient rainfall transports it into the soil for oak roots to absorb it (Berish 1996); hence, application should be timed for periods of periodic rainfall. Granular hexazinone is less subject to this problem, but it potentially causes a greater reduction in the cover of grasses and forbs when it is uniformly applied across the entire site (Brockway et al. 1998).

32.6.3.2 Xeric and subxeric sandhills dominated by other trees with native understory

Scrub oaks have captured substantial areas and have become dominant following the harvest of longleaf pine. Although somewhat suppressed in the absence of frequent fire, the understory plant community still contains many native species. Other areas were converted to slash pine plantations following the removal of longleaf pine. Although understory species, especially the important grasses, are susceptible to severe mortality from soil disturbance on dry sandhills sites (Grelen 1962; Outcalt and Lewis 1990), some slash pine plantations have intact understory communities due to less intense site preparation or high soil moisture levels. A third condition is found on extensive areas in western Florida where Choctawhatchee sand pine (*Pinus clausa* var. *immuginata*) invaded former longleaf pine sites following harvest. Unlike slash pine, sand pine is more adapted to dry sites, forming a nearly continuous canopy that severely reduces understory density. However, plant diversity in these stands is generally unaffected, with native species surviving but much reduced in number (Provencher et al. 2001). Restoration under these conditions requires invigorating the herbaceous understory, if present, removing off-site slash pine or sand pine, reducing the scrub oak tree layer, and establishing longleaf pine seedlings.

Areas dominated by scrub oak can be treated with a small (3 to 5 t) single-drum roller-chopper with no offset. Heavier choppers with offset rollers should be avoided, because they can cause excessive soil disturbance that will harm understory plants. The objective of this treatment is to knock down the oaks and compress them into a layer that will carry a prescribed burn after drying. By contrast, slash pine plantations often have enough

needle litter to support a prescribed burn. Burning these plantations will invigorate the grasses, allowing them to accumulate root reserves, and thereby increase their ability to recover from disturbance associated with removing the slash pine and establishing longleaf pine seedlings. A second fire following harvest will remove logging slash, help control oak sprouts, and increase the cover of herbaceous species. If slash pine plantations have several scrub oaks, hexazinone can be applied as outlined earlier. Application can be made prior to harvest, in which case the logging activity will knock down many of the standing dead stems, which then serve as additional fuel for prescribed burning. If herbicide is applied after logging, the dead oak stems should be allowed to fall before burning, as this will remove debris and facilitate planting. Sand pine often grows so densely that it must be removed to release surviving understory species. Sites can then be burned to remove logging slash, reduce abundant sand pine seedlings, and consume sand pine seed.

Options for establishing longleaf pine seedlings include manual or machine planting of either bareroot or container seedlings (Barnett et al. 1990; Barnett and McGilvray 1997). Site preparation, other than that discussed above, should be avoided to protect the understory plant community. It is much less expensive to plant additional longleaf pine seedlings to compensate for lower survival than it is to reestablish key understory species lost to excessive soil disturbance. If grass competition is vigorous (≥60% cover) and bareroot seedlings are to be used, a planting machine with a small scalper blade can increase seedling survival (Outcalt 1995). Although this removes a strip of vegetation ~1 m wide, native grasses and forbs will recolonize these strips within 3 to 5 years, as long as invasive woody plants are discouraged by periodic growing-season fire. Planting container, longleaf pine seedlings results in acceptable survival rates without site preparation other than burning, although hexazinone application may increase survival on areas with vigorous scrub oak competition.

32.6.3.3 Xeric and subxeric sandhills without a native understory

Highly altered sites that once supported native longleaf pine ecosystems may have no longleaf pine trees and a much altered understory, or longleaf pines may be present but the native understory is not. Most of these sites were once used for agriculture or intensively managed plantations of other pines. Restoration of the understory is a formidable and therefore expensive task. Restoring understory plant communities is also the area where knowledge is most lacking and experience is limited to a few operational-scale restoration projects. In most cases, the first step is removal of trees other than longleaf pine from the overstory. Since there are few understory plants to protect, many options are available for site preparation. Chopping with a double-drum offset roller-chopper effectively controls all competition and produces a clean site for planting (Burns and Hebb 1972). This treatment can be combined with burning if there is sufficient woody residue. Much of the nutrient capital on these sites is in the litter layer and upper soil horizon; therefore, soil and litter movement should be minimized and root raking and shearing, if used, must be carefully applied. Longleaf pine bareroot or container seedlings can be planted after the soil has settled.

Restoration of understory plants is best done simultaneously with replanting longleaf pine seedlings to take advantage of the reduced competition and ease of onsite operability. The most critical part in this process is reestablishing grasses, because of their important role as fuel to support recurrent fire. To date, most work on reestablishment of wiregrass has focused on the eastern portion of the range (Means 1997; Seamon 1998; Mulligan et al. 2002). A planting density of 0.5 to 1 seedlings m^{-2} is recommended for restoration of wiregrass with plugs (Outcalt et al. 1999). To successfully establish wiregrass under existing plantations of longleaf pine, repeated burning, mechanical felling, herbicide application, or some combination must remove any hardwood midstory. A heavy-duty woods-harrow is

then used to disk strips between trees. In the spring, wiregrass plugs can be planted in these strips using 1 × 1 m spacing. Applying fertilizer during the second or third growing season will stimulate wiregrass growth (Outcalt et al. 1999), but should be applied only around wiregrass plants to avoid stimulating the growth of competing vegetation. In pastures occupied by bahia grass (*Paspalum notatum*), cultivation to break up the old sod and herbicide to control the bahia grass will improve both the survival and growth of wiregrass (Uridel 1994).

Direct seeding to reestablish wiregrass between rows of trees in newly planted and existing plantations is less expensive than planting seedlings or plugs (Hattenbach et al. 1998). Small quantities of seed can be collected by hand or with a hand-held seed stripper. For larger quantities, a tractor-mounted flail-vac is effective. Seeds can be stored in woven bags or sown immediately, by hand or with a small bale chopper. Rolling seed into the soil can improve wiregrass establishment and survival (Hattenbach et al. 1998). Other grass species are part of the native understory in sandhills longleaf pine forests and should be included in seed mixes. Pineywoods dropseed (*Sporobolus junceus*), for example, is common on many sites and, like wiregrass, will produce seed following fire. Its seed can be collected by hand and mixed with wiregrass seed when sowing restoration sites.

The most extensive direct seeding program of understory species is at Fort Stewart, GA (Table 32.2), where resource managers have collected and sown seed on site-prepared areas since 1997. Seed is collected using a tractor-mounted flail-vac from areas burned during the growing season yielding from 750 to 1,100 kg year^{-1}. At a mean sowing rate of 13.2 kg ha^{-1}, enough seed is collected to sow 57 to 83 ha year^{-1}. Seed is spread using a platform-mounted bale chopper on the back of a farm tractor. Their goal is to restore 8,100 ha of former agricultural fields to functioning longleaf pine ecosystems (Hilliard 1998).

Many understory species on sandhills sites survive extreme disturbance as propagules in the soil, or reinvade sites after the disturbance ends (Hattenbach et al. 1998). In one comparison, understories of remnant xeric longleaf pine stands and 30- to 40-year-old plantations on old-field sites were similar (Smith et al. 2002). Although the remnant stands had higher species diversity, nearly 90% of the understory species in the plantations were native to natural longleaf pine communities. Similar comparisons for the sandhills of South Carolina showed that species abundance was the same in plantations and reference stands, except for wiregrass and dwarf huckleberry (*Gaylussacia dumosa*), which were significantly reduced in plantations (Walker 1998). Thus, restoration does not require that

Table 32.2 Production Rates, Equipment and Costs[a] for Understory Plant Restoration at Fort Stewart, Georgia (Seed Collection Season Varies from Late October to Late December)

	Seed Collection					Seed Sowing			
Year	days	ha	kg	kg day^{-1}	kg ha^{-1}	days	ha	ha day^{-1}	kg ha^{-1}
1998	17	61.9	821	48.3	13.3	12	62.3	5.2	13.2
1999	24	79.5	938	39.1	11.8	14	74.1	5.3	12.7
2000	20	20.2	539	27.0	26.7	9	40.5	4.5	13.3
2001	30	95.1	1096	36.5	11.5	16	97.2	6.1	11.3
2002	17	57.9	746	43.9	12.9	6	40.5	6.8	18.4
Mean	22	62.9	828	37.6	13.2	11	62.9	5.7	13.2

4-wheel-drive vehicle	$47,594.00	Seed collection labor	$10.74 kg ha^{-1}
Flail-vac seed collector	$11,950.00	Sowing labor	$58.05 ha^{-1}
Small tractor	$35,000.00	Seed cost[a]	$141.77 ha^{-1}
Bale chopper	$3,800.00	Understory restoration cost[a]	$199.82 ha^{-1}

[a]Does not include equipment purchase or operation and maintenance costs.

every plant species be reintroduced. In addition to certain common species that do not easily reinvade or survive, reintroduction of some rare species will likely be required (Glitzenstein et al. 1998, 2001; Walker 1998).

32.6.3.4 *Flatwoods and wet lowlands dominated by longleaf pine with native understory*

Some stands have been degraded by years of fire suppression. Rehabilitation using prescribed burning to reduce woody understory and midstory species and allow grasses and forbs to increase can be effective. Growing-season fires are as useful as dormant-season burns and may be more effective. One or two dormant-season fires will gradually reduce litter buildup and is advisable before the first growing-season burn. Initial burns should be conducted when the Keetch–Byram Drought Index (KBDI) (Keetch and Byram 1968) is less than 250 (Miller and Bossuot 2000). Flatwoods understories dominated by saw palmetto, gallberry (*I. glabra*), waxmyrtle (*Myrica cerifera*), and sweetgum (*Liquidambar styraciflua*) are quite resistant to fire. Only repeated fires at short return intervals over a long period significantly reduce these woody species (Waldrop et al. 1987). Thus, burning every 2 years over a period of 10 to 20 years may be required to readjust the understory composition on wet sites.

Lightweight choppers or heavy-duty mowers may be used to reduce saw–palmetto coverage and dominance (Huffman and Dye 1994). Both methods cause limited soil disturbance and thus do not reduce native grass species. Preliminary findings from research under way at Myakka River State Park in Florida indicate that the chopping treatment is more effective for reducing saw–palmetto cover. Prescribed burning 3 to 6 months before or after these mechanical treatments seems to increase their effectiveness.

32.6.3.5 *Flatwoods and wet lowlands dominated by other trees with native understory*

Longleaf pine overstory on wet sites may have been replaced by other pines, leaving a native understory. Such sites include naturally regenerated stands that were invaded by slash pine and loblolly pine after the removal of longleaf pine, and site-prepared plantations that were planted with other southern pines. Rehabilitation (conversion) requires removal of the loblolly or slash pine overstory and reestablishment of longleaf pine. Prescribed burning 2 years prior to the harvest will reduce woody competition and stimulate the growth of herbaceous understory species. A site-preparation fire following logging may be needed to remove debris and discourage hardwood trees and shrubs. Between the harvest and site preparation burn, chopping may be used to control woody competitors. A single-drum chopper should be used to avoid excessive soil disturbance. Some managers prescribe bedding on these wet sites before planting to increase survival rates of bareroot or container longleaf pine seedlings. Bedding will improve seedling survival during wetter years by about 15%. However, this survival gain comes at a cost, not only of the operation but also from damage to the native groundcover. Bedding may also alter site moisture relations and nutrient distribution for more than 30 years (Schultz 1976). Alternatively, planting additional longleaf pine seedlings during drier seasons can offset lower survival.

32.6.3.6 *Upland and montane sites dominated by longleaf pine with native understory*

Few upland and mountain sites remain in longleaf pine because these were preferred areas for agricultural, urban, and residential development. However, there are upland areas mostly in Alabama, Mississippi, Louisiana, and Texas and montane sites in Alabama and Georgia that have developed unnaturally dense hardwood midstories. Because these are among the most biologically productive longleaf pine sites, they change the most rap-

idly, quickly developing midstory layers in the absence of frequent fire. In addition to a very dense midstory and a shrub-dominated understory, these sites also accumulate significant quantities of potentially hazardous fuel. Frequent growing-season fires are needed on upland sites with better soils to adequately control competition from woody plants. Like flatwoods sites, frequent growing-season fires over many years are required to reduce the hardwood rootstocks (Boyer 1990a). As noted for other longleaf pine ecosystem types, a series of dormant-season fires may be necessary to gradually reduce fuel levels before growing-season burning begins.

A variant of this ecosystem type where longleaf pine is present but other southern pines are dominants or codominants is common. In addition to prescribed burning as outlined above, these stands may need selective harvesting to reduce the presence of other southern pines and hardwoods in the overstory. The objective is not total elimination of other tree species, but rather a proportional adjustment of overstory composition, recognizing that these other species are part of the natural longleaf pine community. Understory burning should begin prior to selective harvest to control competition from woody plants or they will proliferate and form a shrub thicket in openings created by harvesting. Herbicide application and mechanical reduction of nonmerchantable woody species may accelerate the process of adjusting species composition and dominance (Boyer 1991).

32.6.3.7 Upland and montane sites dominated by other species

Only limited research and experience are available to guide restoration on upland sites dominated by other overstory species. The few sites that show no evidence of severe soil disturbance contain scattered natural longleaf pine trees in a mixture dominated by loblolly pine, shortleaf pine (*Pinus echinata*), and hardwoods. Some native understory likely still exists in the soil seed bank or as suppressed individuals (Varner et al. 2000). Therefore, restoration would consist of prescribed burning to reduce fuel and control woody shrubs and hardwood trees. Repeated and prolonged treatment with prescribed burning should eventually reduce the abundance and cover of woody plants in the understory. If timber markets allow, selective harvest can be used to release any native longleaf pine and reduce the hardwood component. Otherwise, thinning would be performed at a financial cost. Other pines may need to be retained onsite to furnish sufficient needlefall for prescribed burning and to avoid release of woody competition. Once prescribed burning and other mechanical or chemical methods have reduced the woody midstory and understory layers, some of these other pines could be removed and replaced with longleaf pine seedlings. This is probably best done by creating canopy gaps in areas where the understory has become dominated by desirable grasses and forbs.

Restoring upland sites with a history of severe soil disturbance from agriculture or intensive forestry will be more challenging. It is unlikely that many native understory grasses and forbs survived intensive soil disturbance; however, there is a large soil seedbank of herbaceous weeds that must be controlled. Restoration techniques being tested include multiple-pass harrowing to reduce weeds followed by planting wiregrass plugs. High survival rates have been obtained with this method, but long-term growth rates are still uncertain (Mulligan and Kirkman 2002).

32.7 Costs and benefits associated with restoration

32.7.1 Estimating restoration costs

Reestablishing longleaf pine as the dominant tree species on a site is often the first and, in many ways, easiest step in the restoration process. Establishment costs vary according to ambient conditions and the type and amount of site preparation needed. On previously

Table 32.3 Comparative Value of Wood Products among Major Southern Pine Species, Assuming a Mean Stand Volume of ~29 m^3 ha^{-1} at Age 55 (Holliday 2001)

	Sawtimber Price m^{-3}	High-Quality Poles	Value ha^{-1}
Longleaf pine	$264	66%	$8,492
Slash pine	$257	12%	$7,640
Loblolly pine	$254	5%	$7,454

harvested or old-field sites, costs typically range from $370 to 740 ha^{-1}, depending on site conditions and whether bareroot seedlings or container seedlings are used. This range reflects the current costs for site preparation, seedlings, and planting. To control competing vegetation, increase survival, and stimulate early growth, an additional $85 to 100 ha^{-1} might be expended for herbicide application. Despite these expenditures occurring early in a timber rotation, the average internal rate of return for such an investment ranges from 8 to 12% (Busby et al. 1996).

Restoring groundcover plants can be very expensive, with costs sharply rising when quick success is desired. In relatively undisturbed forests, many native plants will respond to reintroduction of fire, particularly growing-season burning, through stimulating residual seed banks and inducing flowering and seed production in existing plants. The cost of fire reintroduction varies with existing site conditions, especially the number of fuel reduction burns needed. Where seed banks are depleted from severe soil disturbance, restoring the plant community is more difficult. Reseeding or replanting selected understory plant species has been accomplished successfully, but at a considerable cost, from several hundred to several thousand dollars per ha. Seed collection, cultivation, distribution, planting techniques, and other steps in the process are being developed and generally focus on pyrophytic graminoids (e.g., wiregrass), species consumed by wildlife (e.g., legumes), and species of special concern due to rarity or endangerment, such as American chaffseed (*Schwalbea americana*).

32.7.2 *Benefits of restored longleaf pine ecosystems*

The material and intangible benefits of restoring longleaf pine ecosystems are substantial. The economic value of longleaf pine forests is considerable and sustainable forest management for commercial products is achievable. Longleaf pine is the most versatile of all the southern pines and provides a variety of highly valued products (Table 32.3). Longleaf pine forests typically produce up to five times more tree stems of sufficient quality to be used as utility poles than stands of slash pine or loblolly pine (Boyer and White 1990). Stumpage values for such poles exceed prices for sawtimber by about 40% in local wood markets. When the high value of pine straw (i.e., fallen needles used as landscaping material which may be harvested from stands as early as age 10) is added, the economic value of longleaf pine forests becomes increasingly obvious. Surveys consistently indicate the value of hunter access to private lands as a tradable commodity throughout the natural range of longleaf pine, and private pine forests are leased for hunting rights for more than the timber value. Where longleaf pine forests are maintained in open park-like condition, the higher quality of this habitat for quail, turkey, and deer brings a premium in hunting leases and related services to private landowners.

Acknowledgments

The authors express their appreciation to Becky Estes for searching the literature to identify numerous relevant publications. We are also grateful to John Stanturf, Palle Madsen,

Dave Haywood, Steve Jack, John Kush, Dave Borland, and Ric Jeffers for helpful comments that improved this chapter.

References

Abrahamson, W.G. and Hartnett, D.C., Pine flatwoods and dry prairies, in *Ecosystems of Florida*, Myers, R.L. and Ewel, J.J., Eds., University of Central Florida Press, Orlando, FL, 103, 1990.

Anderson, K.M., Tending the wilderness, *Restor. Manage. Notes*, 14, 154, 1996.

Bailey, R.G., *Description of the Ecoregions of the United States*, U.S. Department of Agriculture, Forest Service, Miscellaneous Publication 1391, Washington, DC, 108 pp., 1995.

Barnett, J.P., Lauer, D.K., and Brissette J.C., Regenerating longleaf pine with artificial methods, in *Management of Longleaf Pine*, Farrar R.M., Ed., U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, General Technical Report SO-75, 72, 1990.

Barnett, J.P. and McGilvray J.M., *Practical Guidelines for Producing Longleaf Pine Seedlings in Containers*, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, General Technical Report SRS-14, 28 pp., 1997.

Bartram, W., *Travel Through North and South Carolina, Georgia and East and West Florida*, Dover Publishers, New York, NY, 414 pp., 1791.

Berish, S.J., *Efficacy of Three Formulations of the Forest Herbicide Hexazinone as an Aid to Reforestation of Longleaf Pine (Pinus palustris) Sandhills at Eglin Air Force Base, Florida*, M.S. thesis, University of Florida, Gainesville, FL, 1996.

Boyer, W.D., *Growing-Season Burns for Control of Hardwoods in Longleaf Pine Stands*, U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, Research Paper SO-256, 7 pp., 1990a.

Boyer, W.D., *Pinus palustris*, Mill. longleaf pine, in *Silvics of North America*, Vol. 1, *Conifers*, Burns, R.M. and Honkala, B.H., Tech. Coords., U.S. Department of Agriculture, Forest Service, Washington, D.C., 405, 1990b.

Boyer, W.D., *Effects of a Single Chemical Treatment on Long-term Hardwood Development in a Young Pine Stand*, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, General Technical Report SE-70, 599, 1991.

Boyer, W.D. and White, J.B., Natural regeneration of longleaf pine, in *Management of Longleaf Pine*, Farrar, R.M., Ed., U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, General Technical Report SO-75, 94, 1990.

Brockway, D.G. and Lewis, C.E., Long-term effects of dormant-season prescribed fire on plant community diversity, structure and productivity in a longleaf pine wiregrass ecosystem, *For. Ecol. Manage.*, 96, 167, 1997.

Brockway, D.G. and Outcalt, K.W., Gap-phase regeneration in longleaf pine wiregrass ecosystems, *For. Ecol. Manage.*, 106, 125, 1998.

Brockway, D.G. and Outcalt, K.W., Restoring longleaf pine wiregrass ecosystems: hexazinone application enhances effects of prescribed fire, *For. Ecol. Manage.*, 137, 121, 2000.

Brockway, D.G., Outcalt, K.W., and Wilkins, R.N., Restoring longleaf pine wiregrass ecosystems: plant cover, diversity and biomass following low-rate hexazinone application on Florida sandhills, *For. Ecol. Manage.*, 103, 159, 1998.

Burns, R.M. and Hebb, E.A., *Site Preparation and Reforestation of Droughty, Acid Sands*, U.S. Department of Agriculture, Forest Service, Washington, DC, Agriculture Handbook No. 426, 61 pp., 1972.

Busby, R.L., Thomas, C.E. and Lohrey, R.E., The best kept secret in southern forestry: longleaf pine plantation investments, in *Longleaf Pine: A Regional Perspective of Challenges and Opportunities*, Kush, J.S., Comp., Longleaf Alliance Report No. 1, Solon Dixon Forestry Education Center, Andalusia, AL, 26, 1996.

Carroll, W.D., Kapeluck, P.R., Harper, R.A., and Van Lear, D.H., Historical overview of the southern forest landscape and associated resources, in *The Southern Forest Resource Assessment*, Wear, D.N. and Greis, J.G., Eds., U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, General Technical Report SRS-53, 583, 2002.

Christensen, N.L., Fire regimes in southeastern ecosystems, in *Fire Regimes and Ecosystem Properties*, Mooney, H.A., Bonnicksen, T.M., Christensen, N.L., Lotan, J.E., and Reiners, W.A., Eds., U.S. Department of Agriculture, Forest Service, Washington, DC, General Technical Report WO-26, 112, 1981.

Clewell, A.F., Natural history of wiregrass (*Aristida stricta* Michx., Gramineae), *Nat. Areas J.*, 9, 223, 1989.

Clewell, A.F., Restoring for natural authenticity, *Ecol. Rest.*, 18, 216, 2000.

Croker, T.C., *Longleaf Pine: A History of Man and a Forest*, U.S. Department of Agriculture, Forest Service, Southern Region, Atlanta, GA, Forestry Report R8-FR7, 37 pp., 1987.

Delcourt, P.A. and Delcourt, H.R., *Long-term forest dynamics of the temperate zone*, Springer-Verlag Publishers, New York, NY, 439 pp., 1987.

Engstrom, R.T., Red-cockaded woodpeckers: prospects for recovery, in *The Fire Forest: Longleaf Pine-wiregrass Ecosystems*, Wilson, J.R., Ed., Georgia Wildlife, 8, 12, 2001.

Engstrom, R.T., Kirkman, L.K., and Mitchell, R.J., The natural history of the fire forest, in *The Fire Forest: Longleaf Pine-wiregrass Ecosystems*, Wilson, J.R., Ed., Georgia Wildlife, 8, 5, 14, 2001.

Franklin, R.M., *Stewardship of Longleaf Pine Forests: A Guide for Landowners*, Longleaf Alliance Report No. 2, Longleaf Alliance, Solon Dixon Forestry Education Center, Andalusia, AL, 44 pp., 1997.

Frost, C.C., Four centuries of changing landscape patterns in the longleaf pine ecosystem, in *Proceedings of the 18th Tall Timbers Fire Ecology Conference*, Herman, S.M., Ed., Tall Timbers Research Station, Tallahassee, FL, 17, 1993.

Garren, K.H., Effects of fire on vegetation of the southeastern United States, *Bot. Rev.*, 9, 617, 1943.

Glitzenstein, J.S., Platt, W.J., and Streng, D.R., Effects of fire regime and habitat on tree dynamics in north Florida longleaf pine savannas, *Ecol. Monogr.*, 65, 441, 1995.

Glitzenstein, J.S., Streng, D.R., and Wade, D.D., A promising start for a new population of *Parnassia caroliniana* Michx., in *Ecological Restoration and Regional Conservation Strategies*, Kush, J.S., Comp., Longleaf Alliance Report No. 3, Solon Dixon Forestry Education Center, Andalusia, AL, 44, 1998.

Glitzenstein, J.S., Streng, D.R., Wade, D.D., and Brubaker, J., Starting new populations of longleaf pine ground-layer plants in the Outer Coastal Plain of South Carolina, USA, *Nat. Areas J.*, 21, 89, 2001.

Grelen, H.E., Plant succession on cleared sandhills in northern Florida, *Am. Midl. Nat.*, 67, 36, 1962.

Hardin, E.D. and White, D.L., Rare vascular plant taxa associated with wiregrass (*Aristida stricta*) in the southeastern United States, *Nat. Areas J.*, 9, 234, 1989.

Hattenbach, M.J., Gordon, D.R., Seamon, G.S., and Studenmund, R.G., Development of direct-seeding techniques to restore native groundcover in a sandhill ecosystem, in *Ecological Restoration and Regional Conservation Strategies*, Kush, J.S., Comp., Longleaf Alliance Report No. 3, Solon Dixon Forestry Education Center, Andalusia, AL, 64, 1998.

Hilliard, T., Longleaf-wiregrass restoration at Fort Stewart, Georgia: the military's role in restoration, in *Ecological Restoration and Regional Conservation Strategies*, Kush, J.S., Comp., Longleaf Alliance Report No. 3, Solon Dixon Forestry Education Center, Andalusia, AL, 32, 1998.

Hilton, J., Biological diversity in the longleaf pine ecosystem, *Alabama's Treasured For.*, 18, 28, 1999.

Holliday, P.P., *Going, going...saving the longleaf pine ecosystem before it's gone*, Sherpa Guides, ⟨www.sherpaguides.com/georgia/fire_forest/saving_ecosystem/index.html⟩, 9 pp., 2001.

Huffman, J.M. and Dye, R., Summary of wiregrass ecosystem restoration projects at Myakka River State Park, in *Proceedings of the Wiregrass Ecosystem Restoration Workshop*, Clewell, A.F. and Cleckley, W., Eds., State of Florida, Northwest Florida Water Management District, Tallahassee, FL, 21, 1994.

Jackson, D.R. and Milstrey, E.R., The fauna of gopher tortoise burrows, in *Proceedings of the Gopher Tortoise Relocation Symposium*, Diemer, J.E., Ed., State of Florida, Game and Freshwater Fish Commission, Tallahassee, FL, 86, 1989.

Keetch, J.J. and Byram, G.M., *A Drought Index for Forest Fire Control*, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, Research Paper SE-38, 1968.

Kelly, J.F. and Bechtold, W.A., The longleaf pine resource, in *Management of Longleaf Pine*, Farrar, R.M., Ed., U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, General Technical Report SO-75, 11, 1990.

Kirkman, L.K., Drew, M.B., West, L.T. and Blood, E.R., Ecotone characterization between upland longleaf pine/wiregrass stands and seasonally-ponded isolated wetlands, *Wetlands*, 18, 346, 1998.

Komarek, E.V., Lightning and lightning fires as ecological forces, in *Proceedings of the 9th Tall Timbers Fire Ecology Conference*, Tall Timbers Research Station, Tallahassee, FL, 169, 1968.

Kush, J.S. and Meldahl, R.S., Composition of a virgin stand of longleaf pine in south Alabama, *Castanea*, 65, 56, 2000.

Landers, J.L., Disturbance influences on pine traits in the southeastern United States, in *Proceedings of the 17th Tall Timbers Fire Ecology Conference*, Tall Timbers Research Station, Tallahassee, FL, 61, 1991.

Landers, J.L. and Boyer, W.D., *An Old-growth Definition for Upland Longleaf and South Florida Slash Pine Forests, Woodlands and Savannas*, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, General Technical Report SRS-29, 15 pp., 1999.

Landers, J.L., Byrd, N.A. and Komarek, R., A holistic approach to managing longleaf pine communities, in *Management of Longleaf Pine*, Farrar, R.M., Ed., U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, General Technical Report SO-75, 135, 1990.

Landers, J.L., Van Lear, D.H. and Boyer, W.D., The longleaf pine forests of the Southeast: requiem or renaissance?, *J. For.*, 93, 39, 1995.

Little, E.L., *Atlas of United States Trees. Volume 1. Conifers and Important Hardwoods*, U.S. Department of Agriculture, Forest Service, Washington, DC, Miscellaneous Publication 1146, 320 pp., 1971.

McMahon, C.K., Tomczak, D.J., and Jeffers, R.M., Longleaf pine ecosystem restoration: the role of the USDA Forest Service, in *Ecological Restoration and Regional Conservation Strategies*, Kush, J.S., Comp., Longleaf Alliance Report No. 3, Solon Dixon Forestry Education Center, Andalusia, AL, 20, 1998.

Means, D.B., Wiregrass restoration: probable shading effects in a slash pine plantation, *Restoration and Manage. Notes*, 15, 52, 1997.

Miller, J.H. and Robinson, K.S., A regional perspective of the physiographic provinces of the Southeastern United States, in *Proceedings of the 8th Biennial Southern Silvicultural Research Conference*, Edwards, M.B., Ed., U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, General Technical Report SRS-1, 581, 1995.

Miller, S.R. and Bossuot, W.R., Flatwoods restoration on the St. Johns River Water Management District, Florida: a prescription to cut and burn, in *Proceedings of the 21st Tall Timbers Fire Ecology Conference*, Tall Timbers Research Station, Tallahassee, FL, 212, 2000.

Mulligan, M.K. and Kirkman, L.K., Competition effects on wiregrass (*Aristida beyrichiana*) growth and survival, *Plant Ecol.*, 167, 39, 2002.

Mulligan, M.K., Kirkman, L.K., and Mitchell, R.J., *Aristida beyrichiana* (wiregrass) establishment and recruitment: implications for restoration, *Restor. Ecol.*, 10, 68, 2002.

Noss, R.F., Longleaf pine and wiregrass: keystone components of an endangered ecosystem, *Nat. Areas J.*, 9, 211, 1989.

Noss, R.F., LaRoe, E.T., and Scott, J.M., *Endangered Ecosystems of the United States: A Preliminary Assessment of Loss and Degradation*, U.S. Department of Interior, National Biological Service, Washington, DC, Biological Report 28, 59 pp., 1995.

Outcalt, K.W., Seed production of wiregrass in central Florida following growing season prescribed burns, *Int. J. Wildland Fire*, 4, 123, 1994.

Outcalt, K.W., *Maintaining the Native Plant Community during Longleaf Pine Establishment*, Forestry Research Institute, Rotorua, New Zealand, Bulletin No. 192, 283, 1995.

Outcalt, K.W., Occurrence of fire in longleaf pine stands in the southeastern United States, in *Proceedings of the 21st Tall Timbers Fire Ecology Conference*, Moser W.K. and Moser, C.F., Eds., Tall Timbers Research Station, Tallahassee, FL, 178, 2000.

Outcalt, K.W. and Lewis, C.E., Response of wiregrass (*Aristida stricta*) to mechanical site preparation, in *Wiregrass Biology and Management*, Duever, L.C. and Noss, R.F., Eds., KBN Engineering and Applied Sciences, Gainesville, FL, 60, 1990.

Outcalt, K.W. and Sheffield, R.M., *The Longleaf Pine Forest: Trends And Current Conditions*, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, Resource Bulletin SRS-9, 23 pp., 1996.

Outcalt, K.W., Williams, M.E., and Onokpise, O., Restoring *Aristida stricta* to *Pinus palustris* ecosystems on the Atlantic Coastal Plain, USA, *Restor. Ecol.*, 7, 262, 1999.

Palik, B.J., Mitchell, R.J., Houseal, G., and Pederson, N., Effects of canopy structure on resource availability and seedling responses in a longleaf pine ecosystem, *Can. J. For. Res.*, 27, 1458, 1997.

Palik, B.J. and Pederson, N., Overstory mortality and canopy disturbances in longleaf pine ecosystems, *Can. J. For. Res.*, 26, 2035, 1996.

Peet, R.K. and Allard, D.J., Longleaf pine-dominated vegetation of the southern Atlantic and eastern Gulf Coast region, USA, in *Proceedings of the 18th Tall Timbers Fire Ecology Conference*, Herman, S.M., Ed., Tall Timbers Research Station, Tallahassee, FL, 45, 1993.

Pickett, S.T.A. and White, P.S., *The Ecology of Natural Disturbance and Patch Dynamics*, Academic Press, Orlando, FL, 1985.

Platt, W.J., Evans, G.W., and Davis, M.M., Effects of fire season on flowering of forbs and shrubs in longleaf pine forests, *Oecologia*, 76, 353, 1988a.

Platt, W.J., Evans, G.W., and Rathbun, S.L., The population dynamics of a long-lived conifer (*Pinus palustris*), *Am. Nat.*, 131, 491, 1988b.

Platt, W.J. and Rathbun, S.L., Dynamics of an old-growth longleaf pine population, in *Proceedings of the 18th Tall Timbers Fire Ecology Conference*, Herman, S.M., Ed., Tall Timbers Research Station, Tallahassee, FL, 275, 1993.

Provencher, L., Litt, A.R., Galley, K.E.M., Gordon, D.R., Tanner, G.W., Brennan, L.A., Gobris, N.M., McAdoo, J.P., and Herring, B.J., *Restoration of fire suppressed longleaf pine sandhills at Eglin Air Force Base, Niceville, Florida*, The Nature Conservancy, Science Division, Gainesville, FL, 294 pp., 2001.

Pyne, S.J., *Fire in America: A Cultural History of Wildland and Rural Fire*, Princeton University Press, Princeton, NJ, 654 pp., 1997.

Robbins, L.E. and Myers, R.L., *Seasonal Effects of Prescribed Burning in Florida: A Review*, Tall Timbers Research Station, Tallahassee, FL, Miscellaneous Publication No. 8, 96 pp., 1992.

Schmidtling, R.C. and Hipkins, V., Genetic diversity in longleaf pine (*Pinus palustris*): influence of historical and prehistorical events, *Can. J. For. Res.*, 28, 1135, 1998.

Schultz, R.P., *Environmental Change After Site Preparation and Slash Pine Planting on a Flatwoods Site*, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, Research Paper SE-156, 20 pp., 1976.

Schwartz, M.W., Natural distribution and abundance of forest species and communities in northern Florida, *Ecology*, 75, 687, 1994.

Schwarz, G.F., *The Longleaf Pine Virgin Forest: A Silvical Study*, John Wiley and Sons, New York, NY, 135 pp., 1907.

Seamon, G., A longleaf pine sandhill restoration in northwest Florida, *Restor. Manage. Notes*, 16, 46, 1998.

Smith, G.P., Shelburne, V.B., and Walker, J.L., Structure and composition of vegetation of longleaf pine plantations compared to natural stands occurring along an environmental gradient at the Savannah River Site, in *Proceedings of the 11th Biennial Southern Silvicultural Research Conference*, Outcalt, K.W., Ed., U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, General Technical Report SRS-48, 481, 2002.

Stanturf, J.A., Wade, D.D., Waldrop, T.A., Kennard, D.K., and Achtemeier, G.L., Fire in southern landscapes, in *The Southern Forest Resource Assessment*, Wear, D.N. and Greis, J.G., Eds., U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, General Technical Report SRS-53, 607, 2002.

Stout, I.J. and Marion, W.R., Pine flatwoods and xeric pine forests of the southern lower coastal plain, in *Biodiversity of the Southeastern United States: Lowland Terrestrial Communities*, Martin, W.H., Boyce, S.G. and Echternacht, A.C., Eds., Wiley, New York, NY, 373, 1993.

Taylor, A.R., Ecological aspects of lightning in forests, in *Proceedings of the 13th Tall Timbers Fire Ecology Conference*, Tall Timbers Research Station, Tallahassee, FL, 455, 1974.

Uridel, K.W., *Restoration of Native Herbs in Abandoned Paspalum notatum (Bahia grass) Pastures*. M.S. thesis, University of Florida, Gainesville, FL, 1994.

Varner, J.M., Kush, J.S., and Meldahl, R.S., Ecological restoration of an old-growth longleaf pine stand utilizing prescribed fire, in *Proceedings of the 21st Tall Timbers Fire Ecology Conference*, Moser, W.K. and Moser, C.F., Eds., Tall Timbers Research Station, Tallahassee, FL, 216, 2000.

Wahlenberg, W.G., *Longleaf Pine: Its Use, Ecology, Regeneration, Protection, Growth and Management*, C.L. Pack Forestry Foundation and U.S. Department of Agriculture, Forest Service, Washington, DC, 429 pp., 1946.

Waldrop, T.A., Van Lear, D.H., Lloyd, F.T. and Harms, W.R., *Long-Term Studies Of Prescribed Burning In Loblolly Pine Forests Of The Southeastern Coastal Plain*, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, General Technical Report SE-45, 23 pp., 1987.

Walker, J.L., Rare vascular plant taxa associated with the longleaf pine ecosystem, in *Proceedings of the 18th Tall Timbers Fire Ecology Conference*, Hermann, S.M., Ed., Tall Timbers Research Station, Tallahassee, FL, 105, 1993.

Walker, J.L., Ground layer vegetation in longleaf pine landscapes: an overview for restoration and management, in *Ecological Restoration and Regional Conservation Strategies*, Kush, J.S., Comp., Longleaf Alliance Report No. 3, Solon Dixon Forestry Education Center, Andalusia, AL, 2, 1998.

Ware, S., Frost, C.C. and Doerr, P.D., Southern mixed hardwood forest: the former longleaf pine forest, in *Biodiversity of the Southeastern United States: Lowland Terrestrial Communities*, Martin, W.H., Boyce, S.G. and Echternacht, A.C., Eds., John Wiley and Sons, New York, NY, 447, 1993.

Watts, W.A., Hansen, B.C.S. and Grimm, E.C., Camel Lake: a 40,000-yr record of vegetational and forest history from north Florida, *Ecology*, 73, 1056, 1992.

Wear, D.N. and Greis, J.G., Summary report, in *The Southern Forest Resources Assessment*, Wear, D.N. and Greis, J.G., Eds., U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, General Technical Report SRS-53, 114 pp., 2002.

Williams, J.L., *The Territory of Florida*, 1962 Edition, University of Florida Press, Gainesville, FL, 1837.