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Restoration of Longleaf Pine Ecosystems

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Abstract

Longleaf pine (*Pinus palustris*) ecosystems once occupied 38 million ha in the Southeastern United States, occurring as forests, woodlands, and savannas on a variety of sites ranging from wet flatwoods to xeric sandhills and rocky mountainous ridges. Characterized by an open parklike structure, longleaf pine ecosystems are a product of frequent fires, facilitated by the presence of fallen pine needles and bunchgrasses in the understory. Timber harvest, land conversion to agricultural and other nonforest uses, and alteration of fire regimes greatly reduced longleaf pine ecosystems, until only 1.2 million ha remained in 1995. Longleaf pine ecosystems are among the most species-rich ecosystems outside the tropics. However, habitat loss and degradation have caused increased rarity of many obligate species. The lack of frequent surface fires and the proliferation of woody plants in the understory and midstory have greatly increased the risk of additional longleaf pine ecosystem losses from catastrophic fire.

Because longleaf pine still exists in numerous small fragments throughout its range, it is reasonable to conclude that it can be restored. Restoration efforts now underway use physical, chemical, and pyric methods to reestablish the natural structure and function in these ecosystems by adjusting species composition, modifying stand structure, and facilitating ecological processes, such as periodic fire and longleaf pine regeneration. The ecological, economic, and social benefits of restoring longleaf pine ecosystems include (1) expanding the habitat available to aid in the recovery of numerous imperiled species, (2) improving habitat quality for many wildlife species, (3) producing greater amounts of high-quality longleaf pine timber products, (4) increasing the production of pine straw, (5) providing new recreational opportunities, (6) preserving natural and cultural legacies, and (7) creating a broader range of management options for future generations.

Keywords: Biological diversity, bluestem grasses, disturbance, fire ecology, gopher tortoise, *Pinus palustris* Mill., red-cockaded woodpecker, wiregrass.

Southern Forest Environment

Longleaf pine ecosystems occur in the southern forest region of the 13 States in the Southeastern United States. This region is bounded by the Atlantic Ocean to the east, the Gulf of Mexico to the south, the Great Plains grasslands to the west, and the interior plateaus, highlands, and mountains to the north (Miller and Robinson 1995). Lower elevations in this region consist of broad Coastal Plains that extend along the shores of the Atlantic Ocean and Gulf of Mexico. In the western part of the region, the Coastal Plain is interrupted by the Mississippi River's alluvial plain. Middle elevations, in the eastern portion of the region, are occupied by the Piedmont, a broad area of uplands which parallels the Atlantic Coastal Plain. Numerous sandhills occur along the contact between the Coastal Plains and the Piedmont, as well as along the Lake Wales Ridge of central Florida and beach ridges in northwestern Florida. Upper elevations, extending to nearly 2000 m, are dominated by the Blue Ridge Mountains, Cumberland Plateau, and Ouachita and Ozark Mountains. Longleaf pine forests naturally occur at elevations < 600 m (with most occurring at < 200 m) in 9 of the States in this region (all those except Oklahoma, Arkansas, Tennessee, and Kentucky, where cooler environments predominate) (Boyer 1990b).

Except in the highlands, most of the southern region is characterized by a humid subtropical climate (Bailey 1995). Temperatures are generally high, with minimums during January ranging from 0 °C to 13 °C and maximums during July ranging from 29 °C to > 35 °C. Annual precipitation varies from 1040 to 1750 mm and is well distributed through the year. During the late summer and fall seasons, hurricanes developing over the Atlantic Ocean move westward and frequently affect Coastal Plain forests in this region. Such tropical storms are one of the principal large-scale damaging agents for longleaf pine forests growing near the seacoast. Growing seasons are comparatively long in the southern region, with those near upper elevations between 160 and 220 days and those in the lower Coastal Plains of central Florida > 300 days.

In the highlands, soils are derived from parent materials largely consisting of granite, quartzite, schist, slate, sandstone, shale, limestone, and dolomite. At lower elevations, parent materials are generally marine sediments ranging from deep, coarse, excessively drained sands to poorly drained clays. Surface soils derived from these progenitors are generally sandy, acidic, low in organic matter, and relatively infertile (Boyer 1990b). The predominant forest soils in the southern region (outside peninsular Florida) are the Ultisols. The red-yellow color in the profile of these soils results from the translocation of iron and aluminum from a lighter-colored upper horizon to a darker red B horizon below (Pritchett 1979). Typic Paleudults and Plinthic Paleudults are the Ultisols most commonly associated with longleaf pine forests. Entisols and Spodosols are the other soil orders most frequently observed to support longleaf pine. Entisols are deep sands, with very weak horizon development, found on relatively xeric sandhills. Most commonly occurring as Quartzisamments, these soils range from elevations of 3 m in coastal Florida to 185 m in the sandhills of the Carolinas, Georgia, northwestern Florida, and the central ridge of Florida (Boyer 1990b). Spodosols, principally Aquods, are characteristic of lower Coastal Plain flatwoods, which have wet sandy soils with a shallow water table that is at or near the ground surface during the rainy season.

Southern forests occupy 87 million ha of a vast and diverse landscape which supports a great number of ecosystems and species, including > 60 forest types (Walker and Oswald 2000). The forests of this region have great commercial importance and produce ~ 16 percent of the world's roundwood supply, more than any other individual nation. The area of naturally regenerated pine forests in the South has declined as a result of natural pine harvesting and establishment of plantations, succession to hardwoods, and conversion to nonforest uses (i.e., urban development or agriculture). The area occupied by pine plantations in the region is forecast to increase by 67 percent to 22 million ha by the middle of the 21st century (Prestemon and Abt 2002). The influence this change will have (along with other stresses) on rare forest communities is uncertain. However, it is widely agreed that habitat reduction and loss are the principal causes of increasing species endangerment throughout the region. Longleaf pine forests are recognized as being among the most endangered of southern ecosystems (Wear and Greis 2002).

Highlands are occupied by various forest types including Fraser fir (*Abies fraseri*) and red spruce (*Picea rubens*) mixed with hardwoods, oak-hickory (*Quercus-Carya*), table mountain pine (*Pinus pungens*), shortleaf pine (*P. echinata*), loblolly pine (*P. taeda*), Virginia pine (*P. virginiana*), and eastern redcedar (*Juniperus virginiana*) (Walker and Oswald 2000). Small amounts of montane longleaf pine, in generally poor condition, still occur in northern Alabama and Georgia (Boyer 1990b). However, most natural stands of longleaf pine in the mountain province have declined greatly, as timber harvesting and fire exclusion resulted in their replacement by loblolly pine, shortleaf pine, and hardwoods. The Piedmont is largely a mixture of southern pines and hardwoods, supporting loblolly pine and shortleaf pine plantations, oak-hickory forests, oak-pine forests, and stands of Virginia pine (Walker and Oswald 2000). The province also supports longleaf pine on xeric sands and mesic uplands, and riparian forests along stream bottoms (Golden 1979). The once extensive longleaf pine forests of the Piedmont have largely been converted to loblolly pine plantations through timber harvesting and replanting (Schultz 1997) or replaced by hardwoods that have flourished in the absence of frequent fire. The Coastal Plain is characterized by forests of loblolly pine and shortleaf pine, longleaf pine and slash pine (*P. elliottii*), oak-pine, upland hardwoods, sand pine (*P. clausa*) and pond pine (*P. serotina*), Virginia pine, eastern redcedar, Atlantic white-cedar (*Chamaecyparis thyoides*), baldcypress (*Taxodium distichum*), and bottomland hardwoods (Walker and Oswald 2000). On the lowest terraces along the coast (at elevations < 8 m), poorly drained but not permanently flooded soils occur over extensive flatwoods areas, which are commonly occupied by pines and hardwoods. Although formerly dominated by longleaf pine, many of these flatwoods sites have been converted to slash pine and loblolly pine plantations. The uplands of the middle and upper Coastal Plains are typically well-drained sites supporting forests of southern pines and hardwoods. While longleaf pine also once dominated these landscapes, it has been largely replaced by plantations of loblolly pine (Schultz 1997). The xeric sandhills located in Florida and along the fall line between the Piedmont and the Coastal Plain are still largely occupied by longleaf pine and its scrub oak associates. The primary threat to the remaining longleaf pine is the absence of frequent fire, which results in encroachment by sand pine, hardwoods, and understory scrub species.

Longleaf Pine Ecology

Longleaf Pine Ecosystems

Longleaf pine forests were once among the most extensive ecosystems in North America (Landers and others 1995). Prior to European settlement, these forests occupied ~ 38 million ha in what is now the Southeastern United States (Frost 1993). Travelers in this region during the late 18th and early 19th centuries reported that there were vast areas in which longleaf pine covered > 90 percent of the landscape (Bartram 1791, Williams 1837). The native range of longleaf pine (fig. 1) extends along the Gulf and Atlantic Coastal Plains from Texas to Virginia, and well into central Florida and the Piedmont and mountains of northern Alabama and northwest Georgia (Boyer 1990b, Stout and Marion 1993). Longleaf pine occurs in forests, woodlands, and savannas on sites that range from wet, poorly drained flatwoods to mesic uplands, xeric sandhills, and rocky mountainous ridges (Boyer 1990b). Associated species are often influenced by site quality, but longleaf pine is a species of great ecological amplitude, and its occurrence is largely unaffected by the soil type (Gilliam and others 1993, Kalisz and Stone 1984), except that there is greater early competition on sites of higher quality.

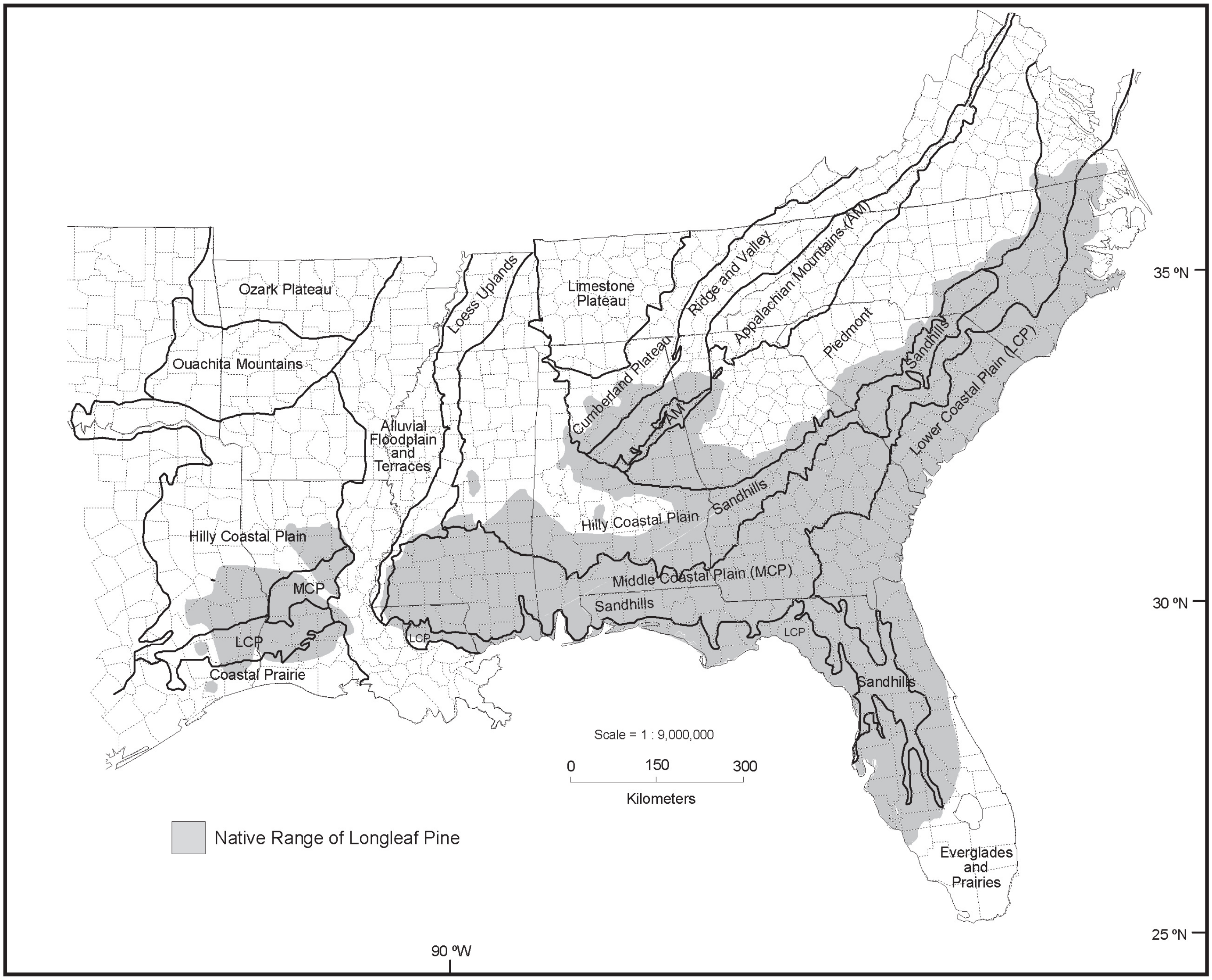

Figure 1—Native range of longleaf pine and physiographic provinces of the Southeastern United States (Little 1971, Miller and Robinson 1995).

An open, parklike stand structure (fig. 2) is a distinguishing characteristic of longleaf pine ecosystems (Edmisten 1963, Schwarz 1907, Wahlenberg 1946). Naturally occurring longleaf pine forests are typically an uneven-aged mosaic of even-aged patches distributed across the landscape, which vary in size, shape, structure, composition, and density, and contain numerous embedded special habitats such as stream bottoms, wetlands, and seeps (Brockway and Outcalt 1998, Hilton 1999, Platt and Rathbun 1993). The natural variability of these ecosystems makes them excellent habitat for game animals such as white-tailed deer (*Odocoileus virginianus*), wild turkey (*Meleagris gallapavo*), and northern bobwhite (*Colinus virginianus*) and numerous nongame and rare animal species, including fox squirrel (*Sciurus niger*), southeastern pocket gopher (*Geomys pinetis*), Bachman's sparrow (*Aimophila aestivalis*), brown-headed nuthatch (*Sitta pusilla*), red-cockaded woodpecker (*Picoides borealis*), gopher tortoise (*Gopherus polyphemus*), eastern indigo snake (*Drymarchon corais couperi*), eastern diamondback rattlesnake (*Crotalus adamanteus*), and flatwoods salamander (*Ambystoma cingulatum*) (Brockway and Lewis 2003, Crofton 2001, Engstrom 1993, Guyer and Bailey 1993, Kantola and Humphrey 1990).

In the west Gulf Coastal Plain, longleaf pine understories are dominated by bluestem grasses (*Schizachyrium scoparium* and *Andropogon* spp.). From Florida north and eastward, longleaf pine is typically associated with wiregrass (*Aristida stricta,* also known as pineland threeawn, and *A. beyrichiana,*

Figure 2—Longleaf pine–wiregrass ecosystem on xeric sandhill site in Florida.

Beyrich threeawn). Because fallen pine needles and understory grasses facilitate the ignition and spread of fire during the growing season, these plant communities often contain relatively few shrubs or hardwood trees (Landers 1991). Although such woody plants may be more numerous on mesic sites, their stature is typically limited by frequent burning. *Quercus*, *Ilex,* and *Serenoa* are common tree and shrub associates of longleaf pine at various locations within its native range. Longleaf pine ecosystems support a great variety of herbaceous plant species (table 1). 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).

Throughout its domain, longleaf pine is closely associated with frequent surface fires (Brockway and Lewis 1997, Garren 1943, Outcalt 2000, Wright and Bailey 1982). In these ecosystems, longleaf pine and bunchgrasses function together as keystone species that facilitate but are resistant to fire (Noss 1989, Platt and others 1988b). They are relatively long-lived and retain nutrients and water to a degree that reinforces their site dominance and minimizes change in the plant community following disturbance (Landers and others 1995). Fire can spread very quickly through a fine-fuel matrix composed of highly flammable longleaf pine needles and the leaves of several bunchgrasses (Abrahamson and Harnett 1990, Landers 1991). The benefits of periodic fire include (1) maintaining the physiognomic character of longleaf pine bunchgrass ecosystems by excluding invasive plants that are poorly adapted to fire, (2) preparing a seedbed favorable for the regeneration of longleaf pine seedlings, (3) reducing the density of understory vegetation and thus providing microsites for a variety of herbaceous plants, (4) stimulating increased seed production by native grasses, (5) releasing nutrients immobilized in accumulated phytomass for recycling to the infertile soil and subsequently more

Table 1—Plants associated with longleaf pine forest ecosystems

Category and common name	Scientific name
Trees	
Pignut hickory	*Carya glabra*
Sweetgum	*Liquidambar styraciflua*
Shortleaf pine	*Pinus echinata*
Slash pine	*P. elliottii*
Longleaf pine	*P. palustris*
Southern red oak	*Quercus falcata*
Bluejack oak	*Q. incana*
Turkey oak	*Q. laevis*
Laurel oak	*Q. hemisphaerica*
Blackjack oak	*Q. marilandica*
Water oak	*Q. nigra*
Post oak	*Q. stellata*
Shrubs	
Polecat bush	*Asimina incana*
Pawpaw	*A. triloba*
Groundsel tree	*Baccharis halimifolia*
American beautyberry	*Callicarpa americana*
Rosemary	*Ceratiola ericoides*
Coastal sweet pepperbush	*Clethra alnifolia*
Garberia	*Garberia fruticosa*
Dwarf huckleberry	*Gaylussacia dumosa*
Blue huckleberry	*G. frondosa*
Gallberry	*Ilex glabra*
Yaupon	*I. vomitoria*
Gopher apple	*Licania michauxii*
Rusty staggerbush	*Lyonia ferruginea*
Coastalplain staggerbush	*L. fruticosa*
Fetterbush lyonia	*L. lucida*
Wax myrtle	*Myrica cerifera*
Prickly pear	*Opuntia humifusa*
Chokeberry	*Pyrus arbutifolia*
Dwarf live oak	*Q. minima*
Running oak	*Q. pumila*
Winged sumac	*Rhus copallinum*
Scrub palmetto	*Sabal etonia*
Saw palmetto	*Serenoa repens*
Sparkleberry	*Vaccinium arboreum*
Shiny blueberry	*V. myrsinites*
Deerberry	*V. stamineum*
Adam's needle	*Yucca filamentosa*
Coontie	*Zamia pumila*
Vines	
Yellow jessamine	*Gelsemium sempervirens*
Morning glory	*Ipomoea* spp.
Virginia creeper	*Parthenocissus quinquefolia*
Vines (cont.)	
Blackberry, dewberry, raspberry	*Rubus* spp.
Greenbrier	*Smilax* spp.
Poison ivy	*Toxicodendron radicans*
Grape	*Vitis* spp.
Graminoids	
Splitbeard bluestem	*Andropogon ternarius*
Broomsedge bluestem	*A. virginicus*
Beyrich threeawn, wiregrass	*Aristida beyrichiana*
Pineland threeawn, wiregrass	*A. stricta*
Switchcane	*Arundinaria gigantea*
Common carpetgrass	*Axonopus fissifolius*
Ware's hairsedge	*Bulbostylis warei*
Sedge	*Carex* spp.
Toothache grass	*Ctenium aromaticum*
Nutsedge	*Cyperus* spp.
Rosette grass	*Dichanthelium* spp.
Purple lovegrass	*Eragrostis spectabilis*
Skeletongrass	*Gymnopogon* spp.
Cutover muhly	*Muhlenbergia capillaris*
Panicgrass	*Dichanthelium* spp.
Paspalum	*Paspalum* spp.
Beakrush	*Rhynchospora* spp.
Sugarcane	*Saccharum* spp.
Little bluestem	*Schizachyrium scoparium*
Nutrush	*Scleria* spp.
Lopsided indiangrass	*Sorghastrum secundum*
Curtis' dropseed	*Sporobolus curtissii*
Pineywoods dropseed	*S. junceus*
Purpletop tridens	*Tridens flavus*
Sand grass	*Triplasis* spp.
Forbs	
Figwort	*Scrophularia* spp.
Milkweed	Asclepias spp.
Scaleleaf aster	*Symphyotrichum adnatum*
Bushy aster	*A. dumosus*
Stiff-leaved aster	*A. linariifolius*
White-topped aster	*A. paternus*
Pinebarren white-topped aster	*Oclemena reticulata*
Wild indigo	*Baptisia lanceolata*
Soft greeneyes	*Berlandiera pumila*
Florida lady's nightcap	*Bonamia grandiflora*
Vanillaleaf, deer tongue	*Carphephorus odoratissimus*
Partridge pea	*Cassia chamaecrista*

continued

Table 1—Plants associated with longleaf pine forest ecosystems (cont.)

Category and common name	Scientific name	Category and common name	Scientific name
Forbs (cont.)		Forbs (cont.)	
Maryland goldenaster	*Chrysopsis mariana*	Candyroot	*P. nana*
Atlantic pigeonwings	*Clitoria mariana*	Wand blackroot	*Pterocaulon virgatum*
Treadsoftly	*Cnidoscolus stimulosus*	Meadowbeauty	*Rhexia* spp.
Rabbitbells	*Crotalaria rotundifolia*	Dollarleaf	*Rhynchosia reniformis*
Healing croton	*Croton argyranthemus*	Blackeyed susan	*Rudbeckia hirta*
Gulf croton, beachtea	*C. punctatus*	Helmet flower	*Scutellaria integrifolia*
Ticktrefoil	*Desmodium* spp.	Seymaria	*Seymaria* spp.
Elephant's foot	*Elephantopus tomentosus*	Rosinweed	*Silphium* spp.
Dogtongue buckwheat	*Eriogonum tomentosum*	Jeweled blue-eyed grass	*Sisyrinchium solstitiale*
Dogfennel	*Eupatorium capillifolium*	Queen's-delight	*Stillingia sylvatica*
Downy milkpea	*Galactia volubilis*	Sidebeak pencilflower	*Stylosanthes biflora*
Coastal bedstraw	*Galium hispidulum*	Hoarypea	*Tephrosia* spp.
Sunflower	*Helianthus* spp.	Noseburn	*Tragia* spp.
Hawkweed	*Hieracium gronovii*	Forked blue curls	*Trichostema dichotomum*
St. Johns-wort	*Hypericum* spp.	Ironweed	*Veronica angustifolia*
Bush clover	*Lespedeza* spp.	Violet	*Viola* spp.
Blazing star	*Liatris* spp.	Carolina yelloweyed grass	*Xyris caroliniana*
Carolina lily	*Lilium michauxii*	Ferns	
Shortleaf lobelia	*Lobelia brevifolia*	Cinnamon fern	*Osmunda cinnamomea*
Sensitive plant	*Mimosa* spp.	Western brackenfern	*Pteridium aquilinum*
Partridgeberry	*Mitchella repens*	Lichens	
Woodsorrel	*Oxalis* spp.	Reindeer lichen	*Cladonia subtenuis*
Virginia plantain	*Plantago virginica*		
Orange milkwort	*Polygala lutea*		

rapid uptake by plants, (6) improving forage for grazing, (7) enhancing wildlife habitat, (8) controlling harmful insects and pathogens, and (9) reducing fuel levels and the wildfire hazard (Brennan and Hermann 1994, Dickmann 1993, Haywood and others 2001, Landers and Boyer 1999, Lemon 1949, McKee 1982, Outcalt 1994, Wade and Lewis 1987, Wade and Lundsford 1990). Fire at intervals as frequent as 2 to 4 years may provide such benefits in these ecosystems without need for measures to protect regeneration. However, recurrent fire in any season can be responsible for growth losses in overstory longleaf pines ranging from 10 to 18 percent (Boyer 2000). Trading these losses for the benefits described above seems worthwhile, especially because the negative effect of fire on growth of longleaf pine trees is greatest at younger ages and diminishes with time.

Prior to landscape fragmentation, natural fires occurred every 2 to 8 years throughout much of the region (Abrahamson and Harnett 1990, Christensen 1981). Longleaf pine was dominant over large areas primarily because it is more tolerant of frequent fire than competing species with thinner-barked seedlings. Although longleaf pine seedlings are very susceptible to fire-caused mortality during the first year following germination, they become increasingly resistant to fire in subsequent years. A unique adaptation of longleaf pine to its fire-prone environment is a seedling "grass stage," during which root growth is favored and the seedling top remains a tuft of needles surrounding a large terminal bud. Because there is no stem, no cambium is directly exposed to damage from surface fires. When sufficient root reserves have accumulated, grass-stage longleaf pine seedlings "bolt" or "rocket," rapidly growing 1 to 2 m in a short time. Such rapid growth puts the terminal bud beyond the lethal reach of most surface fires. Larger longleaf pine trees have relatively 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. The tendency of longleaf pine to regenerate more successfully in forest openings than directly beneath mature trees where long-term survival is poor (Brockway and Outcalt 1998) limits the development of ladder fuels near the crowns of adult trees.

Longleaf pines have the biological potential to live for 500 years, but they seldom survive this long because they exist in an environment that is subject to frequent disturbance (Engstrom and others 2001, Palik and Pederson 1996). Damaging tropical storms, such as hurricanes and the tornadoes associated with them, may fell extensive areas of trees and open numerous gaps in the canopy of longleaf pine forests (Croker 1987). Lightning is another important mortality agent, typically killing individual trees but sometimes striking small groups of trees (Komarek 1968, Palik and Pederson 1996, Taylor 1974). Although insect infestations are uncommon, annosus root rot (*Heterobasidion annosum*), pitch canker (*Fusarium moniliforme* var. *subglutinans*), cone rust (*Cronartium strobilinum*), and other pathogens may infect longleaf pine (Boyer 1990b). Epidemics of brown-spot disease (*Mycosphaerella dearnessii*) occasionally occur in young longleaf pines, and this pathogen is usually fatal unless a surface fire consumes the infected needles and cleanses the stand of innoculum (Boyer 1990b, Wright and Bailey 1982). Fire acts as a principal disturbance agent, influencing many attributes and processes in longleaf pine ecosystems (Christensen 1981, Noss 1989). The long-term result of frequent surface fires is a forest composed primarily of pyrophytic vegetation and other plant and animal species whose life cycles are adapted to the prevailing disturbance regime (Brockway and Lewis 1997, Engstrom and others 2001, Landers 1991). The structure, pattern, and biological diversity in these forest ecosystems are maintained by a combination of disturbance events and site factors. Variation in lightning strikes, tree mortality, and animal interactions at local scales, and wind storms, soil attributes, and hydrologic regimes at broader scales influence the landscape mosaic. Such forces acting across site gradients provide for large living trees, snags, coarse woody debris, hardwood thickets, and forest canopy gaps in this disturbance-prone, yet largely stable ecosystem.

Longleaf pine is shade-intolerant, and its regeneration is largely confined to canopy gaps (Wahlenberg 1946). Establishment of pine seedlings in gaps at different times results in a network of forest patches at various stages of development dispersed across the landscape (Pickett and White 1985). These gap-phase regeneration dynamics give rise to the pattern of even-aged patches distributed across an uneven-aged landscape mosaic commonly observed in natural longleaf pine ecosystems (Palik and others 1997). Canopy gaps resulting from a variety of disturbance agents have recently been recognized as ecologically important features driving the forest cycle through open, growth, and closed phases (Coates and Burton 1997, Whitmore 1989) and may serve in longleaf pine forests as vehicles through which to apply silviculture that is modeled after natural disturbance (Palik and others 2002).

Conditions that ensure reliable regeneration are essential for restoring and sustaining longleaf pine forest ecosystems and can be achieved by combining frequent fire with natural regeneration techniques (Boyer and White 1990). Both abundance and growth of seedlings are negatively related to the presence of adult longleaf pines, which have a competitive influence on seedlings that extends > 15 m into forest gaps (Boyer 1963; Smith 1955; Walker and Davis 1954, 1956). Naturally regenerated longleaf pine seedlings on xeric sandhills cluster near the center of canopy gaps, in an area corresponding to a fine-root gap surrounded by a seedling exclusionary zone (SEZ) approximately 12 to 16 m wide (Brockway and Outcalt 1998). Over many years of competition and repeated fires, seedling density declines more rapidly in the SEZ than near the gap center. This fine-root gap and SEZ structure has not been observed during the short term in newly created gaps on more mesic sites containing greater numbers of woody plants (Gagnon and others 2003, McGuire and others 2001, Palik and others 1997). While a number of even-aged and uneven-aged approaches appear to be compatible with restoring and sustaining longleaf pine ecosystems (Boyer 1993, Farrar 1996, Guldin 1996), silvicultural methods such as group selection and irregular shelterwood, which mimic the pattern of natural disturbance and thus facilitate the normal ecological process of forest regeneration, are especially well suited for these purposes (Brockway and Outcalt 1998).

Ecological Significance

The complex natural pattern and disturbance-mediated processes that characterize longleaf pine forests create extraordinarily high levels of biological diversity in these ecosystems. The great number of plant species per unit area qualifies longleaf pine forests as among the most species-rich terrestrial ecosystems in the temperate zone. As many as 140 species of vascular plants have been observed in a 1000-m^2 area, and > 40 species/m^2 have 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. Among these are two increasingly rare animals that function as important primary excavators. Tree cavities created by red-cockaded woodpeckers and ground burrows dug by gopher tortoises provide homes for a wide variety of secondary users such as insects, snakes, birds, and mammals (Engstrom 2001, Jackson and Milstrey 1989, Speake 1981).

The longleaf pine forests and savannas of the Southeastern Coastal Plain are among the most critically endangered ecosystems in the United States, now occupying < 3 percent of their original extent (Noss and others 1995, Ware and others 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 has principally 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 and others 1995, Wear and Greis 2002). Edaphic variation and land use history, particularly as related to soil disturbance or agriculture, have significant influences on the diversity of understory plants (Hedman and others 2000, Rodgers and Provencher 1999). Frequent fire in differing seasons is appropriate for maintaining a greater variety of native plant species (Hiers and others 2000, Kirkman and others 1998a). However, long-term exclusion of fire typically results in depressed species diversity, development of a substantial hardwood understory and midstory, and accumulation of a thick layer of forest litter (Brockway and Lewis 1997, Kush and Meldahl 2000). Such buildup of forest fuel can transform surface fires into crown fires that can have catastrophic effects on the rare plants and animals. 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 many biotic communities embedded in the forest landscape matrix (Landers and others 1990). Many of these adjacent communities require periodic fire to maintain their ecological structure and health (Kirkman and others 1998b). Fires typically begin in pyrogenic longleaf pine forests and then spread into adjoining habitats such as seepage slopes, canebrakes, treeless savannas, and sand pine scrub. Without periodic fire, these communities, like longleaf pine ecosystems, change in ways that make them less suitable habitats for plants and animals that have evolved with fire. Continued degradation and eventual loss of longleaf pine forests from the southern landscape would not only be tragic for longleaf pine ecosystems, but could very well prove catastrophic for the numerous embedded biotic communities that are ecologically linked to them. The ecological imperative for restoring and sustaining these forest ecosystems is very clear.

History of Longleaf Pine Ecosystems

During the Wisconsinan Ice Age (~ 40,000 to 12,000 years BP), forests in the southern region consisted of boreal elements (*Picea, Pinus*) and temperate species (*Carya, Castanea, Ostrya, Quercus*) intermixed in a pattern that varied both spatially and temporally with the ebb and flow of the vast ice sheet farther to the north (Delcourt 1980, Watts 1970, Watts and others 1992). As the continental glacier retreated, southern forests became dominated by oaks and a diverse array of deciduous hardwoods after 12,000 years BP (Watts 1971, Watts and Hansen 1988, Watts and others 1992). Longleaf pine, moving northward and eastward from its Ice Age refuge in southern Texas or northern Mexico (Schmidtling and Hipkins 1998), became established in the lower Coastal Plain ~ 8,000 years ago (Watts and others 1992) and during the ensuing 4,000 years spread throughout the Southeast (Delcourt and Delcourt 1987). This several-thousand-year pre-Columbian time period coincides with the interval during which populations of Native Americans flourished throughout the region, and their use of fire is thought to be related to the development and maintenance of longleaf pine forest ecosystems (Landers and Boyer 1999, Pyne 1997, Schwartz 1994).

Native Americans frequently used fire to manipulate their environment (Anderson 1996, Carroll and others 2002, Robbins and Myers 1992, Stanturf and others 2002), and early European settlers adopted the practice of periodically burning nearby forests and woodlands to improve forage quality for cattle grazing and discourage the encroachment of shrubby undergrowth. Although well adapted to frequent surface fires, longleaf pine was not well adapted to other disturbances brought by European settlement. As a result of the cumulative impacts brought by three centuries of changing land use, longleaf pine forests declined dramatically. By 1900, logging, harvest of naval stores (chemicals derived from pine resin), and agriculture had reduced by more than half the area dominated by longleaf pine (Frost 1993). Logging continued until only fragments of the original longleaf pine forest remained in 1935. Second-growth longleaf pine stands became reestablished 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). Over the next decade, longleaf pine was further reduced until it occupied < 5 percent of its original area (Outcalt and Sheffield 1996).

The effects of settlement on longleaf pine forests were initially minor, with harvesting limited to areas near early towns and villages where log structures were constructed (Croker 1987). Later, lumber was cut from longleaf pine logs using hand-powered pit-saws, which yielded only a few rough boards per day. By the 1700s, water-powered sawmills became common, but log transportation was inefficient and still largely confined to rivers (Frost 1993), with logging conducted on 5- to 6-km-wide strips along rivers, where logs could be dragged by oxen or horses and floated to the mill (Croker 1987). This so limited harvesting that, by the end of the Revolutionary War, most longleaf pine forests remained intact. After 1830, removal of longleaf pine accelerated significantly with the arrival of steam railroads, which were soon followed by the use of steam skidders. By 1880, most of the longleaf pine along streams and railroads had been harvested (Frost 1993). During the next 40 years, the great forests of yellow pine were harvested, with temporary railroad spur lines laid down every quarter mile (Croker 1987). Skidders dragged logs to these spur lines, often destroying all trees too small to harvest, and left a scarred and mostly barren landscape. Longleaf pine forests were harvested from Virginia and the Carolinas south to Georgia and Florida, then west through Alabama and Mississippi, into Louisiana and finally Texas. During 1896, 11.1 million m^3 of yellow pine timber was cut and shipped to the northern United States and overseas markets (Mohr 1896). 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.

Extraction of naval stores by cutting wound faces in the bark of longleaf pine trees began with the first European settlements (Frost 1993) and continued until the 20th century, when it was supplanted by the petroleum industry. Because the pitch-soaked faces on these trees would readily ignite, many forests worked in this manner were destroyed by wildfire following abandonment. About two-thirds of the sites where longleaf pine was harvested or burned by wildfires following naval stores extraction were later colonized by other tree species. Loblolly pine (a prolific seed producer) captured mesic Coastal Plain sites, slash pine invaded wetter flatwoods areas, and shortleaf pine and hardwoods became dominant on upland sites. Irregular seed production, with good seed years occurring at intervals ≥ 5 years (Boyer 1990b), impaired longleaf pine recovery and contributed to these losses. Even where longleaf pine seedlings survived logging, they were often consumed by feral hogs (*Sus scrofa*), causing many areas of potential longleaf pine forest to be lost (Schwarz 1907). Large areas of longleaf pine forest were also converted to agriculture, beginning with early settlers who, like Native Americans, began by girdling trees and planting crops between dead standing snags. The settlers later burned the snags and burned or dug out the stumps. Annual burning to improve forage for livestock grazing frequently eliminated newly germinated longleaf pine seedlings. Between 1750 and 1850, most of the more fertile longleaf pine sites were converted to fields or pastures (Frost 1993), thereby removing longleaf pine from the best upland areas. Although most of the sandhills, flatwoods, and mountain soils are poorly suited to agriculture, some were converted to pasture (Landers and others 1990). Florida was an exception, where sandhills sites are well suited for citrus fruit production (Mohr 1896).

By the 1940s, harvesting second-growth longleaf pine became an established practice, and construction of kraft-process pulp mills in the 1950s created demand for smaller trees. These developments accelerated conversion of naturally regenerated longleaf pine forests into plantations of species that grow more rapidly in the short term. Because of its slower early growth and lower survival rate, longleaf pine was seldom selected to reforest harvested lands. Thus, many second-growth longleaf pine stands on public and industrial lands were clearcut, mechanically site prepared, and planted with loblolly pine or slash pine. Nonindustrial private landowners often relied on natural regeneration following harvest, and because insufficient longleaf pine seed was often present, many of these sites regenerated into loblolly pine or slash pine forests. Old fields were also planted with these more rapidly growing species or colonized by them through seeding from adjacent areas. The result was a continuous decline in the area occupied by longleaf pine ecosystems. Substantial future losses on private lands remain possible, because most of these longleaf pine stands consist of trees in the valuable sawtimber- and pole-size classes.

Reduction in the frequency of fire further contributed to conversion of longleaf pine lands to other species. Extensive logging during the late 19th and early 20th centuries created very heavy loads of downed fuel, and this fuel supported numerous large wildfires that caused many areas to be devoid of trees. Foresters then began to advocate excluding all fire from the woods to protect young trees and allow for reestablishment of the forest. Although some individuals recognized the natural and essential role of fire in longleaf pine ecosystems (Harper 1913), most people viewed fire as harmful. Since fire control practices aided in establishment of new forests, even though they were usually loblolly pine or slash pine, these procedures were adopted as good forestry practices throughout the region (Frost 1993).

Young hardwoods are quite susceptible to mortality from fire, and frequent fires typically limit hardwoods to a small stature in longleaf pine stands (Komarek 1977, Landers and others 1990). Occasionally, random variation in fires or protective microsite conditions allowed hardwood stems to survive several fires and become large enough to resist future surface fires (Rebertus and others 1993). Thus, scattered hardwood trees occurred in the canopy or subcanopy of longleaf-dominated forests (Greenberg and Simons 1999). However, in the absence of fire, hardwoods are able to quickly emerge from the understory and form a dense midstory that shades out herbaceous species and longleaf pine seedlings. Without frequent fire, hardwoods will ascend to eventually dominate the overstory, degrading sites not captured by other pines (fig. 3). Although the importance of fire in maintaining a healthy longleaf pine ecosystem is now widely recognized, many forests on private lands are still not burned regularly. Recent burning rates on private lands range from a high of 48 percent in Georgia to a low of only 15 percent in North Carolina (Outcalt 2000). Some stands are difficult to burn because they are close to urban areas and highways. Smoke from fires in such locations can have costly offsite effects. This problem is likely to grow worse as population growth creates more wildland-urban interface zones. Also, longleaf pine stands on private lands are small, and this makes burning them more expensive. Because of infrequent burning, many private lands containing longleaf pine are likely to suffer further habitat degradation.

Since European settlement, longleaf pine lands have been lost to urban and residential uses. From 1987 to 1995, conversion of longleaf pine land in Florida to other uses resulted in loss of 37 000 ha of these ecosystems. During this 8-year period, ~ 3000 ha/year were converted from longleaf pine to urban uses, and 1500 ha/year were lost to agriculture (Outcalt 1998). Similar losses occurred in Georgia, while losses in North Carolina and South Carolina were at about half this rate. Future growth of the regional population and expected expansion of industrial plantations will likely result in a continuing decline of longleaf pine ecosystems on private lands.

Social, Political, and Economic Context

Longleaf pine ecosystems have been very important in the Southeastern United States, providing an environmental setting and raw materials for social development in this region. Wild game, forage grasses, wood, and naval stores were principal products of these forests (Franklin 1997).

Figure 3—Former longleaf pine site invaded and occupied by oak.

During the early 20th century, affluent landowners, recognizing the value of longleaf pine forests as habitat for northern bobwhite and white-tailed deer, acquired large tracts to serve as hunting plantations. Many large areas of longleaf pine exist today because of the opportunities for hunting and timber harvesting provided by these lands. The appearance of these forests was also pleasing to many people, as it is today.

Although longleaf pine forests were valued by society, human activities played a major role in their decline, with economic exploitation continuing until the future of these ecosystems appeared quite bleak. However, a combination of recent developments provides new hope that the negative trend for longleaf pine forests can 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. The presence of longleaf pine on public lands has begun to increase as a result of concerted efforts to establish new stands and restore degraded longleaf pine forests with fire and other appropriate techniques (Hilliard 1998, McMahon and others 1998). Interest in longleaf pine reforestation on private lands has surged recently because of incentives to private landowners 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 come to appreciate the natural heritage that will be lost if restoration of these ecosystems is not undertaken. No single entity dominates land ownership in longleaf pine ecosystems, but a common sense of urgency among numerous groups has fostered partnerships that did not exist in the past. The Nature Conservancy, Tall Timbers Research Station, Joseph W. Jones Ecological Research Center, U.S. Department of Agriculture (USDA) Forest Service, U.S. Department of Interior 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 about the regeneration, restoration, and management of longleaf pine ecosystems. It facilitates communication among these groups and provides training for private landowners who are interested in successful longleaf pine regeneration.

The Federal Government uses financial incentives and technical assistance programs to promote restoration of longleaf pine ecosystems (table 2). Modest expansion of these forests was realized when, for a 2-year period, longleaf pine was the most frequently selected tree species for planting because of incentives offered through the Conservation Reserve Program (CRP). Federal tax laws also provide incentives for reforestation activities. In addition to these Federal programs, seven Southeastern States have cost-share programs that encourage landowners to establish and maintain longleaf pine forests. All State forest management agencies in the region also offer free management planning assistance to nonindustrial private forest landowners. In aggregate, these public programs have greatly encouraged establishment of new longleaf pine forests and contributed to the rehabilitation of degraded

Table 2—Federal Government programs promoting restoration of longleaf pine ecosystems

Program	Assistance, incentives, and purpose
Conservation Reserve Program	Financial incentives to landowners for planting and maintaining trees on designated nonforested land
Forestry Incentives Program	Partial reimbursement for costs of establishing new forests, by means of natural or artificial regeneration, and costs of stand improvement
Forest Stewardship Program	Education and technical assistance to landowners who manage forestlands for multiple resource benefits
Partners with Wildlife Program	Cost-share assistance to landowners for restoring longleaf pine habitats
Safe Harbor Program	Encourages voluntary habitat restoration by offering landowners incentives to preserve habitat of federally protected species

longleaf pine ecosystems. However, recently adopted Federal and State laws and regulations that are intended to improve or maintain air quality standards represent a serious challenge to management efforts to burn these forests often enough to restore and sustain them. Mandated smoke management requirements restrict prescribed burning to a narrower set of conditions than in the past, thus reducing the number of possible burning opportunities during the year.

Establishing longleaf pine is more expensive than establishing other southern pines. The price for bare-root seedlings of longleaf pine is about twice that of loblolly pine, because nurseries must grow longleaf pines at wider spacings to produce large seedlings suitable for planting. Seedling prices for containerized longleaf pine are even higher, because greater labor and materials costs are involved. Planting costs are often somewhat higher for longleaf pine than for other pine species, because longleaf pine seedlings require greater care during the planting process.

However, once established, longleaf pine becomes a low-risk investment that is easily managed with prescribed fire, resistant to most pathogens and insects, and inexpensively renewed through natural regeneration. The superior growth form and wood quality of longleaf pine also produces excellent sawtimber. Typically 50 to 80 percent of the trees in forests of naturally regenerated longleaf pine are suitable for producing poles and pilings (Boyer and White 1990). For these reasons, longleaf pine can be marketed at stumpage prices 50 percent greater than those paid for the sawtimber of other southern pines. Longleaf pine forests can be managed to produce quality poles on a 40- to 60-year rotation (Franklin 1997). Also, recent evidence suggests that the rate of timber volume growth for longleaf pine is actually ~ 35 percent greater than previously believed, which indicates that the past lack of appreciation for longleaf pine may have been related to a systematic underestimation of its productive potential (Boyer 2001). In many areas, the high-quality pine straw (i.e., fallen pine needles) produced by longleaf pine provides additional income for landowners and processors, who market it as a landscape mulch (Williston and others 1990).

Restoration Perspectives

Large-scale logging of native forests; conversion to agricultural, industrial, and residential uses; landscape fragmentation; invasion by aggressive species; and interruption of natural fire regimes have all contributed to the historical decline of longleaf pine ecosystems. This trend continued for many decades until the increasing threat to numerous rare plant and animal species and their habitats resulted in a growing social awareness that a very important part of the South's natural heritage was in jeopardy (Means and Grow 1985, Noss and others 1995). Because longleaf pine still occurs over most of its natural range, albeit in isolated fragments, it is reasonable to conclude that restoration of these ecosystems is feasible (Landers and others 1995). Although the long-term negative trend has been recently slowed (reversed on public lands but continuing on private lands), resource assessments forecast a continuing overall decline without active intervention to reverse these losses. While the need for ecological restoration is clear, the choice of methods and the extent to which it should be pursued to ensure long-term ecosystem viability are less clear.

Defining Restoration

Although general definitions of restoration emphasize returning to a former state, it is not the goal of ecological restoration to recreate conditions that existed in North America prior to European contact in 1492. An essential element of all historically focused restoration approaches has been the description of a historically based reference condition, which enumerates the ecological attributes of the native ecosystem (Covington and others 1997, Moore and others 1999, Palik and others 2000, Wagner and others 2000). The degree to which restoration objectives are achieved may then be assessed by mathematically comparing existing community composition with that in the reference condition (Provencher and others 2001). Although such approaches are well intended, returning an ecosystem to pre-European conditions or any other arbitrary point in history is both impractical and impossible for many reasons. Since the Age of Exploration and the Industrial Revolution, human impacts on North American ecosystems have led to extensive landscape domestication and fragmentation. Human activity is also responsible for the widespread occurrence of exotic species and extirpation of many native species. Early records do not provide reliable, detailed data about the composition, structure, and processes in indigenous ecosystems (White and Walker 1997). Restoration efforts based on such limited information would overlook key ecosystem components and processes.

Ecosystem variability is so strongly dependent on scale, or affected by humans, that identification and application of meaningful and relevant historical data for management is essentially impossible. Poorly conceived reference conditions could be used by naive scientists and managers to define a misguided, impractical, or expensive template for the future (Parsons and others 1999). Much of what European immigrants perceived as "pristine wilderness" was actually occupied for > 12,000 years by millions of native people who, although living in preindustrial societies, actively managed their landscape through extensive use of fire and other available technology (Pyne 1997, Pyne and others 1996). By the time significant numbers of immigrants arrived, many of these lands were depopulated of their native inhabitants by newly introduced diseases and occupied by woody vegetation that had invaded former village sites and abandoned agricultural fields during the ensuing decades (Stanturf and others 2002). Thus, much of what is recorded in the journals of early explorers, naturalists, and settlers is the product of both natural processes and the actions of Native Americans (Carroll and others 2002).

Finally, the ecosystems of today are substantially different from those of the past not only because of biological alteration, but also because their physical environment has slowly changed. Natural variations in climate have influenced the establishment and development of forests for millennia. Many forests were initiated during periods when temperatures were much cooler. The composition, structure, and process dynamics of forests that thrived during cooler climatic periods such as the Little Ice Age (1350 to 1850) probably differ from those forests that developed during the 20th century, when temperatures became significantly warmer (Millar and Woolfenden 1999). Therefore, while it may not be desirable or even possible to restore forest ecosystems with historical authenticity, it is quite possible to restore them with natural authenticity; that is, to restore them to a condition in which compositional, structural, and functional components are present within an appropriate physical environment that sustains the ecological processes essential for (1) native species perpetuation and evolution, (2) ecosystem resiliency to disturbance and adaptation to long-term environmental change, (3) providing goods and services for human societies, and (4) harboring rare and endangered species and otherwise conserving biological diversity (Clewell 2000).

Perhaps the broadest definition of ecological restoration is "an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability" (Society for Ecological Restoration International 2002). The National Research Council explains ecological restoration in more detail as "the return of an ecosystem to a close approximation of its condition prior to disturbance; both the structure and the functions of the ecosystem are recreated; merely recreating the form without the functions, or the functions in an artificial configuration bearing little resemblance to a natural resource, does not constitute restoration; the goal is to emulate a natural, functioning, self-regulating system that is integrated with the ecological landscape in which it occurs" (Cairns 1995). These and other definitions raise a number of questions, not the least of which are, "What were predisturbance forest and landscape conditions like, and how have they changed?" and "In view of these changes, how can restoration actions most effectively establish a biotic community that is now suited to the prevailing environment?" Although restoration can never legitimately be a return to the past, an awareness of historical alteration of biota, previous erosion of soils, and former fluctuations and current trends in climate are among the many factors that must be considered. Much like trying to hit a moving target, attempting to restore a previously existing historical ecosystem is less important than matching plant species to site conditions, reestablishing essential natural processes, and mitigating potential threats to the current and future ecosystem (Allen and others 2001).

Measuring Success

Measuring success, with restoration approaches that utilize a vaguely defined historical reference condition as the target, creates inherent difficulties for practitioners. In most instances, appropriate reference areas are largely unavailable, and those that do exist are often degraded by impaired ecological processes and/or past human disturbances that are not readily apparent. Thus in selecting a site as a historical reference area, the individual may, in fact, be choosing a site that is partly or even wholly an artifact of human disturbance on a temporal and/or spatial scale that is not easily recognized. Monitoring schemes which use a historical reference condition to evaluate the progress of restoration typically focus on species similarity, with metrics that merely evaluate the degree to which the biotic community on the reference site is replicated on the site being restored. Little if any regard is accorded the unique ecological attributes of each site that influence community development. Monitoring and evaluation of this type represents a nondynamic approach to restoration that is reflective of a single-condition ecosystem model and analogous to outmoded notions like "climax" and "the balance of nature." Such a static approach will not adequately account for natural disturbance, disequilibrium, and dynamic change in the ecosystem.

Restoration approaches that emphasize the functional nature of ecosystems will likely be more feasible alternatives by reestablishing biota that are compatible with the dynamic changes in present and future ecosystems. Key attributes to be restored include (1) species composition, (2) vertical structure, (3) horizontal pattern, (4) spatial heterogeneity, (5) properly functioning ecological processes, and (6) ecosystem resiliency sufficient to permit recovery from disturbances at multiple scales (Hobbs and Norton 1996). Although the restoration process must identify and mitigate to the degree possible forces that threaten ecosystem integrity, looking beyond historical conditions, it must also accommodate those factors of change that cannot be mitigated and establish a community that is suitably adapted to prevailing environmental conditions. Monitoring is essential and must include data gathering, analysis, and meaningful interpretation that produce useful feedback for the adaptive management process. Although monitoring need not always be sophisticated to be effective, numerous variables related to (1) plant and animal communities, species, and populations; (2) soils, hydrology, and water quality; (3) landscape patterns and functions; and (4) ecological processes and response to disturbance events can be measured (Allen and others 2001). The values of such variables may then be compared with values falling either inside and outside the range of natural variability (Hobbs and Norton 1996).

In an integrated analysis of structure and function, monitoring data are compared with values for ecosystem attributes that facilitate the functioning of natural processes, including recovery from disturbance. Recognizing the widely variable nature of natural longleaf pine ecosystems, the acceptable range of values for many of these attributes will be quite broad. Structurally, success should strive for 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 in the native range, a smaller component of other tree species, such as slash pine or oaks, may be present. These may occur singly or in clusters. Generally, the midstory should be absent or mostly composed of ascending longleaf pines. The understory should be dominated by native grasses and forbs, and few shrubs and vines should be present. Because the composition and abundance of graminoids varies greatly throughout the native range of longleaf pine, specific quotas for representation of individual species (e.g., a specific percent cover for wiregrass) are inappropriate. Functionally, success should consider 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. Reductions in habitat fragmentation, population isolation, and species rarity will be achieved by augmenting existing longleaf pine fragments and creating new habitat patches, increasing connectivity among existing fragments and new habitat patches, and facilitating the role of fire at local and landscape scales to improve habitat quality and enhance biological diversity.

Future Ecosystems

Sole reliance on natural processes may require decades or even centuries to restore degraded ecosystems. Where threatened ecosystems need urgent attention, restorationists must identify environmental problems and intervene with remedial treatments (Dobson and others 1997). Although factors that are unknown or beyond their control may frequently cause restorationists to accept partial solutions to the challenges confronting them, inability to completely restore ecosystems does not diminish the importance of restoring the understood ecological functions and resource values. Using an holistic approach, ecological communities should be established, to the greatest degree possible, that not only resemble original forests but are also well suited to prevailing and future environmental conditions (Allen and others 2001). In longleaf pine forests, the restoration focus is on reestablishing the natural ecosystem structure and function through (1) adjusting composition by favoring native species and suppressing undesirable species, (2) modifying vertical and horizontal structure at the local and landscape scales to provide a full range of habitat conditions that are appropriately interconnected, and (3) ensuring that ecological processes such as periodic fire and natural longleaf pine regeneration remain fully operational at multiple spatial and temporal scales. Restoration is a long-term incremental process of serial approximation, where all gains are valued as forests are progressively transformed from degraded to healthy conditions. Successful restoration requires more than just establishing overstory trees and must also include improving, and establishing where necessary, understory plants and all other appropriate ecosystem components. It may often be best to restore a vigorous cover of native understory plants before establishing the overstory.

Encouraged by ecosystem management policies, cooperative partnerships between research scientists and land managers have facilitated a more effective application of ecological knowledge and silvicultural techniques for addressing forest ecosystem restoration challenges in an adaptive management framework. As application of ecological theory has benefited land management, the practice of ecological restoration will continue to provide insights into the way that ecological communities are assembled and ecosystems function (Dobson and others 1997). A relatively recent advance in this realm has been a greater appreciation for the importance of ecological thresholds and an improved understanding of nonlinear succession processes that appear to be highly relevant to disturbance-prone ecosystems (Friedel 1988, 1991; Westoby and others 1989). Since transforming a degraded ecosystem into a more desirable condition through accelerating biological change or reinitiating succession is the principal paradigm of restoration ecology, the restoration process requires redirecting development of the ecosystem along a trajectory that is assumed to have existed prior to disturbance (Aronson and others 1993). However, ecosystems under stress do not always exhibit an orderly gradual development as suggested by classical succession theory (Clements 1916), but often undergo rapid transitions among multiple metastable states (Drake 1990, Hobbs 1994). These transitions are indicative of a nonlinear successional process with threshold responses to management activities and environmental factors, especially those that generate acute or chronic disturbances.

The occurrence and persistence of particular ecosystem states depend on specific combinations of driving forces, and once an ecosystem proceeds beyond a threshold condition, massive management inputs may be required to restore it to its former state (Hobbs and Norton 1996). Restoration may be viewed as attempting to force transitions toward a more desirable state, an effort that requires knowledge about the factors that must be manipulated to successfully cross or recross these thresholds. The fact that alternative stable states are possible for any individual location even under natural conditions should cause us to reflect carefully when establishing goals for restoration and sharply calls into question restoration efforts based on nondynamic, historically referenced, single-condition ecosystem models (Brockway and others 2002).

When a degraded ecosystem has not yet crossed a critical threshold, removal of the degrading influence may be all that is required to encourage restoration; however, if an important threshold has been crossed, then simply removing the degrading influence will not be sufficient to allow transition back to an approximation of the former state (Hobbs and Norton 1996). Rather, active intervention will be required. Critical thresholds in terrestrial ecosystems have been linked to the magnitude, frequency, and sequencing of multiple disturbances in the physical environment (i.e., windstorms, floods, fire, drought, soil erosion). These thresholds may also involve important changes in functional groups of plants, with transitions between states being much more difficult when one functional group is largely displaced by another (Hobbs 1994, 1996).

A fundamental challenge for restoration ecology is the problem of developing practical and cost-effective methods for forcing these transitions (Hobbs and Norton 1996). An ecological model, using principles from the theory of multiple stable states, has been proposed for restoring longleaf pine ecosystems, without returning them to presettlement conditions (Walker and Boyer 1993). Such an approach could go a long way toward reestablishing continuous forests similar to the Dauerwald of Europe, in which naturally regenerating indigenous forest ecosystems have been restored on suitable sites and are sustained along with other native species in an uneven-aged landscape matrix that provides high-quality habitat for conserving biological diversity and goods and services for human societies (Schabel and Palmer 1999).

Restoration Methods

Restoration Framework

Recent research has produced a wealth of knowledge and experience about the restoration of longleaf pine ecosystems. Valuable restoration techniques are also being developed by forestland managers who are making observations and using monitoring procedures in successful application of adaptive management strategies. Despite these advances, the remaining uncertainty has fostered debate about the best approaches for restoring longleaf pine ecosystems. This debate has focused on whether restoration is best achieved by (1) a passive approach, (2) restoring structure, (3) restoring function, or (4) restoring both structure and function. The passive or non-manipulative approach is based on the belief that protection from all natural and human disturbances is the best alternative and was the chosen option for much of the 20th century, when fire exclusion was a major emphasis. The restoring function approach is tested by use of prescribed fire in longleaf pine forests and is based on the idea that fire is the principal natural driving force for development and maintenance of these ecosystems. The restoring structure approach is tested by using mechanical treatments to remove invasive woody plants and is based on the idea that an ecosystem that is outside its range of natural variation requires intervention to restore forest structure and ecosystem health. The structure and function approach employs both mechanical treatments to manipulate structure and reintroduction of fire as an ecological process.

Desirable changes in longleaf pine communities can be achieved by using a variety of methods, machines, and products, singly or in combination. Physical or mechanical treatments include complete overstory harvesting, 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 reduce undesirable plants. Prescribed fire may also be used to reduce midstory, understory, and occasionally overstory layers and encourage fire-tolerant plants. In fact, frequent fire is crucial for ecosystem restoration, and the use of other treatments should be planned so as to facilitate the eventual application of prescribed fire. In highly degraded ecosystems, biological approaches such as reintroducing extirpated species will likely be required for full restoration. Each type of treatment could be appropriate for restoring particular longleaf pine ecosystems, depending on their current condition, location, and ownership.

Selecting Techniques

Historical events and changing patterns of land use have resulted in an array of sites in various conditions that are candidates for restoration of longleaf pine ecosystems. While about 1.2 million ha currently support an overstory of longleaf pine (Outcalt and Sheffield 1996), only 0.5 to 0.8 million ha of these lands have intact native understories (Noss 1989). Additional candidate areas exist that have overstories with little longleaf pine and understories that range from having most of the native species to some that are highly altered by past disturbance (Outcalt 2000). This variety of conditions exists throughout the range of longleaf pine, on sites from dry sandhills to wet savannas. Suitable restoration techniques depend on the site type and degree of ecosystem degradation (table 3). The types of longleaf pine ecosystems discussed in the following section on restoration prescriptions 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.

Restoration Prescriptions

Exclusion of fire from many existing longleaf pine forests allowed forest fuels to accumulate to hazardous levels and permitted substantial expansion of understory shrubs and hardwoods. Although the introduction of dormant-season prescribed burning reduced the fuel buildup, midstories were often so far advanced that they were only minimally affected by these cool-season fires. To restore these ecosystems more fully, it is necessary to reintroduce growing-season fire, the ecological process that most effectively creates and maintains the structure, composition, and function of such forests. Growing-season burning is usually conducted from March to July, with the period from late August through September avoided to prevent excessive mortality among young longleaf pines (Robbins and Myers 1992).

Some longleaf pine forests, such as those on wet sites (i.e., flatwoods), may require biennial burning over a period of several decades to substantially improve understory composition and structure. Where it took > 30 years of dormant-season burning (every 4 to 6 years) for the understory to reach its current status, there is no reason to expect that this condition can be reversed with a single fire or during a 5-year period. As long as the sequence of treatments is progressively changing the community along a desired trajectory, then progress is being made toward eventual restoration.

Xeric and subxeric sandhills dominated by longleaf pine with native understory—In many existing longleaf pine forests, the lack of frequent fire 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. However, because moisture and nutrients are very limited on these sites, they do not develop a continuous closed canopy of midstory hardwoods even in the absence of frequent fire. Therefore, some of the understory grasses survive. These grasses and the needle litter from longleaf pines can carry at least a patchy prescribed fire. Repeated

Table 3—Prescriptions for restoring longleaf pine ecosystems in varying degrees 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 harvesting 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 midstory	Growing-season fire Mechanical harvesting 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 harvesting Roller-chop once and burn Plant LLP seedlings	Roller-chop twice and burn Herbicide if needed Plant LLP seedlings Sow native understory used

LLP = longleaf pine.

applications of fire during the growing season are effective in restoring these sites by gradually reducing the density of the midstory scrub oaks (Glitzenstein and others 1995). Fire causes wounds on the stems of these hardwoods, and these wounds are enlarged by subsequent fires until the stem is girdled, the top dies, and the trunk breaks. Sprouts arise from some top-killed stems, but their growth is curtailed by recurrent fire. This process is aided by increases in understory grasses that are stimulated by fire to produce more biomass that becomes fuel for future fires. Fires stimulate grasses and forbs to produce flowers and seeds (Christensen 1981, Clewell 1989, Outcalt 1994, Platt and others 1988a), that aid in colonization of newly exposed microsites. Although some of the hardwood stems survive, this is not undesirable since they are a natural part of longleaf pine ecosystems (Greenberg and Simons 1999). Restoration aims to decrease the number of midstory hardwoods, not completely eliminate them.

Reintroducing growing-season fires into xeric longleaf pine forests that have not been burned for a prolonged period may result in increased mortality among older trees during the 1- to 3-year interval following burning. The cause of this is not known, but it seems to be related to excessive accumulation of forest litter around the base of larger longleaf pines and damage to roots or cambium or both as a result of smoldering combustion of this litter. To decrease this mortality, a series of dormant-season fires at the shortest intervals fuel levels should be applied to reduce the litter buildup. Growing-season fire may then follow, when fuel is sufficient. In all prescribed burning, duff moisture levels must be high enough to prevent ignition of the litter layer at the base of larger longleaf pines, in order to avoid excessive fine-root damage and girdling of trees by cambial injury at the root collar. In many areas, the duff layer around the base of large trees is dry down to the mineral soil in the spring, during the early part of the growing season. Summer rains then occur, the drought index drops, and conditions seem suitable for prescribed burning. However, if rainfall has not been sufficient to completely re-wet the duff layer at the tree base, enough heat will be generated by a prescribed fire to evaporate the modest amount of moisture that is stored in the upper litter layer. The litter will then ignite and burn slowly for many hours, producing temperatures sufficient to cause cell death in roots and the base of the tree. Thus, it is important to determine whether the lower duff layer (i.e., the part that is in contact with mineral soil) at the base of larger trees is sufficiently wet. If the lower duff is wet and the upper duff is dry, fire should consume the dry top layer while the wet lower layer protects the roots and root collar. This favorable wet duff condition may not occur until late in the growing season during some years, because it takes significant precipitation to re-wet this layer once it has been dried completely. If the duff layer is thick and precipitation is below normal, this favorable condition may not occur until the dormant season in some years. Thus, it seems prudent to use a series of dormant-season fires to gradually reduce the accumulated litter before switching to growing-season burning. However, some older longleaf pine will die even if prescribed burning is done carefully. Studies underway at Eglin Air Force Base in Florida are aimed at identifying the factors most critical in predicting tree mortality and should provide information useful in refining burning prescriptions to minimize such losses.[1] Managers should be prepared for some mortality among older longleaf pine trees, because completely eliminating such mortality in long-unburned ecosystems may not be possible. Fire-killed trees may be salvaged to obtain some economic benefit or retained onsite as snags to enhance wildlife habitat. The ecological negative effects of not burning longleaf pine forests will far outweigh the loss of some older trees. Delays in reintroducing prescribed burning only increase the likelihood that these ecosystems will be lost as a result of catastrophic wildfire and invasion by aggressive pines and hardwoods.

Although sandhills where scrub oak expansion is the major problem tend to respond quickly after three or four growing-season fires, application of supplemental treatments can accelerate the restoration process. Mechanical methods such as chain saw felling, girdling, or chipping on site can reduce midstory hardwoods (Provencher and others 2001), and following these with prescribed fire 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 must be allowed to decay before prescribed fire is introduced, so that it does not add to fuel levels. These mechanical treatments can be expensive and are most appropriate for critical areas in need of rapid restoration, such as red-cockaded woodpecker colony sites or areas along the wildland-urban interface where it is difficult to schedule the series of prescribed fires required for restoration.

Hexazinone herbicide can also be useful in accelerating the restoration process, although it may significantly contribute to onsite fuel levels if used in areas containing high numbers of large target species. It is very effective in decreasing midstory hardwoods, with little or no short-term reductions in understory grasses and forbs on sandhills sites (Brockway and others 1998). The rate of restoration is significantly more rapid when hexazinone treatment is combined with prescribed burning than when only prescribed burning is employed. The combined treatment can produce the desired results with

[1] Personal communication. 2002. J. Morgan Varner, Graduate Student, University of Florida, 118 Newins-Ziegler Hall, Gainesville, FL 32611.

the first fire following hexazinone application (Brockway and Outcalt 2000). Because hexazinone does affect woody species, the cover of desirable nontarget species, gopher apple (*Licania michauxii*), for example, may be reduced for a time. However, hexazinone application is a one-time treatment intended to restore an area that can subsequently be maintained easily by periodic prescribed fires that mimic the natural fire regime. Application rates of 1 to 2 kg a.i./ha will produce 80 to 90 percent oak mortality without long-term damage to herbaceous understory species. When the liquid formulation is applied in a 2- by 2-m grid pattern, only a very small portion of the soil surface is treated directly. This minimizes damage to grasses and forbs, but kills many oaks. During dry periods, however, hexazinone may photo-degrade before there is enough rainfall to carry it into the soil where the oak roots absorb it. This problem was encountered by managers at Eglin Air Force Base, where very little or spotty oak mortality was observed after application (Berish 1996). This problem can be avoided by applying hexazinone during periods prior to anticipated precipitation. Granular hexazinone is less subject to this problem because it will lie on the soil surface, without significant loss in strength, until rain arrives. However, granular hexazinone does have the potential to cause a greater reduction in the cover of grasses and forbs when it is applied uniformly over the entire site (Brockway and others 1998). Broadcast application must also be conducted with care to avoid distribution overlap that could double the applied rate and create strips where no understory plants survive. Oak roots are extensively distributed in the soil, and it is better to miss a small area between strips than to overlap strips during application. If some larger oaks are to be retained, hexazinone application should be kept ≥ 30 m away from these trees, because of their widely spreading root systems. Even at this distance, some oak trees may be killed. Leaving completely untreated areas of 0.5 to 1 ha may be the most effective way of creating refuges for larger oaks.

Xeric and subxeric sandhills dominated by other trees with native understory—Large areas exist where scrub oaks have become dominant following the harvesting of longleaf pine. Although somewhat suppressed in the absence of frequent fire, the understory plant community in such areas still contains many of the native species. There are also many areas that were converted to slash pine plantations following the removal of longleaf pine. Although understory species, especially the important grasses, can be killed when the soil is disturbed on dry sandhills sites (Grelen 1962, Outcalt 1983, Outcalt and Lewis 1990), some of these areas also have fairly intact understory communities. These understories survived largely because site preparation was not intensive or because of fortuitous rainfall and higher soil moisture levels following soil disturbance. There are also extensive areas in western Florida where Choctawhatchee sand pine (*P. clausa* var. *immuginata*) invaded former longleaf pine lands following harvest. Unlike slash pine, sand pine is well adapted to dry sites, where it forms nearly continuous canopies that severely reduce understory density. However, plant diversity in these stands is generally unaffected, with native species surviving but being less numerous (Provencher and others 2001). Restoration under these conditions requires invigorating the herbaceous understory, reducing the scrub oak tree layer, removing slash pine or sand pine if present, and establishing longleaf pine seedlings.

Areas dominated by scrub oak are often difficult to burn because fuel is sparse and not contiguous. These sites can be improved by mechanical treatment 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 ground layer that, after drying, will carry a prescribed fire. By contrast, slash pine plantations often have enough needle litter to support a prescribed fire. Burning these plantations will invigorate the grasses, allowing them to accumulate root reserves and thereby increase their ability to recover from the adverse effects associated with removal of the slash pine and establishment of longleaf pine seedlings. A second fire following harvest will remove logging slash, help control oak sprouts, and increase the cover of herbaceous species. If scrub oaks are a serious problem, 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 will then serve as additional fuel for prescribed fire. If herbicide is applied after logging, it is best to let most dead oak stems fall over before burning, as this will help remove debris prior to planting of longleaf pine seedlings. 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 planting of bare-root and containerized seedlings by manual or machine methods (Barnett 1992, Barnett and McGilvray 1997, Barnett and others 1990). 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 as a result of excessive soil disturbance. If grass competition is vigorous (≥ 60 percent cover) and bare-root seedlings are being used, a planting machine with a small scalper blade can be used to 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, if invasive woody plants are discouraged by periodic growing-season fire. Planting containerized longleaf pine seedlings on sites prepared only by burning results in acceptable survival rates, but hexazinone application may increase survival on areas with vigorous scrub oak competition.

Xeric and subxeric sandhills without native understory— These sites once supported native longleaf pine ecosystems, but severe disturbance has altered their vegetation greatly. They either have no longleaf pine trees and a much altered understory, or longleaf pines have been reestablished but the native understory has not. Most of these sites were once used for agriculture or intensively managed forest plantations. Restoration of the once diverse understory is a formidable and expensive task on such sites. We do not know a great deal about restoring understory plant communities; in this area our experience is limited to a very 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 restoration (Burns and Hebb 1972). This treatment can be combined with burning if there are significant quantities of woody residue. Because much of the nutrient capital on these sites is in the litter layer and upper soil horizon, any root raking and shearing must be done carefully so that soil and litter movement is minimized. Longleaf pine bare-root or containerized seedlings can be planted on the site after the soil has settled.

Understory plants should be restored while longleaf pine seedlings are being planted, because the site treatments associated with planting reduce competition and increase onsite operability. The most critical part in this process is the reestablishment of grasses, because of their importance as fuel to support recurrent fire. To date, most work has been in the eastern portion of the range and has focused on reestablishment of wiregrass (Means 1997, Seamon 1998). A native bunchgrass, wiregrass has an average density of 5 bunches/m^2 in healthy longleaf pine ecosystems (Clewell 1989). Wiregrass seed has been collected efficiently, and its seedlings have been grown and planted successfully using recently developed technologies. Planting wiregrass seedlings at the high densities typical of natural stands is too expensive and fortunately unnecessary. Once established, wiregrass bunches will expand vegetatively and, if frequently burned, will produce seed that can aid in spreading the grass to unoccupied areas. Thus, a planting density of 0.5 to 1 seedling/m^2 can be used to successfully reestablish this species (Outcalt and others 1999). Wiregrass plugs can also be planted successfully under existing plantations of longleaf pine (Mulligan and others 2002).

Any existing hardwood midstory must first be removed by repeated burning, mechanical felling, or herbicide application. A heavy-duty woods-harrow is then used to disk strips between trees. In the spring, wiregrass plugs can be planted at a 1- by 1-m spacing in these strips. Application of fertilizer during the second or third growing season will stimulate wiregrass growth (Outcalt and others 1999). Fertilizer should be applied only around wiregrass plants to avoid stimulating the growth of competing vegetation. In pastures occupied by bahia grass (*Paspalum notatum*), cultivation will break up the old sod, and use of herbicide will improve both the survival and growth of wiregrass (Uridel 1994).

Direct seeding can also be used to reestablish wiregrass between rows of trees in newly planted and existing plantations. This method is less expensive than growing seedlings or planting plugs (Hattenbach and others 1998). Small quantities of seed can be collected by hand or with a hand-held seed stripper. A tractor-mounted flail-vac is useful for collecting larger quantities of seed. Seed can also be collected by harvesting the entire seed stalk. If entire seed stalks are collected, they should be spread on the restoration site soon after harvest to prevent seed loss from heating and fungal growth. Seed can be spread manually or with a small bale chopper. Seed or seed stalks can be collected from native understories that are purposely burned during the growing season to stimulate flower and seed production. The collection of seed from native understories diversifies the seed mix because it includes the seed of other native species that have mature seed at the time of collection. Reestablishment through seeding is more versatile than planting, because seeds can either be stored in woven bags or taken directly to the site and sown. Rolling sown seed into the soil can improve wiregrass establishment and survival (Hattenbach and others 1998). Other grass species are also part of the native understory in sandhills longleaf pine forests and should be included in seed mixes. Pineywoods dropseed (*Sporobolus junceus*), for example, is quite common on many sites. It, like wiregrass, will produce seed following fire. Its seed can be collected by hand and mixed with wiregrass seed for sowing on restoration sites. Preliminary trials suggest that more pineywoods dropseed seedlings than wiregrass seedlings become established if equal amounts of seed of these species are sown. In addition, many of the young dropseed plants produce seed during the first year following establishment.

Longleaf pine forest understories are of course more than just grass. Smith and others (2002) compared the understories of remnant xeric longleaf pine areas with those of plantations on old-field sites established 30 to 40 years ago. Although the remnant longleaf pine sites did have a higher species diversity, nearly 90 percent 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 that wiregrass and dwarf huckleberry (*Gaylussacia dumosa*) were significantly reduced in plantations (Walker 1998). These and other restoration studies (Hattenbach and others 1998) strongly suggest that many of the understory species on sandhills sites either survive extreme disturbance as propagules in the soil or are able to reinvade sites after the disturbance ends. Thus, restoration does not require that every plant species be reintroduced. Nevertheless, it will probably be necessary to reintroduce certain common species that do not easily reinvade or survive and some rare species (Glitzenstein and others 1998, 2001; Walker 1998).

Flatwoods and wet lowlands dominated by longleaf pine with native understory—As with other site types, restoration on these lower, wetter areas is designed to restore diversity to longleaf pine communities that have an understory that has been captured by woody species and has in many cases developed a substantial midstory layer. The management objective is to reduce woody understory and midstory species and allow grasses and forbs to increase and eventually become dominant. Prescribed fire is one tool for accomplishing this transition, with growing-season fires being at least as useful as and often more effective than dormant-season burns for readjusting understory composition. Although growing-season fire should be favored, dormant-season fire may be necessary to reduce fuel loads before initiating growing-season burning. One or two dormant-season fires may be used to gradually reduce litter buildup before the first growing-season burn is applied. These dormant-season fires should occur within a 2-year period to minimize accumulation of fuel between burns. Miller and Bossuot (2000) recommend that initial burns be conducted when the Keetch-Byram Drought Index (KBDI) is < 250 (Keetch and Byram 1968). Flatwoods understories dominated by saw palmetto (*Serenoa repens*), gallberry (*I. glabra*), wax myrtle (*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 and others 1987). Thus, burning every 2 years for a period of 10 to 20 years may be required to readjust the understory composition on wet sites.

Managers at Myakka River State Park in Florida have had some success using lightweight choppers or heavy-duty mowers to reduce saw palmetto coverage and dominance (Huffman and Dye 1994). Both of these mechanical methods cause very limited soil disturbance and thus do not reduce native grass species. Preliminary findings from research underway 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.

Flatwoods and wet lowlands dominated by other trees with native understory—These sites are a mixture of naturally regenerated stands that were invaded by slash pine and loblolly pine after the removal of native longleaf pine and plantations that were site-prepared and planted with these other southern pines. Restoration requires removal of the loblolly or slash pine overstory and establishment of longleaf pine seedlings. If possible, prescribed burning should be conducted ~ 2 years prior to the harvest, to reduce woody competition and stimulate growth of herbaceous understory species. A site-preparation fire following logging is needed to remove debris and discourage hardwood trees and shrubs. Chopping may be used after harvesting and prior to the site-preparation fire to help control woody plant competition and reduce the density of loblolly and slash pine seedlings. A single-drum chopper should be used to avoid excessive soil disturbance. Repeated prescribed fires after establishment will determine which species are best adapted to particular microsites. Although longleaf pine once dominated these sites, loblolly and slash pines often occurred with them as natural components of these forests. Therefore, the objective is not to totally eliminate competing pines, but rather to provide longleaf pine with an advantage that compensates for past actions that selected against it.

Understories on these wetter sites seem to be more resistant to changes caused by soil disturbance, probably because moisture availability is greater on such sites than on the sandhills (Outcalt and Lewis 1990). Therefore, many existing slash and loblolly pine plantations have fairly complete and healthy understory communities, even if the sites were bedded when the plantation was established. As a consequence, some managers prescribe bedding prior to planting of bareroot or containerized longleaf pine seedlings for restoration, to increase survival rates. However, extensive studies indicate that survival of slash pine is not increased by this reduction in competition. Even where bedding was done following double disking, a practice that greatly reduces competition, slash pine survival after 10 years was not improved over that on wet flatwoods sites in northern Florida that were only burned (Outcalt 1983). The improved microsite conditions created by bedding do increase survival rates in years that are wetter than normal. However, on average, the increase in slash pine seedling survival is only ~ 15 percent (Schultz 1976). Although adult longleaf pines grow on very wet sites, longleaf pine seedlings seem more susceptible to mortality than slash pine seedlings during periods of soil saturation (Wahlenberg 1946). Under natural conditions, longleaf pines very likely become established on wet sites during drier periods.

Bedding could be expected to increase longleaf pine seedling survival rates during wetter years by ≥ 15 percent. However, this survival gain must be weighed against the extra cost of bedding and against the damage to the native groundcover. Bedding may also alter site moisture relations and nutrient distribution for ≥ 30 years (Schultz 1976). In such a case, the ecosystem will not be truly restored even if longleaf pine is successfully established and native species dominate the understory. Restoration methods can be modified on wet sites to improve survival without resorting to bedding. It would be more economical and ecologically advantageous to plant additional longleaf pine seedlings, as a hedge against lower survival, than to bed a site. Other adjustments can be made: for example, planting can be done during drier seasons or postponed when sites are flooded and longleaf pine seedling survival would likely be low. Although container seedlings could be planted where this is justified on economic or other grounds, it is also reasonable to accept lower rates of longleaf pine survival or to accept a resulting mixture of longleaf pine and other southern pines that naturally occur in the wetter depressions embedded in flatwoods areas.

Upland and montane sites dominated by longleaf pine with native understory—Few upland and mountain sites remain in longleaf pine, because these sites were preferred for agricultural, urban, and residential development. However, many of the longleaf pine forests that now exist on such sites are in fair to good condition. These include sizable areas on Fort Bragg in North Carolina, which have been subjected to frequent fires associated with military training activities. A substantial area of upland longleaf pine ecosystem exists on large hunting plantations in the Red Hills area of southwestern Georgia and is maintained by frequent burning. Relatively healthy montane longleaf pine forest still exists at Fort McClellan in Alabama, where frequent fires associated with military training activities have maintained the open understory and discouraged invasion by woody species (Varner and others 2001). However, upland areas mostly in Alabama, Mississippi, Louisiana, and Texas and montane sites in Alabama and Georgia have developed unnaturally dense hardwood midstories and require restoration. Because these are among the most biologically productive longleaf pine sites, they change most rapidly, 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 potentially hazardous quantities of fuel. Frequent growing-season fires are needed to adequately control competing woody plants on upland sites with better soils. As on flatwoods sites, frequent growing-season fires over many years are required to reduce the hardwood rootstocks (Boyer 1990a). As in other longleaf pine ecosystem types, a series of dormant-season fires may be necessary to gradually reduce fuel levels before growing-season burning begins.

In a common variant of this ecosystem type, longleaf pine is present, but other southern pines are also present as dominants or co-dominants. In addition to prescribed burning as outlined above, these stands 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 readjustment of overstory composition, recognizing that these other species are part of the natural longleaf pine community. Burning should commence before selective harvesting begins, to prevent woody plants from proliferating and forming a shrub thicket in openings that will be created by harvesting operations. Herbicide application and mechanical reduction of nonmerchantable woody species may also be useful in accelerating the process of readjusting species composition and dominance (Boyer 1991).

Upland and montane sites dominated by other species—Little research information or management experience is available to guide restoration on these sites. Most native longleaf pine forests on such sites were converted to agriculture or loblolly pine plantations, and this conversion significantly altered composition of the understory plant community. The few sites that show no evidence of severe soil disturbance support scattered natural longleaf pine trees in a mixture dominated by loblolly pine, shortleaf pine, and hardwoods. Restoration is made more difficult by the high biological productivity of these sites. Repeated and prolonged treatment with prescribed fire should eventually reduce the abundance and cover of woody plants in the understory. It is probable that at least a portion of the native understory still exists in the soil seed bank or as suppressed individuals (Varner and others 2000). Therefore, restoration would begin with burning to reduce fuel and initiate control of woody shrubs and hardwoods. If timber markets allow, selective harvesting could then 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 needle fall for prescribed burning and to prevent 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. The best way to do this would probably be to create canopy gaps in areas where the understory has become dominated by grasses and forbs.

Development of restoration techniques for upland sites once used for agriculture or intensive forestry has begun only recently. It is unlikely that many of the native understory grasses and forbs survived intensive soil disturbance; however, there is a large soil seed bank of herbaceous weeds that must be controlled. A restoration technique being tested consists of multiple-pass harrowing to reduce weeds followed by direct seeding of native species. Although native species have been established by this method, their long-term survival and growth are as yet uncertain.[2] There is a need to develop new techniques that would provide the option to restore a more complete biotic community on the many areas of privately owned land that have been reforested with longleaf pine.

Restoration Efforts

Restoration of longleaf pine forest ecosystems first began on public lands as part of an effort to halt decline of the endangered red-cockaded woodpecker. Initial efforts focused on mechanical removal of midstory hardwoods near cavity nest trees and was augmented with prescribed fire to control hardwood sprouts. This effort later expanded to a more general approach of improving habitat for all species, with special consideration given to imperiled species. As a major public landholder, the USDA Forest Service conducts an active program for restoring longleaf pine ecosystems on national forests in the Southeast. In the late 1990s, longleaf pine ecosystems occupied 307 000 ha on national forestlands (McMahon and others 1998). To improve the condition of these forests, managers have begun to implement more burning during the growing season on a 3- to 4-year cycle. Mechanical removal and herbicide treatments are used, where appropriate, to augment fire. Loblolly pine and slash pine are being removed, and longleaf pine is being reestablished on its former sites. The goal is to increase the area occupied by longleaf pine ecosystems by 50 percent, to a total of 451 600 ha.

The U.S. Department of Defense also has substantial land holdings within the native range of longleaf pine. One of the largest of these holdings, Eglin Air Force Base, is an important part of the largest remaining concentration of longleaf pine habitat, the gulf coast area of Florida and Alabama (Outcalt and Sheffield 1996). This base contains large areas of the longleaf pine sandhills ecosystem that has been maintained in healthy condition by the frequent fires resulting from military training activities. However, it also contained a large area of forest with a well-developed midstory of scrub oaks. In 1993, land managers began an ambitious restoration program that employed fire and supplemental mechanical treatments and herbicides when these were needed. Between 1993 and 1997, they burned an average of 16 200 ha/year, with 70 percent of these prescribed fires being conducted during the growing season (McWhite and others 1999). This significantly reduced the hardwood midstory and improved the composition and density of the understory herbaceous plant community. Managers also selectively harvested sand pine from 4750 ha of longleaf pine stands it had invaded during the period of fire exclusion. Between 1993 and 1997, offsite slash pine (1360 ha) and sand pine (1950 ha) plantations were harvested and replaced with longleaf pine seedlings. Manual planting was used on all sites, and 90 percent of the seedlings were containerized to improve survival. A smaller area of coastal longleaf pine flatwoods at Eglin Air Force Base is being restored through the reintroduction of prescribed fire.

Other military bases across the region have been following or are adopting similar policies and practices. Fire is being reintroduced where needed, and areas occupied by offsite species are being converted back to longleaf pine, with recognition that the understory plant community must be conserved during this process. Military installations on the lower Coastal Plain, such as Camp Lejeune in North Carolina and Fort Stewart in Georgia, have many areas of flatwoods and lowland longleaf pine ecosystems. Substantial restoration is taking place in these wetter longleaf pine ecosystems as well as in the drier sandhills.

Restoration activities are taking place on almost all other Federal and State lands that have longleaf pine or sites suitable for its establishment. Private landowners with larger tracts have used periodic prescribed fire in their management, and there is growing interest in doing at least a portion of this burning during the growing season. However, because of the high cost of treating small parcels, most small landowners are unable to burn their sites (Outcalt 1998), and very little restoration is occurring on these areas.

Understory restoration on areas that have been substantially altered is more difficult and expensive. Therefore, it is not surprising that only a limited amount of restoration work is being done on such sites. Wiregrass plugs are being grown

[2] Personal communication. 2002. L. Katherine Kirkman, Research Scientist, J.W. Jones Ecological Research Center, Rt. 2, Box 2324, Newton, GA 31770.

Table 4—Production rates, equipment, and costs for understory plant restoration at Fort Stewart, GA

	Seed collection[a]					Seed sowing			
Year	Days	ha	kg	kg/day	kg/ha	Days	ha	ha/day	kg/ha
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
Flail-vac seed collector	$11,950.00	Sowing labor	$58.05/ha
Small tractor	$35,000.00	Seed cost[b]	$141.77/ha
Bale chopper	$3,800.00	Understory restoration cost[b]	$199.82/ha

[a] Seed collection season varies from late October to late December.
[b] Does not include equipment purchase or operation and maintenance costs.

and outplanted along with longleaf pine seedlings on both State land (Pittman and Karrfalt 2000) and national forest-land in Florida. At the Savannah River Site in South Carolina, the USDA Forest Service has recently planted wiregrass plugs under longleaf pines planted on old-field sites during the 1950s, to restore fuel and improve the habitat of red-cocked woodpecker colony sites. The Nature Conservancy is restoring both longleaf pine and wiregrass on a sandhills site at their Apalachicola Bluffs and Ravines Reserve in northern Florida (Hattenbach and others 1998, Seamon 1998). They are also experimenting with direct seeding of other native understory species. The most extensive program for direct seeding of understory species is being conducted at Fort Stewart (table 4). Resource managers have collected seed and sown it on site-prepared areas since 1997.[3] A tractor-mounted flail-vac seed harvester is used to collect seed from onsite areas burned during the growing season. Collections vary from 750 to 1100 kg/year, which at a mean sowing rate of 13.2 kg/ha is enough to sow 57 to 83 ha/year. Seed is spread on restoration sites by means of a platform-mounted bale chopper on the back of a farm tractor. Flatwoods and sandhills sites are being restored with seed from appropriate donor sites. The goal at Fort Stewart is to restore 8100 ha of old fields to functioning longleaf pine ecosystems (Hilliard 1998).

[3] Personal communication. 2001. Dena Thompson, Wildlife Biologist, Department of Environmental Health, Forestry Branch, Fort Stewart, GA 31314.

Costs and Benefits Associated with Restoration

Estimating Restoration Costs

Disagreement over what constitutes restoration and lack of precise criteria for judging the success of restoration make estimating the cost of restoring longleaf pine forest ecosystems quite difficult. If the focus is limited to restoring longleaf pine as the dominant overstory tree through reforestation, then reasonable cost estimates can be made using readily available economic data. However, if the intent is to restore a completely functional ecosystem, then cost estimation becomes very difficult. The necessarily long-term nature of ecosystem restoration also introduces temporal considerations that significantly affect costs incurred by forest managers. Although this time frame can be shortened somewhat by management techniques that accelerate the restoration process, the use of these techniques may involve increases in short-term 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. Reforestation costs vary according to ambient conditions and the type and amount of site preparation needed to achieve successful establishment of tree seedlings. On previously harvested or old-field sites, costs typically range from $370 to $740/ha, depending on site conditions and whether bare-root seedlings or containerized seedlings are selected. 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 might be expended for herbicide application. Because these costs occur early in the investment, they cannot be discounted over time when calculating net present value, internal rate of return, or other economic indices. Despite these expenditures, the average internal rate of return for such an investment is estimated at 10.1 percent, with a range from 8 to 12 percent (Busby and others 1996).

On sites that already support forests, the presence and distribution of longleaf pine in the canopy may be sufficient to allow for natural regeneration. In such cases, unwanted tree species should be harvested and removed, leaving the longleaf pine as the dominant seed-producing tree for future generations. Prescribed fire or selective herbicides or both are usually required to prevent woody shrubs and trees from developing into a midstory layer and to prepare a seedbed of mineral soil favorable for germination of longleaf pine seed. While natural regeneration appears to be free, determining its true cost in economic terms requires assessing assumed risk, calculating opportunity cost, and considering the time-value of money.

In forests with degraded understories or understories composed of nonnative plants, establishing longleaf pine as the dominant overstory tree is only the beginning of the restoration process. Without the species richness and diversity unique to their native plant and animal communities, these ecosystems cannot be considered fully restored. Restoring groundcover plants can be very expensive, with costs rising sharply as the time scale is compressed. In relatively undisturbed forests, many plants native to the site may be reestablished by the reintroduction of fire, particularly growing-season fire. Fires facilitate reestablishment of vascular plants by stimulating seed banks and inducing flowering and seed production in many existing plants. The cost of fire reintroduction varies with existing site conditions. Long-term fire exclusion can cause fuel accumulations that make fire reintroduction potentially very destructive. Mitigating this danger can be quite labor intensive and very expensive. In frequently burned areas, the risks and cost of burning are greatly reduced. In such cases, changing the fire frequency or season of burning or both may be sufficient to initiate the recovery of native plant communities. Where seed banks are depleted or severe soil disturbance has occurred, restoring the plant community is more problematic. Reseeding or replanting selected understory plant species has been accomplished successfully, but at considerable economic cost. Estimates of the cost of artificially reestablishing sustainable populations of native groundcover plants range from several hundred to several thousand dollars per hectare. Techniques for seed collection, cultivation, distribution, planting, and other steps in the process are only in the developmental stages at this time and are generally focused on pyrophytic graminoids (e.g., wiregrass), species consumed by wildlife (e.g., legumes), and species of special concern (e.g., American chaffseed, *Schwalbea americana*).

Restoration of a diverse understory of native plants and a suitably structured overstory are viewed as crucial in reestablishing and sustaining viable populations of the many wildlife species indigenous to these ecosystems. At this time, efforts to restock these animals are very limited, because the costs of such programs are high and because capture and relocation permits must be obtained from State and Federal authorities. Efforts to restock pocket gophers and fox squirrels, both indicators of healthy ecosystems, are virtually unknown and would likely be unsuccessful at any cost if the plant community does not provide suitable habitat conditions. Because northern bobwhite are game birds of substantial economic importance and are well adapted to longleaf pine ecosystems, their establishment and maintenance has received significant attention. The red-cockaded woodpecker is a major indicator of the health of longleaf pine ecosystems, and costs associated with its recovery represent a substantial component of the cost of restoring these ecosystems. Red-cockaded woodpeckers have exacting habitat requirements. They require a relatively open overstory canopy with widely spaced mature pines, trees of large diameter that may serve as nesting sites following cavity excavation, a sparse or absent midstory, and groundcover vegetation that is low in stature. Wildlife biologists consider the creation of these conditions as being synonymous with longleaf pine ecosystem restoration. Restoring red-cockaded woodpeckers to areas of suitable but unoccupied habitat is a highly regulated and expensive activity. Costs of such efforts include (1) construction of artificial cavities in large pines; (2) capture, transportation, and release of the birds; and (3) population monitoring for an extended period after relocation.

Benefits of Restored Longleaf Pine Ecosystems

Both the material and intangible benefits resulting from restoration of longleaf pine ecosystems are substantial. The economic value of longleaf pine forests is considerable, and commercial products can be extracted from a properly functioning forest without significantly disrupting ecological processes. Longleaf pine is the most versatile of all the southern pines and provides a wide variety of products, many of which are highly valued (table 5). Longleaf pine forests typically produce up to five times more tree stems of sufficient quality to be used as utility poles than do stands of slash pine or loblolly pine. Stumpage values for such poles

Table 5—Value of wood products from major southern pine species[a]

	Sawtimber price/m^3	High-quality poles	Value/ha
Longleaf pine	$264	66%	$8,492
Slash pine	$257	12%	$7,640
Loblolly pine	$254	5%	$7,454

[a] Assuming a mean stand volume of ~ 29 m^3/ha at age 55 (Holliday 2001).

exceed prices for sawtimber by ~ 40 percent. When the high value of pine straw (i.e., fallen needles, which may be harvested from stands as early as age 10) is added, the economic value of longleaf pine forests becomes increasingly obvious. Contingency or "willingness to pay" surveys consistently indicate that hunter access to private lands has value as a tradable commodity throughout the natural range of longleaf pine. Where longleaf pine forests are maintained in open parklike condition, the higher quality of this habitat for quail, turkey, and deer brings premium economic returns in the form of hunting leases and related services to private landowners. Revenues correspondingly decline as habitat conditions become degraded.

Enhanced recreational opportunities, greater esthetic appeal, and higher real estate values associated with restored longleaf pine ecosystems are attributes that are more difficult to measure. However, ecological values resulting from restoration of ecosystem health are perhaps the greatest benefits that defy easy quantification (Constanza and others 1992). Redevelopment of appropriate community structure and composition and reinitiation of essential ecological processes promote improved ecosystem resilience and stability. Ecosystem services are of inestimable value and include climate amelioration, water purification, soil stabilization, flood control, nutrient cycling, providing habitat, and serving as a reservoir for genetic material that could be a source for new medicines, energy, and industrial feedstock (Burton and others 1992, Ledig 1988, Riggs 1990).

Influence of Forestland Ownership

Regional Patterns

Of the 87 million ha of forest in this region, 81.3 million ha are classified as timberland, that is, land capable of producing forest products and not withdrawn from potential timber harvesting for special uses (Conner and Hartsell 2002). Timberland in the region is held by many groups, which can be broadly divided into public and private ownerships (table 6). About 8.7 million ha of this timberland is publicly owned, including lands administered by Federal, State, county, and municipal government agencies, as well as by the tribal governments of Native Americans. The USDA Forest Service manages the largest area of public land, with 4.7 million ha under its administration. Private interests own the remaining 72.6 million ha of timberland in the region. Forest industry manages 15.1 million ha, other corporations own 8.8 million ha, and nonindustrial private landowners hold 48.7 million ha. It is worth noting that the total area owned by private individuals has increased by 18 percent since 1982. One potential result of this increase is forest fragmentation, the division of larger contiguous tracts of forest into smaller, more isolated parcels. Although it was not monitored closely in the past, information on the tract size of forestland is now being collected to aid in the forecasting of future trends in ownership and landscape condition.

Table 6—Regional forestland ownership

	Million ha	Percent of forestland
Forestland	87.0	100.0
Nontimberland	5.7	6.6
Timberland	81.3	93.4
Public	8.7	10.0
USDA Forest Service	4.7	5.4
Other Federal agencies	1.9	2.2
State and local agencies	2.1	2.4
Private	72.6	83.4
Forest industry	15.1	17.3
Other corporations	8.8	10.0
Nonindustrial private landowners	48.7	56.0

Source: Conner and Hartsell (2002).

Land Ownership Patterns in Longleaf Pine Ecosystems

There are now < 1.2 million ha of longleaf pine forest in the Southeastern United States, and much of that is in poor condition. About 51 percent of the existing longleaf pine forest is owned by nonindustrial private landowners, 16 percent by forest industry, and 33 percent by public land management agencies (Outcalt and Sheffield 1996). Public lands constitute only 10 percent of forestland in the region, but they support a larger percentage of the area in longleaf pine. Ownership stability over the long term and public agency ecosystem management programs that do not exclusively emphasize commodity production provide a more secure habitat for this long-lived tree species that can be sustained by less intensive management practices. Public lands also more often exist as larger, less fragmented tracts with linkages that provide ecological connections among otherwise isolated longleaf pine forest "islands." The many resource values and desirable ecological attributes of longleaf pine forests also complement the land management mission of most public agencies. While immediate emphasis should be placed on restoring lands currently occupied by degraded longleaf pine forests, estimates indicate that several million additional hectares may ultimately be suitable for restoration to longleaf pine ecosystems.

A recent survey of longleaf pine stands in North Carolina, South Carolina, Georgia, and Florida revealed that ~ 50 percent of the sites currently dominated by longleaf pine are in fair to good condition with a healthy understory of native plant species, no extensive midstory, and little or minimal soil disturbance (Outcalt 2001). If the western portion of the range has a similar distribution of conditions, the remaining area of healthy longleaf pine ecosystems is ~ 560 000 ha. An additional 480 000 ha is also dominated by longleaf pine but requires restoration to reduce the midstory layer or improve the understory plant community or both. Most of the latter areas (400 000 ha) are owned by private nonindustrial forest landowners, while the 80 000 ha on public lands have not yet been restored. A 1995 survey found another 180 000 ha of longleaf pine growing as plantations on lands owned by forest industry and nonindustrial private landowners. Since that time, an additional 70 000 ha of longleaf pine plantations have been planted on private lands with funding provided by the CRP. Most of these sites have been altered greatly (especially the CRP areas), and it would require considerable investment to fully restore native longleaf pine ecosystems on them. It is estimated that public agencies other than the USDA Forest Service control about 200 000 ha of lands that have some native understory components and are dominated by other overstory tree species (McMahon and others 1998). USDA Forest Service inventory and analysis data indicate that ≥ 600 000 ha of privately owned forestland that is dominated by other tree species (mostly scrubs oaks, loblolly pine, or slash pine) supports at least some of the understory plants native to longleaf pine ecosystems. This land is potentially available for restoration by replacing the current overstory dominants with longleaf pine. There are additional plantations of other tree species across the entire former range of longleaf pine that could be restored to the longleaf pine ecosystem, but for a majority of these, this would be a difficult task. Overall, we estimate that there are 280 000 ha on public lands and 1 million ha on nonindustrial private lands that could be fully restored at a reasonable cost with current knowledge. Clearly, the greatest opportunity for future restoration of longleaf pine ecosystems resides with nonindustrial private forest landowners.

Influence of Ownership on Restoration

Individual forest landowners elect or decline to restore longleaf pine forest ecosystems on suitable lands for a variety of reasons. Private nonindustrial landowners are diverse and have widely varying land management objectives. Generally, the strongest incentives for private nonindustrial landowners to proceed with restoration activities are government-funded programs that share the cost of artificially regenerating and maintaining longleaf pine forests. Without these cost-share programs, many landowners would not consider longleaf pine restoration as a land management option, because any short-term financial reward for doing so would be absent. However, some affluent landowners do implement longleaf pine restoration on their lands without seeking financial assistance from government programs. They do so because they feel it is the ecologically right thing to do or because they wish to leave a natural heritage legacy to their heirs.

Forest industry and other corporations in the region typically manage forests on short rotations (< 30 years) for fiber products in order to maximize profits, especially in the short term. Because longleaf pine must usually be grown on longer rotations to produce larger trees for sawtimber, poles, and pilings, forest industry has generally shown less interest in restoring and managing longleaf pine forest ecosystems than have other landowners. Some private industrial companies do infrequently grow longleaf pine forests on their lands in an attempt to diversify their financial assets and contribute to the achievement of broader resource conservation goals. During the past several years, some companies have begun establishing longleaf pine on sites that are better suited to it than to loblolly pine or slash pine, and at least one forest industry firm is planning an ambitious program to restore longleaf pine forests across a substantial area.

In recent years, numerous public land management agencies have actively sought to restore longleaf pine forest ecosystems on national and State forests, national and State wildlife refuges, State parks, military bases, and other public lands. Longleaf pine restoration efforts undertaken in accordance with ecosystem management policies are a major component of the long-range mission of various public agencies to protect populations of rare plants and animals, conserve biological diversity, and provide the public with multiple benefits such as recreational opportunities, clean water, wood, and other forest products. Unfortunately, costs associated with restoration efforts and the regulatory and procedural constraints on forest management practices that are necessary to convert sites occupied by other forest types to longleaf pine forests have impeded the rate of restoration of longleaf pine ecosystems on public lands.

Research and Management Needs and Policy Implications

Scientific Knowledge

For decades, southern research and development efforts by industry, government, and universities focused on short-rotation plantations of loblolly pine and slash pine for paper pulp production, with little investment in research work on longleaf pine regeneration, growth, and productivity (Boring 1999). Although increasing research emphasis on longleaf pine in recent years has produced some very encouraging results, a great many questions remain partly or largely unanswered. An entire publication would be required to present an exhaustive list of longleaf pine research needs (Walker 1995). Therefore, only major topics of scientific inquiry are summarized below.

Although they are incomplete, historical data about the composition, structure, and function of natural ecosystems may serve as a reference to promote general understanding (White and Walker 1997). These include quantitative and qualitative descriptions of (1) understory components and the processes by which they were established and maintained, (2) age and spatial structure of even-aged and uneven-aged forests and the processes that influenced canopy condition, (3) landscape structure and its variation across the region, and (4) the interaction between fire regimes and landscape structure, particularly as this interaction influenced ecosystem processes (Walker and Boyer 1993). Better quantitative data about existing longleaf pine forest ecosystems would facilitate comparative analyses that would support appropriate restoration efforts. Such analyses include (1) examination of local biotic community quality and degree of deviation from historical patterns; (2) assessment of the responses of ecosystems in various conditions to restoration treatments and fire regimes; (3) identifying and explaining the processes that underlie the population dynamics of native plants and the influence of silvicultural treatments on them; (4) quantitatively describing landscape scale structures, flows, and functions and showing how these currently depart from historical patterns; and (5) cumulative effects evaluation of historical land uses, contemporary management treatment regimes, and catastrophic events such as hurricanes and fires.

Because ecological restoration is a management process that is essentially goal-driven, it is essential that the desired result be defined as precisely as possible. Various kinds of basic knowledge can help us identify realistically appropriate target conditions. Such scientific knowledge includes (1) patterns of genetic variation in longleaf pine and associated native species and the effects of habitat fragmentation on this variation, (2) life-cycle dynamics of rare plant and animal species and the factors essential for population viability, (3) the forest site and microsite affinities of native species, (4) the influence of natural and anthropogenic disturbances at local and landscape scales and especially the influence of fire as a driving ecological process, (5) ecological thresholds related to multiple stable states and how they are influenced by various disturbances, and (6) appropriate criteria for defining longleaf pine ecosystem health and measures of ecosystem integrity that can be monitored effectively.

Management Information

Forestland managers involved in restoration efforts throughout the region have identified many pressing management information needs. Key among these needs is a better understanding of the ecology and dynamics of fire in longleaf pine forests, including (1) the effects of growing-season fire and dormant-season burning in a wide range of habitat types; (2) appropriate fire frequencies, intensities, and ignition techniques to achieve various objectives; (3) the influence of fire on important game species and numerous nongame species; (4) the role of fire in sustaining various at-risk species and the selection of burning methods to ensure their continuing viability; (5) techniques for safely reintroducing fire into long-unburned ecosystems and mitigating loss of resource values; (6) the degree to which and under what conditions chemical and mechanical treatments can be substituted for periodic prescribed fire (especially at the wildland-urban interface, where burning may be restricted); and (7) models that will enable managers to better predict and manage smoke resulting from prescribed burning.

Successful regeneration of longleaf pine is an essential element of efforts to restore and sustain these ecosystems. Information needs in this area include improved understanding of (1) the structures and processes that affect longleaf pine regeneration, including canopy-gap and root-gap dynamics and the influences of light, nutrients, moisture, and fuels that support fire on seedling survival and growth; (2) variation in intraspecific and interspecific competition across a wide range of site types; (3) silvicultural methods for effectively regenerating longleaf pine in uneven-aged, two-aged, and even-aged forests and the use of these to mimic natural disturbance patterns; and (4) appropriate densities for planting longleaf pine seedlings across a range of site types.

Conservation efforts that do not consider social and economic costs and benefits are usually doomed to fail in the long term (Kimmins 1992, Oliver 1992). To be successful, restoration efforts aimed at sustainable management must provide opportunities to achieve stewardship goals and allow for the use of natural resources. Information needed to address these concerns includes (1) periodically updated estimates of the economic costs and expected returns of restoring longleaf pine, (2) accurate projections of the quantity and quality of longleaf pine wood products (and pine straw, where appropriate) that can be expected to result from restoration efforts, (3) economical methods for reestablishing both overstory trees and understory plants, (4) impacts of logging and replanting on longleaf pine forest environments, and (5) public knowledge about and attitudes toward longleaf pine ecosystem restoration, conservation, and utilization.

Restoration of longleaf pine forests requires looking beyond the trees and considering, to the greatest degree practical, all ecosystem components. In striving toward this goal, managers need information on (1) the effectiveness of various mechanical, chemical, and pyric site preparation techniques and their impacts on native plants in the understory; (2) techniques for efficiently establishing native understory plants; (3) methods for suppressing invasive species and discouraging the spread of nonnative species; (4) methods for restoring forests across the full range of suitable site types and techniques for improving degraded longleaf pine ecosystems; and (5) computerized management support systems (i.e., expert systems) that assist managers in identifying potential problems and opportunities that arise during restoration efforts.

Policy Implications

Public policies promoted by government agencies that facilitate stewardship and restoration of longleaf pine ecosystems have long been in need of implementation (Boring 1999). During the period when management of longleaf pine was discouraged by Federal and State foresters, it seemed reasonable that little if any public funding should be expended to support programs for this species. However, social attitudes toward longleaf pine forests have changed in recent decades, with interest in these ecosystems rising each year. In response to this change, greater public funding could be allocated for programs that develop and disseminate new knowledge in support of managers interested in longleaf pine.

As ecosystem management has become the dominant theme on public lands, goals for restoring longleaf pine have been established throughout the region. There are indications that the area in longleaf pine ecosystems could be doubled in the future. However, such an effort would require the endorsement of policymakers and need substantial financial support over a long period. Although longleaf pine restoration efforts on private lands have been impeded by various factors, a frequently lacking ingredient for success is timely and appropriate management information for nonindustrial private landowners. Clearly, greater resources are needed to provide technical assistance to these important members of the southern forestry community.

Conservation and restoration of longleaf pine ecosystems might be more effectively achieved by creating a reserve program modeled on the Wetlands Reserve Program, which has been very successful in maintaining wetland habitats at the State and national levels. Longleaf pine ecosystems have declined by 97 percent, while the historical losses of wetlands are estimated at only 47 percent. Certainly, longleaf pine ecosystems deserve such consideration.

Many private landowners are seriously concerned about the implications of managing forests that also may serve as habitat for endangered or threatened species. Technical assistance programs could not only provide important habitat management guidance, but also advise landowners on how to enroll in Safe Harbor and conservation easement programs to effectively address these concerns (Costa 1999). Also, the need to periodically burn longleaf pine forests and the limitations placed on prescribed fire by government regulations have dissuaded many landowners from managing longleaf pine on their lands. Right-to-burn laws would, to a substantial degree, address this issue and need to be adopted widely in the region.

Urbanization at the wildland-urban interface continues to result in loss of longleaf pine sites. Such urban development fragments land ownership into a series of smaller tracts that are permanently lost from the land base of functioning longleaf pine ecosystems. The current structure of estate and property tax laws also places a heavy financial burden on private landowners, with the result that large land holdings are frequently divided and sold as smaller parcels, further fragmenting the ownership of longleaf pine lands. Although use of conservation easements tied to land deeds affords tax relief while diminishing fragmentation, and recent tax law reform provides some benefits to landowners, these developments have been insufficient to change this negative trend. The substantial initial costs of establishing longleaf pine can also be a problem for many landowners, despite the fact that several of the government assistance programs discussed earlier aid in partially offsetting some of these costs. Overall, financial difficulties still remain a major disincentive for many landowners. Therefore, perhaps the greatest policy need for the private sector is a comprehensive change in tax laws to provide specific and substantial benefits to landowners who restore and maintain longleaf pine forest ecosystems on their lands.

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Literature Cited

Abrahamson, W.G.; Hartnett, D.C. 1990. Pine flatwoods and dry prairies. In: Myers, R.L.; Ewel, J.J., eds. Ecosystems of Florida. Orlando, FL: University of Central Florida Press: 103-149.

Allen, J.A.; Keeland, B.D.; Stanturf, J.A. [and others]. 2001. A guide to bottomland hardwoods restoration. Information and Technology Report USGS/BRD/ITR-2000-0011. U.S. Department of the Interior, Geological Survey, Biological Resources Division. Gen. Tech. Rep. SRS-40. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 132 p.

Anderson, K.M. 1996. Tending the wilderness. Restoration and Management Notes. 14: 154-166.

Aronson, J.; Floret, C.; Le Floc'h, E. [and others]. 1993. Restoration and rehabilitation of degraded ecosystems in arid and semiarid regions I: a view from the South. Restoration Ecology. 1(1): 8-17.

Bailey, R.G. 1995. Description of the ecoregions of the United States. Misc. Publ. 1391. Washington, DC: U.S. Department of Agriculture Forest Service. 108 p.

Barnett, J.P. 1992. The South's longleaf pine: it can rise again! Forests and People. 41: 14-17.

Barnett, J.P.; Lauer, D.K.; Brissette, J.C. 1990. Regenerating longleaf pine with artificial methods. In: Farrar R.M., ed. Management of longleaf pine. Gen. Tech. Rep. SO-75. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station: 72-93.

Barnett, J.P.; McGilvray J.M. 1997. Practical guidelines for producing longleaf pine seedlings in containers. Gen. Tech. Rep. SRS-14. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 28 p.

Bartram, W. 1791. Travels through North and South Carolina, Georgia, and east and west Florida. New York: Dover Publishers. 414 p.

Berish, S.J. 1996. 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, Gainesville, FL: University of Florida. 51 p.

Boring, L.R. 1999. External forces in longleaf ecosystems: the public and public policy. In: Kush, J.S., comp. Longleaf pine: a forward look. Longleaf Alliance Rep. 4. Andalusia, AL: Solon Dixon Forestry Education Center:.10-11.

Boyer, W.D. 1963. Development of longleaf pine seedlings under parent trees. Res. Pap. SO-4. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 5 p.

Boyer, W.D. 1990a. Growing-season burns for control of hardwoods in longleaf pine stands. Res. Pap. SO-256. New Orleans: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 7 p.

Boyer, W.D. 1990b. *Pinus palustris* Mill. longleaf pine. In: Burns, R.M.; Honkala, B.H., tech. coordinators. Silvics of North America. Washington, DC: U.S. Department of Agriculture Forest Service:. 405-412. Vol. 1.

Boyer, W.D. 1991. Effects of a single chemical treatment on long-term hardwood development in a young pine stand. In: Coleman, S.S.; Neary, D.G., eds. Proceedings of the 6th biennial silvicultural research conference. Gen. Tech. Rep. SE-70. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station: 599-606.

Boyer, W.D. 1993. Long-term development of regeneration under longleaf pine seedtree and shelterwood stands. Southern Journal of Applied Forestry. 17(1): 10-15.

Boyer, W.D. 2000. Long-term effects of biennial prescribed fires on the growth of longleaf pine. In: Moser W.K.; Moser, C.F., eds. Proceedings of the 21st Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 18-21.

Boyer, W.D. 2001. A generational change in site index for naturally established longleaf pine on a south Alabama Coastal Plain site. Southern Journal of Applied Forestry. 25(2): 88-92.

Boyer, W.D.; White, J.B. 1990. Natural regeneration of longleaf pine. In: Farrar, R.M., ed. Management of longleaf pine. Gen. Tech. Rep. SO-75. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station: 94-113.

Brennan, L.A.; Hermann, S.M. 1994. Prescribed fire and forest pests: solutions for today and tomorrow. Journal of Forestry. 92(11): 34-37.

Brockway, D.G.; Gatewood, R.G.; Paris, R.B. 2002. Restoring grassland savannas from degraded pinyon-juniper woodlands: effects of mechanical overstory reduction and slash treatment alternatives. Journal of Environmental Management. 64: 179-197.

Brockway, D.G.; Lewis, C.E. 1997. Long-term effects of dormant-season prescribed fire on plant community diversity, structure and productivity in a longleaf pine wiregrass ecosystem. Forest Ecology and Management. 96(1, 2): 167-183.

Brockway, D.G.; Lewis, C.E. 2003. Influence of deer, cattle grazing and timber harvest on plant species diversity in a longleaf pine bluestem ecosystem. Forest Ecology and Management. 175(1-3): 49-69.

Brockway, D.G.; Outcalt, K.W. 1998. Gap-phase regeneration in longleaf pine wiregrass ecosystems. Forest Ecology and Management. 106(2, 3): 125-139.

Brockway, D.G.; Outcalt, K.W. 2000. Restoring longleaf pine wiregrass ecosystems: hexazinone application enhances effects of prescribed fire. Forest Ecology and Management. 137(1-3): 121-138.

Brockway, D.G.; Outcalt, K.W.; Wilkins, R.N. 1998. Restoring longleaf pine wiregrss ecosystems: plant cover, diversity and biomass following low-rate hexazinone application on Florida sandhills. Forest Ecology and Management. 103(2, 3): 159-175.

Burns, R.M.; Hebb, E.A. 1972. Site preparation and reforestation of droughty, acid sands. Agric. Handb. 426. Washington, DC: U.S. Department of Agriculture Forest Service. 61 p.

Burton, P.J.; Balisky, A.C.; Coward, L.P. [and others]. 1992. The value of managing for biodiversity. The Forestry Chronicle. 68(2): 225-237.

Busby, R.L.; Thomas, C.E.; Lohrey, R.E. 1996. The best kept secret in southern forestry: longleaf pine plantation investments. In: Kush, J.S., comp. Longleaf pine: a regional perspective of challenges and opportunities. Longleaf Alliance Rep. 1. Andalusia, AL: Solon Dixon Forestry Education Center: 26-27.

Cairns, J. 1995. Ecosocietal restoration: reestablishing humanity's relationship with natural systems. Environment. 37(5): 4-9, 30-33.

Carroll, W.D.; Kapeluck, P.R.; Harper, R.A.; Van Lear, D.H. 2002. Historical overview of the southern forest landscape and associated resources. In: Wear, D.N.; Greis, J.G., eds. The southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 583-605.

Christensen, N.L. 1981. Fire regimes in southeastern ecosystems. In: Mooney, H.A.; Bonnicksen, T.M.; Christensen, N.L. [and others], eds. Fire regimes and ecosystem properties. Gen. Tech. Rep. WO-26. Washington, DC: U.S. Department of Agriculture Forest Service: 112-136.

Clements, F.E. 1916. Plant succession: analysis of development of vegetation. Washington, DC: Carnegie Institute. 512 p.

Clewell, A.F. 1989. Natural history of wiregrass (*Aristida stricta* Michx., Gramineae). Natural Areas Journal. 9: 223-233.

Clewell, A.F. 2000. Restoring for natural authenticity. Ecological Restoration. 18(4): 216-217.

Coates, K.D.; Burton, P.J. 1997. A gap-based approach for development of silvicultural systems to address ecosystem management objectives. Forest Ecology and Management. 99(3): 337-354.

Conner, R.C.; Hartsell, A.J. 2002. Forest area and conditions. In: Wear, D.N.; Greis, J.G., eds. The southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 357-402.

Constanza, R.; Norton, B.G.; Haskell, B.D., eds. 1992. Ecosystem health: new goals for environmental management. Washington, DC: Island Press. 269 p.

Costa, R. 1999. Safe harbor: a private lands conservation strategy for longleaf pine habitat and red-cockaded woodpeckers. In: Kush, J.S., comp. Longleaf pine: a forward look. Longleaf Alliance Rep. 4. Proceedings of the 2d Longleaf Alliance conference. Andalusia, AL: Solon Dixon Forestry Education Center: 42-44.

Covington, W.W.; Fule, P.Z.; Moore, M.M. [and others]. 1997. Restoring ecosystem health in ponderosa pine forests of the Southwest. Journal of Forestry. 95(4): 23-29.

Crofton, E.W. 2001. Flora and fauna of the longleaf pine-grassland ecosystem. In: Wilson, J.R., ed. The fire forest: longleaf pine-wiregrass ecosystem. Georgia Wildlife. 8(2): 69-77.

Croker, T.C. 1987. Longleaf pine: a history of man and a forest. For. Rep. R8-FR7. Atlanta: U.S. Department of Agriculture Forest Service, Southern Region. 37 p.

Delcourt, P.A. 1980. Goshen Springs: late Quaternary vegetation record for southern Alabama. Ecology. 61(2): 372-386.

Delcourt, P.A.; Delcourt, H.R. 1987. Long-term forest dynamics of the temperate zone. New York: Springer-Verlag Publishers. 439 p.

Dickmann, D.I. 1993. Management of red pine for multiple benefits using prescribed fire. Northern Journal of Applied Forestry. 10(2): 53-62.

Dobson, A.P.; Bradshaw, A.D.; Baker, A.J.M. 1997. Hopes for the future: restoration ecology and conservation biology. Science. 277(July 25): 515-522.

Drake, J.A. 1990. Communities as assembled structures: do rules govern pattern? Trends in Ecology and Evolution. 5: 159-164.

Edmisten, J.A. 1963. The ecology of the Florida pine flatwoods. Ph.D. dissertation. Gainesville, FL: University of Florida. 108 p.

Engstrom, R.T. 1993. Characteristic mammals and birds of longleaf pine forests. In: Herman, S.M., ed. Proceedings of the 18th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 127-138.

Engstrom, R.T. 2001. Red-cockaded woodpeckers: prospects for recovery. In: Wilson, J.R., ed. The fire forest: longleaf pine-wiregrass ecosystem. Georgia Wildlife. 8(2): 12-13.

Engstrom, R.T.; Kirkman, L.K.; Mitchell, R.J. 2001. The natural history of the fire forest. In: Wilson, J.R., ed. The fire forest: longleaf pine-wiregrass ecosystem. Georgia Wildlife. 8(2): 5-11, 14-17.

Farrar, R.M. 1996. Fundamentals of uneven-aged management in southern pine. Misc. Publ. 9. Tallahassee, FL: Tall Timbers Research Station. 68 p.

Franklin, R.M. 1997. Stewardship of longleaf pine forests: a guide for landowners. Longleaf Alliance Rep. 2. Andalusia, AL: Solon Dixon Forestry Education Center. 44 p.

Friedel, M.H. 1988. Range condition and the concept of thresholds. In: Singh, P.; Shankar, V.; Srivastava, A.K., eds. Third international rangeland congress. New Delhi, India: Range Management Society of India: 1-3.

Friedel, M.H. 1991. Range condition assessment and the concept of thresholds: a viewpoint. Journal of Range Management. 44(5): 422-426.

Frost, C.C. 1993. Four centuries of changing landscape patterns in the longleaf pine ecosystem. In: Herman, S.M., ed. Proceedings of the 18th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 17-43.

Gagnon, J.L.; Jokela, E.J.; Moser, W.K.; Huber, D.A. 2003. Dynamics of artificial regeneration in gaps within a longleaf pine flatwoods ecosystem. Forest Ecology and Management. 172: 133-144.

Garren, K.H. 1943. Effects of fire on vegetation of the Southeastern United States. Botanical Review. 9: 617-654.

Gilliam, F.S.; Yurish, B.M.; Goodwin, L.M. 1993. Community composition of an old growth longleaf pine forest: relationship to soil texture. Bulletin of the Torrey Botanical Club. 120(3): 287-294.

Glitzenstein, J.S.; Platt, W.J.; Streng, D.R. 1995. Effects of fire regime and habitat on tree dynamics in north Florida longleaf pine savannas. Ecological Monographs. 65(4): 441-476.

Glitzenstein, J.S.; Streng, D.R.; Wade, D.D. 1998. A promising start for a new population of *Parnassia caroliniana* Michx. In: Kush, J.S., comp. Ecological restoration and regional conservation strategies. Longleaf Alliance Rep. 3. Andalusia, AL: Solon Dixon Forestry Education Center: 44-58.

Glitzenstein, J.S.; Streng, D.R.; Wade, D.D.; Brubaker, J. 2001. Starting new populations of longleaf pine ground-layer plants in the outer Coastal Plain of South Carolina, USA. Natural Areas Journal. 21(1): 89-110.

Golden, M.S. 1979. Forest vegetation of the lower Alabama Piedmont. Ecology. 60(4): 770-782.

Greenberg, C.H.; Simons, R.W. 1999. Age, composition and stand structure of old-growth oak sites in the Florida high pine landscape: implications for ecosystem management and restoration. Natural Areas Journal. 19(1): 30-40.

Grelen, H.E. 1962. Plant succession on cleared sandhills in northern Florida. American Midland Naturalist. 67: 36-44.

Guldin, J.M. 1996. The role of uneven-aged silviculture in the context of ecosystem management. Western Journal of Applied Forestry. 11(1): 4-12.

Guyer, C.; Bailey, M.A. 1993. Amphibians and reptiles of longleaf pine communities. In: Herman, S.M., ed. Proceedings of the 18th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 139-158.

Hardin, E.D.; White, D.L. 1989. Rare vascular plant taxa associated with wiregrass (*Aristida stricta*) in the Southeastern United States. Natural Areas Journal. 9: 234-245.

Harper, W.M. 1913. A defense of forest fires. Literary Digest. 47: 208.

Hattenbach, M.J.; Gordon, D.R.; Seamon, G.S.; Studenmund, R.G. 1998. Development of direct-seeding techniques to restore native groundcover in a sandhill ecosystem. In: Kush, J.S., comp. Ecological restoration and regional conservation strategies. Longleaf Alliance Rep. 3. Andalusia, AL: Solon Dixon Forestry Education Center: 64-70.

Haywood, J.D.; Harris, F.L.; Grelen, H.E.; Pearson, H.A. 2001. Vegetative response to 37 years of seasonal burning on a Louisiana longleaf pine site. Southern Journal of Applied Forestry. 25(3): 122-130.

Hedman, C.W.; Grace, S.L.; King, S.E. 2000. Vegetation composition and structure of southern Coastal Plain pine forests: an ecological comparison. Forest Ecology and Management. 134: 233-247.

Hiers, K.; Wyatt, R.; Mitchell, R.J. 2000. The effects of fire regime on legume reproduction in longleaf pine savannas: is a season selective? Oecologia. 125: 521-530.

Hilliard, T. 1998. Longleaf-wiregrass restoration at Fort Stewart, Georgia: the military's role in restoration. In: Kush, J.S., comp. Ecological restoration and regional conservation strategies. Longleaf Alliance Rep. 3. Andalusia, AL: Solon Dixon Forestry Education Center: 32.

Hilton, J. 1999. Biological diversity in the longleaf pine ecosystem. Alabama's Treasured Forests. 18(4): 28-29.

Hobbs, R.J. 1994. Dynamics of vegetation mosaics: can we predict responses to global change? Ecoscience. 1: 346-356.

Hobbs, R.J. 1996. Can we use plant functional types to describe and predict responses to environmental change? In: Smith, T.M.; Shugart, H.H., eds. Plant functional types. Cambridge, UK: Cambridge University Press: 41-61.

Hobbs, R.J.; Norton, D.A. 1996. Towards a conceptual framework for restoration ecology. Restoration Ecology. 4(2): 93-110.

Holliday, P.P. 2001. Going, going... saving the longleaf pine ecosystem before it's gone. Sherpa Guides. http://www.sherpaguides.com/georgia/fire_forest/saving_ecosystem/ index.html. [Date accessed: June 7, 2004].

Huffman, J.M.; Dye, R. 1994. Summary of wiregrass ecosystem restoration projects at Myakka River State Park. In: Clewell, A.F.; Cleckley, W., eds. Proceedings of the wiregrass ecosystem restoration workshop. Tallahassee, FL: State of Florida, Northwest Florida Water Management District: 21.

Jackson, D.R.; Milstrey, E.R. 1989. The fauna of gopher tortoise burrows. In: Diemer, J.E., ed. Proceedings of the gopher tortoise relocation symposium. Tallahassee, FL: State of Florida, Game and Freshwater Fish Commission: 86-98.

Kalisz, P.J.; Stone, E.L. 1984. The longleaf pine islands of the Ocala National Forest, Florida: a soil study. Ecology. 65(6): 1743-1754.

Kantola, T.A.; Humphrey, S.R. 1990. Habitat use of Sherman's fox squirrel (*Sciurus niger shermanni*) in Florida. Journal of Mammalogy. 71: 411-419.

Keetch, J.J.; Byram, G.M. 1968. A drought index for forest fire control. Res. Pap. SE-38. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 35 p.

Kelly, J.F.; Bechtold, W.A. 1990. The longleaf pine resource. In: Farrar, R.M., ed. Management of longleaf pine. Gen. Tech. Rep. SO-75. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station: 11-22.

Kimmins, J.P. 1992. Balancing act: environmental issues in forestry. Vancouver, BC, Canada: University of British Columbia Press. 305 p.

Kirkman, L.K.; Drew, M.B.; Edwards, D. 1998a. Effects of experimental fire regimes on the population dynamics of *Schwalbea americana* L. Plant Ecology. 137: 115-137.

Kirkman, L.K.; Drew, M.B.; West, L.T.; Blood, E.R. 1998b. Ecotone characterization between upland longleaf pine/wiregrass stands and seasonally-ponded isolated wetlands. Wetlands. 18(3): 346-364.

Komarek, E.V. 1968. Lightning and lightning fires as ecological forces. In: Proceedings of the 9th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 169-198.

Komarek, E.V. 1977. Tall Timbers Research Station, a quest for ecological understanding. Misc. Publ. 5. Tallahassee, FL: Tall Timbers Research Station. 140 p.

Kush, J.S.; Meldahl, R.S. 2000. Composition of a virgin stand of longleaf pine in south Alabama. Castanea. 65(1): 56-63.

Landers, J.L. 1991. Disturbance influences on pine traits in the Southeastern United States. In: Proceedings of the 17th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 61-98.

Landers, J.L.; Boyer, W.D. 1999. An old-growth definition for upland longleaf and south Florida slash pine forests, woodlands and savannas. Gen. Tech. Rep. SRS-29. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 15 p.

Landers, J.L.; Byrd, N.A.; Komarek, R. 1990. A holistic approach to managing longleaf pine communities. In: Farrar, R.M., ed. Management of longleaf pine. Gen. Tech. Rep. SO-75. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station: 135-167.

Landers, J.L.; Van Lear, D.H.; Boyer, W.D. 1995. The longleaf pine forests of the Southeast: requiem or renaissance? Journal of Forestry. 93(11): 39-44.

Ledig, F.T. 1988. The conservation of diversity in forest trees. BioScience. 38: 471-479.

Lemon, P.C. 1949. Successional responses of herbs in the longleaf-slash pine forest after fire. Ecology. 30(2): 135-145.

Little, E.L. 1971. Atlas of United States trees. Conifers and important hardwoods. Misc. Publ. 1146. Washington, DC: U.S. Department of Agriculture Forest Service. 320 p. Vol. 1.

McGuire, J.P.; Mitchell, R.J.; Moser, E.B. [and others]. 2001. Gaps in a gappy forest: plant resources, longleaf pine regeneration and understory response to tree removal in longleaf pine savannas. Canadian Journal of Forest Research. 31: 765-778.

McKee, W.H. 1982. Changes in soil fertility following prescribed burning on Coastal Plain pine sites. Res. Pap. SE-234. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 23 p.

McMahon, C.K.; Tomczak, D.J.; Jeffers, R.M. 1998. Longleaf pine ecosystem restoration: the role of the USDA Forest Service. In: Kush, J.S., comp. Ecological restoration and regional conservation strategies. Longleaf Alliance Rep. 3. Andalusia, AL, Solon Dixon Forestry Education Center: 20-31.

McWhite, R.W.; Furman, J.; Petrick, C.J. [and others]. 1999. Eglin Air Force Base integrated natural resources transitional plan 1998-2001. Niceville, FL: U.S. Department of Defense, Air Force, Natural Resources Management Branch. 225 p.

Means, D.B. 1997. Wiregrass restoration: probable shading effects in a slash pine plantation. Restoration and Management Notes. 15: 52-55.

Means, D.B.; Grow, G. 1985. The endangered longleaf pine community. ENFO (Winter Park, FL: Florida Conservation Foundation) 85(4): 1-12.

Millar, C.I.; Woolfenden, W.B. 1999. The role of climate change in interpreting historical variability. Ecological Applications. 9(4): 1207-1216.

Miller, J.H.; Robinson, K.S. 1995. A regional perspective of the physiographic provinces of the Southeastern United States. In: Edwards, M.B., comp. Proceedings of the eighth biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-1. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 581-591.

Miller, S.R.; Bossuot, W.R. 2000. Flatwoods restoration on the St. Johns River Water Management District, Florida: a prescription to cut and burn. Proceedings of the 21st Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 212-215.

Mohr, C.T. 1896. The timber pines of the Southern United States. Bull.13. Washington, DC: U.S. Department of Agriculture, Division of Forestry. 176 p.

Moore, M.M.; Covington, W.W.; Fule, P.Z. 1999. Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. Ecological Applications. 9(4): 1266-1277.

Mulligan, M.K.; Kirkman, L.K.; Mitchell, R.J. 2002. *Aristida beyrichiana* (wiregrass) establishment and recruitment: implications for restoration. Restoration Ecology. 10(1): 68-76.

Noss, R.F. 1989. Longleaf pine and wiregrass: keystone components of an endangered ecosystem. Natural Areas Journal. 9: 211-213.

Noss, R.F.; LaRoe, E.T.; Scott, J.M. 1995. Endangered ecosystems of the United States: a preliminary assessment of loss and degradation. Biol. Rep. 28. Washington, DC: U.S. Department of the Interior, National Biological Service. 59 p.

Oliver, C.D. 1992. Achieving and maintaining biodiversity and economic productivity. Journal of Forestry. 90(9): 20-25.

Outcalt, K.W. 1983. Mechanical site preparation improves growth of genetically improved and unimproved slash pine on a Florida flatwoods site. In: Jones, E.P., ed. Proceedings of the 2d biennial southern silvicultural research conference. Gen. Tech. Rep. SE-24. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station: 11-13.

Outcalt, K.W. 1994. Seed production of wiregrass in central Florida following growing season prescribed burns. International Journal of Wildland Fire. 4(1): 123-125.

Outcalt, K.W. 1995. Maintaining the native plant community during longleaf pine establishment. FRI Bull. 192. Rotorua, New Zealand: Forestry Research Institute: 283-285.

Outcalt, K.W. 1998. Needs and opportunities for longleaf pine ecosystem restoration in Florida. In: Kush, J.S., comp. Ecological restoration and regional conservation strategies. Longleaf Alliance Rep. 3. Andalusia, AL: Solon Dixon Forestry Education Center: 38-43.

Outcalt, K.W. 2000. Occurrence of fire in longleaf pine stands in the Southeastern United States. In: Moser, W.K.; Moser, C.F., eds. Proceedings of the 21st Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 178-182.

Outcalt, K.W. 2001. Condition of longleaf communities in the Southeast. In: Kush, J.S., comp. Forests for our future—restoration and management of longleaf pine ecosystems: silvicultural, ecological, social, political and economic challenges. Longleaf Alliance Rep. 5. Andalusia, AL: Solon Dixon Forestry Education Center: 178-180.

Outcalt, K.W.; Lewis, C.E. 1990. Response of wiregrass (*Aristida stricta*) to mechanical site preparation. In: Duever, L.C.; Noss, R.F., eds. Wiregrass biology and management. Gainesville, FL: KBN Engineering and Applied Sciences: 60-71.

Outcalt, K.W.; Sheffield, R.M. 1996. The longleaf pine forest: trends and current conditions. Resour. Bull. SRS-9. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 23 p.

Outcalt, K.W.; Williams, M.E.; Onokpise, O. 1999. Restoring *Aristida stricta* to *Pinus palustris* ecosystems on the Atlantic Coastal Plain, USA. Restoration Ecology. 7: 262-270.

Palik, B.J.; Goebel, P.C.; Kirkman, L.K.; West, L. 2000. Using landscape hierarchies to guide restoration of disturbed ecosystems. Ecological Applications. 10(1): 189-206.

Palik, B.J.; Mitchell, R.J.; Hiers, J.K. 2002. Modeling silviculture after natural disturbance to sustain biodiversity in the longleaf pine (*Pinus palustris*) ecosystem: balancing complexity and implementation. Forest Ecology and Management. 155: 347-356.

Palik, B.J.; Mitchell, R.J; Houseal, G.; Pedersen, N. 1997. Effects of canopy structure on resource availability and seedling responses in a longleaf pine ecosystem. Canadian Journal of Forest Research. 27: 1458-1464.

Palik, B.J.; Pedersen, N. 1996. Overstory mortality and canopy disturbances in longleaf pine ecosystems. Canadian Journal of Forest Research. 26: 2035-2047.

Parsons, D.J.; Swetnam, T.W.; Christensen, N.L. 1999. Uses and limitations of historical variability concepts in managing ecosystems. Ecological Applications. 9(4): 1177-1178.

Peet, R.K.; Allard, D.J. 1993. Longleaf pine-dominated vegetation of the southern Atlantic and eastern gulf coast region, USA. In: Herman, S.M., ed. Proceedings of the 18th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 45-81.

Pickett, S.T.A.; White, P.S. 1985. The ecology of natural disturbance and patch dynamics. Orlando, FL: Academic Press. 472 p.

Pittman T.; Karrfalt, R.P. 2000. Wiregrass propagation at the Andrews Nursery in Florida. Native Plants Journal. 1: 45-47.

Platt, W.J.; Evans, G.W.; Davis, M.M. 1988a. Effects of fire season on flowering of forbs and shrubs in longleaf pine forests. Oecologia. 76: 353-363.

Platt, W.J.; Evans, G.W.; Rathbun, S.L. 1988b. The population dynamics of a long-lived conifer (*Pinus palustris*). American Naturalist. 131(4): 491-525.

Platt, W.J.; Rathbun, S.L. 1993. Dynamics of an old-growth longleaf pine population. In: Herman, S.M., ed. Proceedings of the 18th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 275-297.

Prestemon, J.P.; Abt, R.C. 2002. Timber products and supply and demand. In: Wear, D.N.; Greis, J.G., eds. The southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 299-325.

Pritchett, W.L. 1979. Properties and management of forest soils. New York: John Wiley. 500 p.

Provencher, L.; Litt, A.R.; Galley, K.E.M. [and others]. 2001. Restoration of fire suppressed longleaf pine sandhills at Eglin Air Force Base, Niceville, Florida. Gainesville, FL: The Nature Conservancy, Science Division. 294 p.

Pyne, S.J. 1997. Fire in America: a cultural history of wildland and rural fire. Princeton, NJ: Princeton University Press. 654 p.

Pyne, S.J.; Andrews, P.L.; Laven, R.D. 1996. Introduction to wildland fire. New York: John Wiley. 769 p.

Rebertus, A.J.; Williamson, G.B.; Platt, W.J. 1993. The impact of temporal variation in fire regime on savanna oaks and pines. In: Herman, S.M., ed. Proceedings of the 18th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 215-225.

Riggs, L.A. 1990. Conserving genetic resources on-site in forest ecosystems. Forest Ecology and Management. 35: 45-68.

Robbins, L.E.; Myers, R.L. 1992. Seasonal effects of prescribed burning in Florida: a review. Misc. Publ. 8. Tallahassee, FL: Tall Timbers Research Station. 96 p.

Rodgers, H.L.; Provencher, L. 1999. Analysis of longleaf pine sandhill vegetation in northwest Florida. Castanea. 64(2): 138-162.

Schabel, H.G.; Palmer, S.L. 1999. The Dauerwald: its role in the restoration of natural forests. Journal of Forestry. 97(11): 20-25.

Schmidtling, R.C.; Hipkins, V. 1998. Genetic diversity in longleaf pine (*Pinus palustris*): influence of historical and prehistorical events. Canadian Journal of Forest Research. 28: 1135-1145.

Schultz, R.P. 1976. Environmental change after site preparation and slash pine planting on a flatwoods site. Res. Pap. SE-156. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 20 p.

Schultz, R.P. 1997. The ecology and culture of loblolly pine (*Pinus taeda* L.). Agric. Handb. 713. Washington, DC: U.S. Department of Agriculture Forest Service. 493 p.

Schwartz, M.W. 1994. Natural distribution and abundance of forest species and communities in northern Florida. Ecology. 75(3): 687-705.

Schwarz, G.F. 1907. The longleaf pine virgin forest: a silvical study. New York: John Wiley. 135 p.

Seamon, G. 1998. A longleaf pine sandhill restoration in northwest Florida. Restoration and Management Notes. 16: 46-50.

Smith, G.P.; Shelburne, V.B.; Walker, J.L. 2002. Structure and composition of vegetation of longleaf pine plantations compared to natural stands occurring along an environmental gradient at the Savannah River Site. In: Outcalt, K.W., ed. Proceedings of the 11th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-48. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 481-485.

Smith, L.F. 1955. Development of longleaf pine seedlings near large trees. Journal of Forestry. 53(4): 289-290.

Society for Ecological Restoration International. 2002. The SER primer on ecological restoration. Tucson, AZ: SERI Science and Policy Working Group. 8 p.

Speake, S.W. 1981. The gopher tortoise burrow community. In: Lohoefener, R.; Lohmeier, L.; Johnston, G., eds. The future of gopher tortoise habitats. Proceedings of the 2d annual meeting of the gopher tortoise council. Jackson, MS: Mississippi Museum of Natural Science: 44-47.

Stanturf, J.A.; Wade, D.D.; Waldrop, T.A. [and others]. 2002. Fire in southern landscapes. In: Wear, D.N.; Greis, J.G., eds. The southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 607-630.

Stout, I.J.; Marion, W.R. 1993. Pine flatwoods and xeric pine forests of the southern lower Coastal Plain. In: Martin, W.H.; Boyce, S.G.; Echternacht, A.C., eds. Biodiversity of the Southeastern United States: lowland terrestrial communities. New York: John Wiley: 373-446.

Taylor, A.R. 1974. Ecological aspects of lightning in forests. In: Proceedings of the 13th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 455- 482.

Uridel, K.W. 1994. Restoration of native herbs in abandoned *Paspalum notatum* (Bahia grass) pastures. M.S. thesis. Gainesville, FL: University of Florida. 61 p.

Varner, J.M.; Kush, J.S.; Meldahl, R.S. 2000. Ecological restoration of an old-growth longleaf pine stand utilizing prescribed fire. In: Moser, W.K.; Moser, C.F., eds. Proceedings of the 21st Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 216-219.

Varner, J.M.; Kush, J.S.; Meldahl, R.S. 2001. Understory species composition of old-growth mountain longleaf pine (*Pinus palustris* Mill.) stands at Fort McClellan, Alabama. In: Kush, J.S., comp. Forests for our future—restoration and management of longleaf pine ecosystems: silvicultural, ecological, social, political and economic challenges. Longleaf Alliance Rep. 5. Andalusia, AL: Solon Dixon Forestry Education Center: 209-213.

Wade, D.D.; Lewis, C.E. 1987. Managing southern grazing ecosystems with fire. Rangelands. 9(3): 115-119.

Wade, D.D.; Lundsford, J. 1990. Fire as a forest management tool: prescribed burning in the Southern United States. Unasylva. 162(41): 28-38.

Wagner, M.R.; Block, W.M.; Geils, B.W.; Wenger, K.F. 2000. Restoration ecology: a new forest management paradigm, or another merit badge for foresters? Journal of Forestry. 98(10): 22-27.

Wahlenberg, W.G. 1946. Longleaf pine: its use, ecology, regeneration, protection, growth and management. Washington, DC: C.L. Pack Forestry Foundation; U.S. Department of Agriculture Forest Service. 429 p.

Waldrop, T.A.; Van Lear, D.H.; Lloyd, F.T.; Harms, W.R. 1987. Long-term studies of prescribed burning in loblolly pine forests of the Southeastern Coastal Plain. Gen. Tech. Rep. SE-45. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 23 p.

Walker, J.L. 1993. Rare vascular plant taxa associated with the longleaf pine ecosystem. In: Hermann, S.M., ed. Proceedings of the 18th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 105-125.

Walker, J.L. 1995. Longleaf pine ecosystem restoration: toward a regional strategy. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station; Atlanta; U.S. Department of Agriculture Forest Service, Southern Region. 42 p. [Report to participants].

Walker, J.L. 1998. Ground layer vegetation in longleaf pine landscapes: an overview for restoration and management. In: Kush, J.S., comp. Ecological restoration and regional conservation strategies. Longleaf Alliance Rep. 3. Andalusia, AL: Solon Dixon Forestry Education Center: 2-13.

Walker, J.L.; Boyer, W.D. 1993. An ecological model and information needs assessment for longleaf pine ecosystem restoration. In: Foley, L.H., comp. Silviculture from the Cradle of Forestry to ecosystem management. Gen. Tech. Rep. SE-88. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station: 138-147.

Walker, L.C.; Davis, V.B. 1954. Forest walls retard young longleaf pine. Res. Note 93. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 1 p.

Walker, L.C.; Davis, V.B. 1956. Seed trees retard longleaf pine seedlings. Journal of Forestry. 54(4): 269.

Walker, L.C.; Oswald, B.P. 2000. The southern forest: geography, ecology and silviculture. New York: CRC Press. 332 p.

Ware, S.; Frost, C.C.; Doerr, P.D. 1993. Southern mixed hardwood forest: the former longleaf pine forest. In: Martin, W.H.; Boyce, S.G.; Echternacht, A.C., eds. Biodiversity of the Southeastern United States: lowland terrestrial communities. New York: John Wiley: 447-493.

Watts, W.A. 1970. The full-glacial vegetation of northwestern Georgia. Ecology. 51(1): 17-33.

Watts, W.A. 1971. Postglacial and interglacial vegetation history of southern Georgia and central Florida. Ecology. 52(4): 676-690.

Watts, W.A.; Hansen, B.C.S. 1988. Environments of Florida in the late Wisconsin and Holocene. In: Purdy, B.A., ed. Wet site archeology. Caldwell, NJ: Telford Press: 307-323.

Watts, W.A.; Hansen, B.C.S.; Grimm, E.C. 1992. Camel Lake: a 40,000-yr record of vegetational and forest history from north Florida. Ecology. 73(3): 1056-1066.

Wear, D.N.; Greis, J.G. 2002. Summary report. In: Wear, D.N.; Greis, J.G., eds. The southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 114 p.

Westoby, M.; Walker, B.; Noy-Meir, I. 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management. 43(4): 266-274.

White, P.S.; Walker, J.L. 1997. Approximating nature's variation: selecting and using reference information in restoration ecology. Restoration Ecology. 5(4): 338-349.

Whitmore, T.C. 1989. Canopy gaps and the two major groups of forest trees. Ecology. 70(3): 536-538.

Williams, J.L. 1837. The territory of Florida. Gainesville, FL: University of Florida Press. 304 p.

Williston, H.L.; Guthrie, J.G.; Hood, C.A. 1990. Managing and harvesting longleaf pine for specialty products. In: Farrar, R.M., ed. Management of longleaf pine. Gen. Tech. Rep. SO-75. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station: 209-214.

Wright, H.A.; Bailey, A.W. 1982. Fire ecology of the United States and Southern Canada. New York: John Wiley. 501 p.

METRIC CONVERSION TABLE

Symbol	*When You Know*	*Multiply by*	*To Find*	*Symbol*
		LENGTH		
mm	millimeters	0.0394	inches	in
cm	centimeters	0.3937	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
cm^2	square centimeters	0.1550	square inches	in^2
m^2	square meters	1.196	square yards	yd^2
km^2	square kilometers	0.3861	square miles	mi^2
ha	hectares (10 000 m^2)	2.471	acres	
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
t	metric ton (1 000 kg)	1.102	short tons	
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
mL	milliliters	0.0610	cubic inches	in^3
L	liters	2.113	pints	pt
L	liters	1.057	quarts	qt
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		TEMPERATURE		
°C	degrees Celsius	multiply by 9/5, add 32	degrees Farenheit	°F

Brockway, Dale G.; Outcalt, Kenneth W.; Tomczak, Donald J.; Johnson, Everett E. 2005. Restoration of longleaf pine ecosystems. Gen. Tech. Rep. SRS-83. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 34 p.

Longleaf pine (*Pinus palustris*) ecosystems once occupied 38 million ha in the Southeastern United States, occurring as forests, woodlands, and savannas on a variety of sites ranging from wet flatwoods to xeric sandhills and rocky mountainous ridges. Characterized by an open parklike structure, longleaf pine ecosystems are a product of frequent fires, facilitated by the presence of fallen pine needles and bunchgrasses in the understory. Timber harvest, land conversion to agricultural and other nonforest uses, and alteration of fire regimes greatly reduced longleaf pine ecosystems, until only 1.2 million ha remained in 1995. Longleaf pine ecosystems are among the most species-rich ecosystems outside the tropics. However, habitat loss and degradation have caused increased rarity of many obligate species. The lack of frequent surface fires and the proliferation of woody plants in the understory and midstory have greatly increased the risk of additional longleaf pine ecosystem losses from catastrophic fire.

Because longleaf pine still exists in numerous small fragments throughout its range, it is reasonable to conclude that it can be restored. Restoration efforts now underway use physical, chemical, and pyric methods to reestablish the natural structure and function in these ecosystems by adjusting species composition, modifying stand structure, and facilitating ecological processes, such as periodic fire and longleaf pine regeneration. The ecological, economic, and social benefits of restoring longleaf pine ecosystems include (1) expanding the habitat available to aid in the recovery of numerous imperiled species, (2) improving habitat quality for many wildlife species, (3) producing greater amounts of high-quality longleaf pine timber products, (4) increasing the production of pine straw, (5) providing new recreational opportunities, (6) preserving natural and cultural legacies, and (7) creating a broader range of management options for future generations.

Keywords: Biological diversity, bluestem grasses, disturbance, fire ecology, gopher tortoise, *Pinus palustris* Mill., red-cockaded woodpecker, wiregrass.

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