CHAPTER 2.

Silviculture of Forests in the Eastern United States

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The forests of the Eastern United States are diverse and provide many products and amenities for people living in the area and beyond. Eastern temperate forests play an important role in determining water yield and quality. They have the potential to sequester large quantities of carbon and influence air quality, and thus climate. Our standard of living is very much linked to the health and productivity of forests. Forests cover approximately 41 percent of the Eastern United States, on average, but vary considerably at the State level, ranging from 6 percent in Iowa to 89 percent in Maine (Smith and others 2004).

This chapter provides a brief overview of the silviculture of eastern forests beginning with some fundamental definitions and concepts in silviculture that will be more fully applied in syntheses for northern conifers, northern and central hardwoods, southern hardwoods, and southern pines (table 1, fig. 1). These silvicultural overviews will allow us to address, to an extent, how silvicultural systems differ across a landscape that is highly variable in climate, soils, geology, biodiversity, and ecology.

The forest management plan considers the entire forest estate, which may range from hundreds to millions of acres. It identifies the broad goals and objectives of the landowner and guides management activities at finer spatial and temporal scales. In practice, forest operations occur at the stand scale (usually <100 acres); this is where silviculture is practiced. A recent exception is in the restoration of fire-dependent communities, where prescribed burning may be applied across landscapes of thousands of acres. Even on landscape-scale restoration projects, treatments such as thinning and midstory reduction are usually conducted in "stand-sized" areas to manage glades, fens, and other site specific communities. Also, smaller areas within the greater restoration area may need to be treated differently to create a diverse mosaic of stand composition and density as hardwood or conifer savannas, woodlands, and forests.

Good forest management requires that good silviculture be practiced.

Silviculture

Silviculture is the science and art of cultivating forests by controlling their establishment, growth, composition, structure, health, and quality by applying planned and deliberate treatments to achieve specific objectives on a sustainable basis (Helms 1998). Silviculture is applied forest ecology: selection and implementation of treatments are

Table 1. Forest regions and ecological divisions with division numbers in parentheses

Forest region	Warm Continental (210)	Hot Continental (220)	Subtropical (230)	Warm Continental Mountains (M210)	Hot Continental Mountains (M220)	Subtropical Mountains (M230)
Northern conifers	X			X		
Northern hardwoods	X			X		
Central hardwoods		X	X		X	X
Southern hardwoods			X			
Southern pines			X			

Sources: Bailey (1995), Braun (1950), Hicks (1998), and Johnson and others (2002).

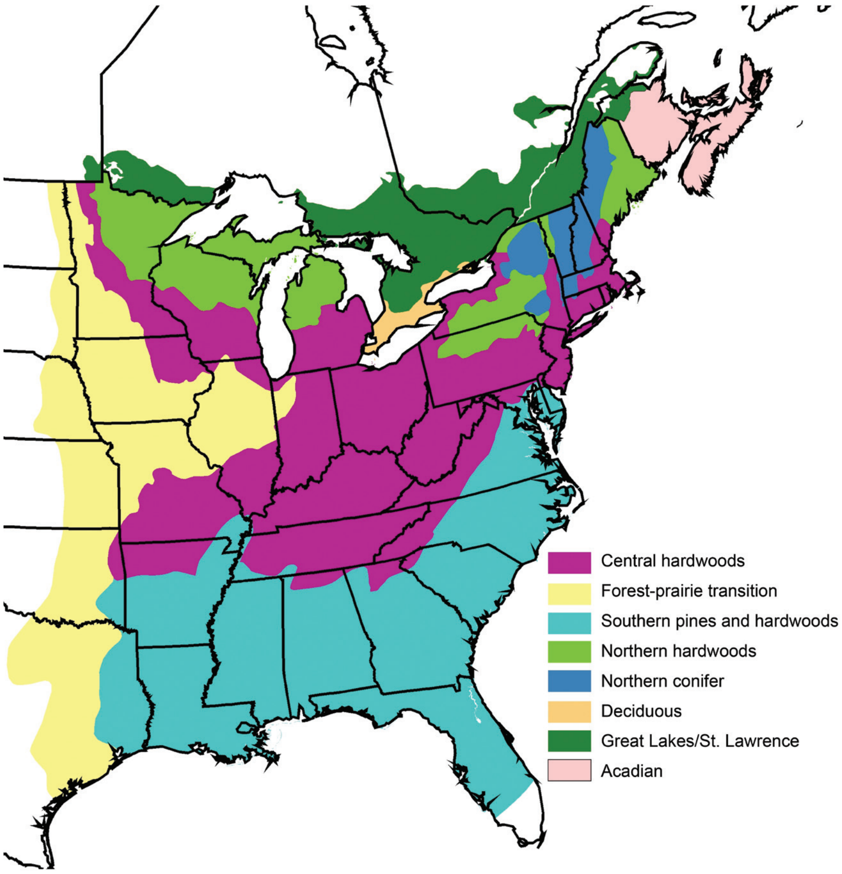

Figure 1. Major forest regions of the Eastern United States (Johnson and others 2002).

founded on the knowledge of ecosystem process and function, disturbance ecology, silvics, and stand dynamics. The practice of silviculture requires integration of many disciplines including ecology, genetics, entomology, pathology, soils, and other physical, biological, and social sciences.

Silvicultural Treatments

Silvicultural treatments are applied to regenerate forests or promote stand development within existing forests. The clearcutting, shelterwood, and seed-tree regeneration methods create even-aged stands, in which trees are of a single age class and the range in age does not exceed 20 percent of the rotation (Helms 1998) or how long the stand is allowed to grow until it is regenerated again. Single-tree and group selection regeneration methods produce uneven-aged stands, in which there are at least three distinct age classes of trees intermingled (table 2).

Table 2. Silvicultural treatments for stand regeneration or intermediate tending

Regeneration	Age structure	Method
	Even-aged	Clearcut
		Seed tree
		Shelterwood
	Uneven-aged	Single-tree selection
		Group selection
Intermediate tending	Thinning	
	Release cutting	Weeding
		Cleaning
		Liberation
	Pruning	
	Sanitation cutting	
	Salvage harvesting	

Tending treatments (intermediate cuttings) may be applied in conjunction with the regeneration harvest in an uneven-aged system, or at various times in an even-aged system. Tending alters stand character because it results in removal of some trees to achieve specific responses from remaining trees. The tending treatment is named according to the intended purpose or stage of stand development. For example, (1) thinning reduces stand density and increases growth (stem diameter or crown size) of residual trees; (2) release cuttings before the sapling stage free seedlings from competing vegetation (weeding), from overtopping undesirable competing trees of the same age (cleaning), or from overtopping older trees (liberation); (3) pruning removes branches to improve future tree grade and log quality; (4) sanitation cutting reduces the threat of insect and disease pests by improving tree health and vigor; and (5) salvage harvesting recovers dead or dying trees after pest outbreaks or wildfire.

Silvicultural System

A silvicultural system is a comprehensive program of planned treatments, including regeneration and tending, that are applied to manage a forest stand through its life. Its name either describes the number of age classes (even- or uneven-aged) or the regeneration method, such as clearcutting, shelterwood, or selection harvesting (fig. 2). A silvicultural prescription outlines for each stand the timing and sequence of all treatments in the silvicultural system, including the specific regeneration method and the tending treatments needed to carry the stand from its existing condition to the desired future condition (the condition that meets the needs of the landowner).

Development of a silvicultural prescription for a stand begins with the assessment of the current stand and site conditions and consideration of any expected problems from insect and disease pests, nonnative invasive species, and damaging wildlife—such as white-tailed deer (*Odocoileus virginianus)* browsing. Then comes a thorough evaluation of how well alternative silvicultural systems could achieve management objectives in light of social, economic, and ecological constraints and opportunities. The prescription identifies the type and timing of activities needed to meet other objectives listed in the management plan—for example, reducing fire risk, retaining trees and coarse woody debris for wildlife habitat, sustaining native biodiversity, protecting culturally sensitive sites, mitigating soil erosion, or maintaining an ecological legacy from the previous stand—and describes which objectives will be achieved through implementation of each silvicultural treatment. The prescription also provides quantitative benchmarks at various key stages in stand development that indicate whether the outcomes of silvicultural treatments will be desirable and sustainable.

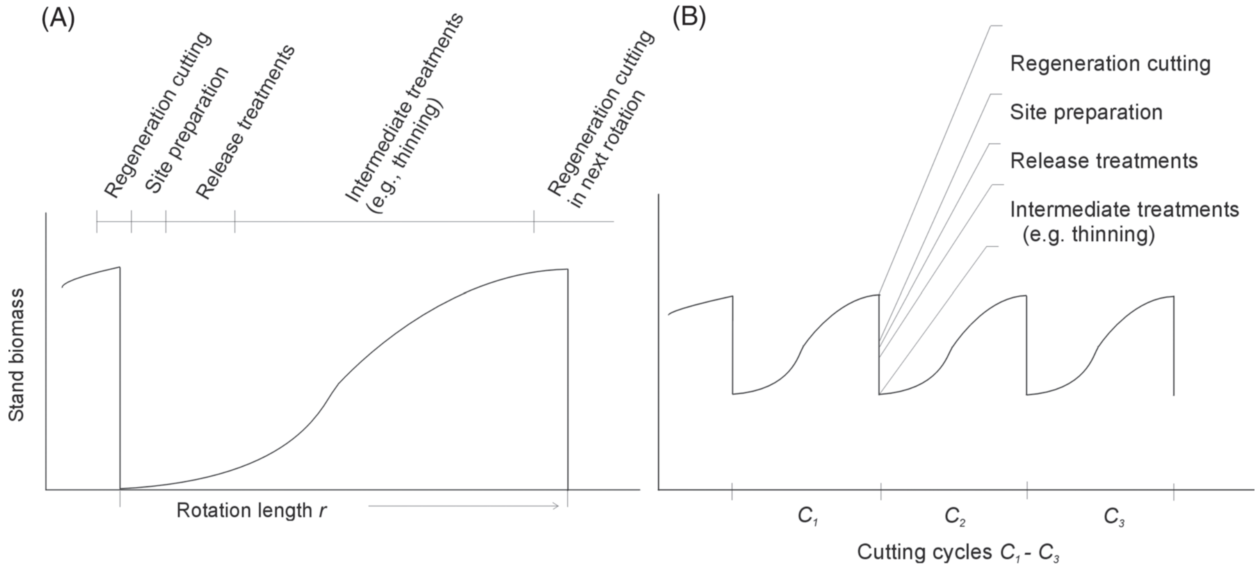

Figure 2. Schematics showing (A) chronosequential application of individual practices of a silvicultural system in an even-aged stand, with treatments applied across the entire stand to meet age-class silvicultural objectives during the rotation period, and (B) concurrent application of individual practices of an uneven-aged silvicultural system during a cutting cycle harvest in a balanced uneven-aged stand; with each cutting cycle harvest supporting similar treatments (Guldin 2006).

Regeneration Methods

A brief review of the common regeneration methods used in the Eastern United States will provide a common understanding for the discussions of silvicultural systems for specific forests. It is important to distinguish between acceptable regeneration methods and practices—such as diameter-limit cutting, selective cutting, and high grading commonly practiced on nonindustrial private lands—that are not recommended because their main goal is to remove commercial timber with little thought for regeneration, future productivity and value, or other long-term benefits to landowners.

Even-Aged Regeneration Methods

The following methods regenerate even-aged stands:

Clearcutting

Clearcutting removes the entire stand in one operation. Some trees may be left in the clearcut to achieve goals other than regeneration, but their density is not enough to inhibit the development of reproduction. Natural reproduction is by seeding from adjacent stands and harvested trees, advance reproduction (seedlings or saplings in the understory before harvesting), stump sprouts (shoots arising from stumps of harvested trees), and root suckers (shoots arising from tree roots). Artificial regeneration methods, either by direct seeding or planting, can be applied before (but more commonly after) clearcutting.

Seed-tree

Seed-tree is similar to clearcutting except that a small number of mature trees are left singly or in groups throughout the harvested area to supply seed for natural regeneration. The residual crown cover of seed trees is not large enough to create more modifications to the physical environment than would have been created by a clearcut.

Shelterwood

Shelterwood removes the overstory in a series of harvests over a relatively short portion of the rotation. The goal is to retain enough seed producers to naturally regenerate the stand and enough residual overstory to shelter both newly established seedlings and existing advance reproduction from environmental extremes. Harvesting is usually from below (with trees in the smaller diameter classes and lower crown classes removed first), leaving the prescribed stocking of codominant and dominant trees of desirable species. The shelterwood is removed in a final harvest once sufficient numbers of competitive stems are established. The shelterwood system can be applied uniformly across the stand (uniform shelterwood) or in patterns such as groups (group shelterwood) or strips (strip shelterwood). In addition, a portion of the shelterwood (shelterwood with reserves) may be retained throughout the rotation for purposes other than regeneration, such as mast production, aesthetics, and structure for wildlife habitat. The shelterwood method may consist of three harvests:

- A preparatory cut removes the seed source of undesirable species and low-quality individuals and promotes the crown expansion of seed trees. This is not necessary if the existing stand has adequate seed production potential or if advance reproduction is present.
- A seed or establishment cut further reduces canopy closure in (or just before) a seed year, provides opportunities for site preparation before seed fall, and creates environmental conditions that favor germination and seedling establishment.
- A removal cut harvests the residual overstory to release well established reproduction.

Uneven-Aged Regeneration Methods

The following methods regenerate uneven-aged stands:

Single-tree selection

Single-tree selection is practiced by harvesting individual or small groups of trees indefinitely on a 5- to 25-year cutting cycle. Both regeneration and tending take place simultaneously in each harvest. Trees are considered for removal from all diameter classes in the stand with the goal of establishing reproduction and allowing recruitment of existing trees into larger size classes. Selection of an individual tree for removal is also influenced by its quality, vigor, and growing space requirements and by its potential contributions to wildlife habitat. Regeneration is largely from natural seedfall, existing advance reproduction, or stump sprouts and root suckers that develop after harvesting.

Group selection

Group selection is applied on small patches, in which all trees are cut to create openings that are larger than single-tree gaps but smaller than clearcuts. The size of a group opening varies, depending on the regeneration requirements of the desired species, but is commonly twice the height (about 125 to 250 feet) of adjacent mature trees, or about 0.2 to 1.1 acres. The abundance and size of advance reproduction largely determines what reproduction will dominate forest openings: when advance reproduction is small, sparse, or absent, then regeneration is from seed. Group openings are often located where abundant advance reproduction occurs in patches within the stand.

Combining prescriptions

Stand prescriptions for single-tree or group selection are guided by the desire to maintain a specified stand structure that sustainably yields a flow of products. In single-tree selection, the intensity and frequency of harvesting and the selection of trees for removal is determined by growth rate, target basal area, maximum tree diameter, and diameter distribution. In a stand or management unit, the area harvested by group selection is often regulated by area control and the length of the rotation. Practically, single-tree and group selections are applied together in a stand, with group openings being opportunistically used to increase forest diversity by favoring species that are intolerant-to-intermediately tolerant of shade.

Northern Conifer Silviculture

Stands dominated by spruces (*Picea* spp.) and balsam fir (*Abies balsamea*) are common throughout the Laurentian Mixed Forest Province (212) of the Warm Continental Division (210) described by Bailey (1995). This province (fig. 1) stretches from northern Minnesota to northern Michigan; is found in parts of upper New York State and northern New England, especially eastern Maine; and straddles the border with Canada, where it is called the Great Lakes/St. Lawrence forest region in Ontario and Quebec, and the Acadian forest region in New Brunswick, Prince Edward Island, and Nova Scotia (Rowe 1972). Although often named after their two dominant species, the conifer stands in this province are commonly diverse with important components of pine (*Pinus* spp.), eastern hemlock (*Tsuga canadensis*), northern white cedar (*Thuja occidentalis*), and hardwoods, especially aspen (*Populus* spp.), birch (*Betula* spp.), and red maple (*Acer rubrum*). Thus, "northern conifers" is a more appropriate name. The mix of species varies across the province. White spruce (*Picea glauca*) is common throughout, but red spruce (*Picea rubens*)—the signature species of the Acadian Forest—is seldom seen west of the Adirondacks. Also, eastern hemlock is absent in most of Minnesota.

Soils are of glacial origin throughout the province. Vast areas of northern conifers are found on sites that are relatively flat with soils that are poorly to somewhat poorly drained. On very poorly drained sites, swamp species such as black spruce (*Picea mariana*) and tamarack (*Larix laricina*) dominate. As drainage improves, pines become increasingly prominent. Northern conifers are also found at high elevations in the mountainous sections (M211), but are less extensive in area than they are in the lowlands.

Natural Disturbances

Natural stand-replacing disturbances are rare in northern conifer forests. Partial disturbances resulting from windthrow and isolated pockets of insects and diseases are common. With cyclic outbreaks that cause mortality and growth suppression, spruce budworm (*Choristoneura fumiferana*) has a significant impact on forest structure and composition (MacLean 1984), especially in balsam fir and (to a lesser extent) in spruce dominated forests. The extent of spruce budworm mortality is determined by the proportion of balsam fir and poor vigor trees (Baskerville 1975a, McClintock and Westveld 1946), soil drainage (Osawa 1989), and tree age (MacLean 1980, 1984). The relationship between stand structure and budworm susceptibility is less certain, and both even-aged (Baskerville 1975b) and uneven-aged (Crawford and Jennings 1989) structures have been recommended. However, when a spruce budworm outbreak is at full strength, structure may not be a factor because many of the ecological and stand relationships that normally prevail are simply overwhelmed.

Ecology and Silvicultural Systems

Spruce, balsam fir, eastern hemlock, and northern white cedar are all shade-tolerant species; even eastern white pine (*Pinus strobus*) is intermediate in tolerance. They produce seed crops with regularity; and on most sites, they seldom experience water deficits of extended duration. Thus, advance natural regeneration is prolific under a broad range of overstory densities (Brissette 1996). Prevailing site conditions and silvics of the major species provide a range of silvicultural options for naturally regenerated stands, including both even-aged and uneven-aged systems. The major requirement is advance reproduction before harvesting the overstory; without it, regenerated stands are converted to hardwoods (Hart 1963).

Clearcutting is not effective for natural regeneration of northern conifers because they cannot compete with fast growing intolerant species in an open stand. Additionally, seeds of northern conifers remain viable for up to a year in the forest floor; consequently, they are not a reliable source of natural regeneration following harvesting (Frank and Safford 1970). The seed-tree method is also not effective for northern conifers because of competition with shade-intolerant species, and—perhaps more importantly—because the shallow-rooted residuals lack windfirmness (Frank and Bjorkbom 1973, Seymour 1995). The seed-tree method has been used with some success for eastern white pine (Wendel and Smith 1990), but does not provide the overhead shade that affords protection from white pine weevil (*Pissodes strobi*).

The most effective even-aged regeneration method for northern conifers is the shelterwood (Brissette and Swift 2006, Seymour 1995). Unmanaged stands being regenerated are often in the reinitiation stage of development (Oliver and Larson 1996) and will be well stocked with seedlings and saplings of desirable advance reproduction. For them, the first cut of the shelterwood may remove a third to a half of the overstory basal area (Frank and Bjorkbom 1973), followed by one or more additional removal cuts over the next decade or longer to release the new cohort. In situations where advance reproduction is insufficient for regeneration, overstory removal should be preceded by a light preparatory cut followed by a seed or establishment cut.

Perhaps the most innovative shelterwood variation in northern conifers is the Acadian *Femelschlag*, named by Seymour (2005) to describe an irregular group shelterwood with reserves. Emulating natural gap dynamic disturbances, its purpose is restoring complexity to stands that have been structurally and compositionally simplified by a century of repeated heavy partial harvests.

Thinning has not been a common practice in northern conifers (Seymour 1999). The combination of vast acreages of mature forests and a thriving pulpwood market made thinning an expense that many considered unwarranted. Predicted timber shortages, a strengthening market for small diameter sawlogs, and improvements in harvesting technology have all led to an increase in thinning over the past quarter century. And following the spruce budworm outbreak in the 1970s and 1980s, precommercial thinning became a routine means of accelerating merchantability in dense young stands.

Precommercial thinning is also an effective way to favor spruces over the typically more abundant and budworm-susceptible balsam fir (Brissette and others 1999). In the mid-1990s, new cut-to-length harvesting technology and a reduction in minimum top diameter specifications combined to make commercial thinning viable on an operational scale (McNulty 1999). The type of commercial thinning employed depends on whether a precommercial thinning has taken place. If so, crown thinning should be favored, although selection thinning may still be appropriate in some situations or in some parts of the stand. In stands that were not precommercially thinned, free thinning is recommended because it simultaneously controls spacing, captures mortality, and favors the best dominant and codominant trees.

Excessive thinning can reduce density to a point where the stands are vulnerable to windthrow. Also, tree height, crown length, diameter, and depth of rooting should all be considered when making thinning prescriptions.

Although multiaged northern conifer stands are not uncommon, the application of selection systems is not often rigorous. Some of the problems with the selection system in northern conifers have been reported by Kenefic and Seymour (2001), who showed that trees in the upper canopy generally produce more stemwood per unit leaf area than those lower in the canopy. Furthermore, trees released from suppression do not grow as well as those that have been free-to-grow; this is because older trees in uneven-aged stands grow less stemwood for the same amount of foliage compared to younger trees (Seymour and Kenefic 2002). These findings illustrate the perplexing question about applying the selection system in stands of species with quite different silvics: What is the proper structure to ensure sustainability over the long term?

In northern conifers, too much overstory suppresses the development of trees in the understory; it can also impede regeneration, although Brissette (1996) found that this is less of a concern than suppressed tree development. The amount of overstory that can be carried without suppressing smaller trees to the point of structural instability has yet to be determined for northern conifers, although species competitive advantage clearly depends on the amount and quality of overstory light (Moores 2003). In a long-term study on the Penobscot Experimental Forest in eastern central Maine (Sendak and others 2003), analyses of sapling ingrowth revealed slow growth, generating concern about the long-term sustainability of selection cutting in northern conifer stands (Kenefic and Brissette 2005).

Although it is critical to avoid carrying too many trees in the sawtimber classes, it is also important to maintain balances in other portions of the structure to (1) provide sufficient trees in each size class to replace those from larger classes as they grow or are cut, and (2) influence growth of smaller trees (Arbogast 1957, Solomon and Frank 1983). Timely regeneration of desired species is necessary, not only to sustain uneven-aged stands but also to tend immature trees and thereby accumulate high-quality growing stock (Hart 1963).

The abundance of site and species characteristics allows managers to choose from an array of silvicultural options for managing most northern conifer stands. What silvicultural system to adopt depends on stand attributes and management objectives. The key to success is having adequate advance reproduction before harvesting all of the overstory. Advance reproduction of northern conifers may already be sufficient in previously unmanaged stands that are in the reinitiation stage of development. If advance reproduction is not adequate, it can be achieved through application of shelterwood silviculture. Stand development and composition can be managed with precommercial thinning; and commercial thinning can help achieve a range of objectives. Selection silviculture can also regenerate and tend northern conifer stands. However, ensuring long-term sustainability requires careful monitoring of stand dynamics and periodic harvesting across all merchantable diameter classes to promote regeneration and sustain ingrowth of trees into larger size classes.

Northern and Central Hardwood Silviculture

Northern hardwood forests

According to Johnson and others (2009), northern hardwood forests extend from northern Minnesota eastward through the Northeastern United States (fig. 1). Northern hardwoods in Canada (Anderson and others 1990) occur in the Deciduous, Great Lakes/St. Lawrence, and Acadian forest regions (Rowe 1972). More than 18 forest cover types identified by Society of American Foresters (Burns and Honkala 1990) are present, representing various combinations of sugar maple (*Acer saccharum*), red maple, American beech (*Fagus grandifolia*), yellow birch (*B. alleghaniensis*), white birch (*B. papyrifera*), American basswood (*Tilia americana*), northern red oak (*Quercus rubra*), eastern hemlock, black cherry (*Prunus serotina*), aspen, and others on approximately 92 million acres of forest land in Bailey's (1995) Mixed Deciduous–Coniferous Forest Province (211) and Mixed Forest–Coniferous Forest–Tundra Province (M211b) of the Warm Continental Division (210 and M210). Northern hardwood forests are found in Fenneman's (1938) Laurentian Upland Division, Appalachian Highlands Division [Appalachian Plateaus Province (Mohawk, Catskill, and Southern New York Sections) and New England Province], and Interior Plains Division (Central Lowland Provinces).

Central hardwood forests

Johnson and others (2009) report that the central hardwoods extend from the Ouachita and Ozark Mountains of Arkansas and Missouri; east to the Appalachian Mountains in northern Georgia and western North Carolina; northeast to southern New York, Connecticut, and Massachusetts; and west to central Minnesota (fig. 1). A significant inclusion in the west-central portion is the Prairie Peninsula of Iowa, northern Missouri, Illinois, Indiana, and central Ohio (Transeau 1935). The central hardwood range covers about 220 million acres of which 50 percent is forested today by a diversity of deciduous broadleaf species and several associated conifers [shortleaf pine (*Pinus echinata*) and eastern redcedar (*Juniperus virginiana*)]. The oaks represent the largest proportion of growing stock but many species of hickory (*Carya* spp.), sassafras (*Sassafras albidum*), flowering dogwood (*Cornus florida*), blackgum (*Nyssa sylvatica*), red maple, black cherry, yellow-poplar (*Liriodendron tulipifera*), elms (*Ulmus* spp.) and other upland hardwood species grow with the oaks. The central hardwood range includes Bailey's (1995) Eastern Broadleaved Forests (Oceanic) Province (221a) and Eastern

Broadleaved Forest (Continental) Province (221b) of the Hot Continental Division (220); and the Central Appalachian Broadleaf Forest–Coniferous Forest–Meadow Province (M221) and the Ozark Broadleaf Forest–Meadow Province (M222) of the Hot Continental Mountains Division (M220). Central hardwoods occur in Fenneman's (1938) Interior Highlands Division (Ozark Plateaus Province), Appalachian Highlands Division (Blue Ridge and Valley Province, Ridge Province, and southern sections of the Appalachian Plateaus and New England Provinces), and Interior Plains Division.

Natural Disturbances

In western portions of northern and central hardwood forests, historic wildfire frequency and intensity were sufficient to retard tree regeneration and growth, thus creating woodlands and savannas; and in effect, extending eastward the ecotone between the Great Plains and the eastern deciduous forests. Wherever Native Americans lived, their use of fire resulted in local forest openings, barrens, savannas, and woodlands (Guyette and others 2002, Pyne 1982). However, decades of fire suppression in modern time have allowed trees to invade savannas and woodlands rapidly, transforming them into forests. Fires are still numerous, but most are kept small (<10 acres) by fire suppression. It is primarily in severe drought years that wildfires affect significant forest acreage.

Natural disturbances such as wildfire, hurricanes, tornadoes, and insect and disease outbreaks can initiate stand regeneration. The scale may be large enough to produce even-aged forests, but such severity of disturbance occurs infrequently and affects relatively small areas. More common is the mortality of individual mature trees or small groups that occurs annually in a forest stand. However, the probability of catastrophic mortality from invasive species or extreme weather events is increasing as the age structures and species diversity of forests become more homogeneous on the landscape.

Individual tree species have been seriously compromised by introduced pathogens. The chestnut blight (*Cryphonectria parasitica*) and Dutch elm disease (*Ophiostoma novo-ulmi*) have effectively eliminated the once prominent American chestnut (*Castanea dentata*) and American elm (*U. americana*) from eastern forests. Today, the gypsy moth (*Lymantria dispar*) is causing large-scale mortality and growth reductions in hardwoods throughout much of the Northeastern and Lake States. Emerald ash borer (*Agrilus planipennis*) is threatening to eliminate ash species (*Fraxinus* spp.) from all eastern forests. Large-scale homogeneity in forest composition and structure across the landscape could result in devastating ecological and economic losses following oak decline or outbreak of southern pine beetle (*Dendroctonus frontalis*).

Ecology and Silvicultural Systems

Natural reproduction, the primary source of regeneration in northern and central hardwood forests, is from seeds produced in the current season or stored in the forest floor, advance reproduction, stump sprouts, and root suckers. Reproduction that dominates after harvesting is strongly influenced by preharvesting composition and structure of the trees in the overstory, midstory, and understory (Johnson and others 2009). The only silvicultural method not commonly used for regenerating northern and central hardwoods is the seed-tree method. The factors that affect regeneration success under alternate regeneration methods include the mix of desired species and their silvical requirements, physical environment, initial stand structure and composition, and vulnerability to deer browsing, invasive species, competing vegetation, insects, and diseases. Often critical to the success of any regeneration method is the planning and implementation of site preparation treatments—such as prescribed burning, mechanical scarification, and herbicide application—and preharvest or postharvest mechanical, chemical, or fire vegetation management treatments. Collectively, these treatments ensure establishment and dominance of the desired reproduction over its major competitors.

Even-aged systems are appropriate for most of the species found in northern and central hardwood forests. Clearcutting is effective for shade-intolerant species that move into highly disturbed environments and grow quickly in open environments (fig. 3). Aspen grows fastest in openings created by clearcutting, catastrophic wildfire, or blowdown; because its seed viability is short lived (weeks) and any seedlings that do germinate are highly susceptible to moisture stress, regeneration is primarily from root suckering, (Laidly 1990, Perala 1990). Clearcutting also favors prolific and frequent seeders that are capable of rapid growth: white birch, sweet birch (*B. lenta*), yellow-poplar, and black cherry (Burns and Honkala 1990).

Regeneration failures can result from insufficient seed supply at the time of harvesting or unsuitable seedbed conditions (deep litter and humus layers). Seed sources include mature trees in the harvested stand or adjacent forests, and dormant seed in the forest litter. Seed dispersal into openings has its limits, and the centers of very large clearcuts may experience understocking. Seed stored in the forest floor can provide a buffer to poor seed production or lack of dispersal into harvested areas. Although the seeds of most tree species either germinate or are destroyed within a year of dispersal, viability is 4 to 7 years for yellow-poplar and 3 to 5 years for white ash (*Fraxinus americana*) and black cherry (Marquis 1975).

Figure 3. Clearcutting is an effective way of regenerating species that do not survive or grow well in shaded conditions, provided the regeneration potential of the desired species is adequate before harvesting. Tree regeneration and stand development occurs relatively rapidly in clearcuts, and stands can reach the complex stage in less than 100 years in northern and central hardwood forests, as shown here in a set of photos taken from several stands (1-year, 2-year, 10-year, 45-year, and 85-year) in the Ozark Highlands of Missouri. (Photos by Daniel C. Dey)

Clearcutting success for oaks and many other hardwood species depends on advance reproduction in sufficient numbers and size. In these stands, it is the composition of large advance reproduction that determines what species will prevail or will share dominance with fast growing shade-intolerant species.

Natural populations of oak advance reproduction are more likely to be sufficient for successful regeneration by clearcutting on lower quality, xeric sites (Johnson and others 2009). On high-quality mesic sites, advance reproduction of oaks and other intermediately shade-tolerant species is often absent or has low regeneration potential due to its small size. Clearcutting on these sites accelerates the loss of these species and the succession either to shade-tolerant species (such as sugar maple, red maple, or American beech) or to pioneer reproduction of yellow-poplar, aspen, or other shade-intolerant species.

Light-seeded species such as birches, pines, and hemlocks germinate best on mineral soil. Therefore, the regeneration prescription for these species may include mechanical scarification or prescribed burning to provide a suitable seedbed (fig. 4). Black cherry, white ash, and yellow-poplar can establish seedlings in humus or light-to-moderate amounts of leaf litter. The nut producing species—such as black walnut (*Juglans*

Figure 4. Site preparation to expose mineral soil for light seeded species, such as yellow birch, white pine, red pine, and shortleaf pine: (A) mechanical scarification of the ground by anchor chains dragged behind rubber-tired skidder, (B) mechanical scarification by dozers with brush blades, or (C) prescribed fires to consume fine litter and expose duff or soil, such as this low intensity spring burn in an Ontario northern hardwood stand (note that although low intensity fires can reduce competition from many herbaceous species and woody species up to about 5 inches in diameter, the benefits of competition control are ephemeral and treatments may need to be applied again); in contrast, (D) logging in the winter over frozen and snow covered ground, which can minimize the disturbance to soil, existing seedlings, and other desirable ground cover. (Photos by Daniel C. Dey)

nigra), pecan (*Carya illinoinensis*), hickory, and oak—can germinate in relatively deep litter. In fact, a covering of litter or mineral soil helps acorns and other recalcitrant seeds maintain adequate moisture content, thereby improving viability (Korstian 1927).

Control of competing vegetation may be needed to favor certain species. Beginning several years before the clearcut and extending for up to 5 years after harvesting, one or more applications of herbicides, mechanical cutting, mowing or disking, or prescribed burning may be required to allow growth of the desired reproduction (fig. 4). Small reproduction of intermediately tolerant-to-intolerant species that have relatively slow juvenile growth rates—such as the oak, hickory, and pecan—can be overtopped and suppressed by dense herbaceous vegetation or fast growing, shade-intolerant trees and shrubs.

Soil and air temperatures in clearcuts can be so high that new germinants perish, regardless of species (Dey and MacDonald 2001). Mortality of new seedlings increases further when surface soils and litter dry rapidly in spring and early summer, before tree roots grow deeper into the soil. Although growth of surviving seedlings of shade-intolerant species is greatest in the full sunlight of clearcuts, partial overstory shade moderates moisture and temperature extremes, improving the establishment of seedlings for most species.

The shelterwood method is a useful and flexible system, capable of regenerating a wide variety of hardwood species including black cherry, white ash, and oak (fig. 5). It is highly effective for species that rely on an abundance of large advance reproduction, which is typically absent or underdeveloped in species of low-to-moderate shade tolerance in mature forests. The density and arrangement (uniform, group, strip, or

Figure 5. Even-aged systems for regenerating a variety of hardwood and conifer species, including (A) the seed-tree method, in which often fewer than 15 trees per acre are left in the stand to provide a uniform dispersal of seed after the harvest—most often used to promote light seeded species that can regularly produce good seed crops such as eastern white pine in Ontario, and (B) shelterwood with only 30 to 50 percent of the original basal area, or (C) shelterwood more heavily stocked. (Photos by Daniel C. Dey)

irregular) of the shelterwood is calibrated to provide a favorable atmospheric and soil environment (light, moisture, and temperature) for regeneration of the desired species. Depending on the density and spatial arrangement of the shelterwood, sunlight levels in the understory may range from 20 to 60 percent (Marquis 1973), which is sufficient for species of intermediate shade tolerance to survive and grow. Under fully stocked, closed-canopied forests, light levels (1 to 3 percent of full sunlight) are only sufficient for the more shade-tolerant species to persist or grow (Dey and others 2008b).

As with clearcutting, treatments to prepare a suitable seedbed or to control competing vegetation may be needed for the shelterwood method. Many options are available for combining these activities before and after the preparatory, seed, or removal cuts. Because herbicides used to control competing woody vegetation are also lethal to the desired hardwood reproduction, the prescription should include the timing and method of application needed to avoid exposure to nontarget species.

Mechanical scarification exposes mineral soil and retards competing vegetation by uprooting and breaking stems of the woody understory. However, without followup herbicide treatment, woody shrubs and hardwood stems have a high probability of resprouting, limiting the time of effective release for desired reproduction.

Prescribed burning is effective for controlling the density of competing woody vegetation to favor the development of oaks and other fire-adapted species (fig. 6). Fires are

Figure 6. Prescribed burning (center), often in conjunction with tree harvesting, is done to restore and manage (A) savanna and (B) woodland ecosystems, and to (C) promote oak and pine regeneration in forest management by judicial and targeted use of fire to reduce (D) shade tolerant understory woody species and control other competing vegetation both before and following regeneration harvesting. (Photos by Daniel C. Dey)

often limited to the dormant season to reduce the risk of killing the shelterwood, especially after harvesting when fuel loading may be high. Dormant season fires can kill or cause shoot dieback in hardwood stems up to about 5 inches d.b.h. or diameter at breast height (Waldrop and others 1992). Many hardwood species can resprout after one fire, but oaks are preferentially favored by additional burning.

Finally, the density of the shelterwood can be calibrated to control, to some extent, the growth of competing shade-intolerant species such as yellow-poplar, sassafras, and aspen in the understory, while at the same time providing enough light for reproduction of oaks and other intermediately tolerant species (fig. 5). This is an effective means of favoring oak advance reproduction development on higher quality sites (Loftis 1990, Schlesinger and others 1993).

Of the uneven-aged systems (fig. 7), the single-tree selection method is effective for regenerating and sustaining forests dominated by shade-tolerant species such as sugar maple, red maple, American beech, and eastern hemlock (Hicks 1998). After a single-tree selection harvest, light levels in the understory are similar to those found in unmanaged, mature, closed-canopied forests—too low for any but the most shade-tolerant reproduction to persist. This method is not well suited for regenerating black cherry, white ash, birch, oak, and other light-demanding species in northern and central hardwood forests. However, evidence suggests that it can sustainably regenerate oak forests in the Missouri Ozark Highlands (Iffrig and others 2008, Loewenstein 2008, Loewenstein and others 2000), where a suite of competing shade-tolerant species such as American beech and maples is lacking, leaving white oak (*Q. alba*) as one of the more tolerant species. Harvesting by the single-tree method in these ecosystems is shifting forest composition toward a dominance of white oak from the current mixture of black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), white oak, and shortleaf pine (Kabrick and others 2008).

The group selection method can regenerate shade-tolerant species, but is more often used for intermediate and intolerant species (fig. 7). The abundance and size of advance reproduction before harvesting largely determines what species will benefit. In most forest systems, the advance reproduction is dominated by sugar maple, red maple, and American beech, unless measures have been taken to reduce the stocking of these species in the understory and midstory before or during harvesting. If the diameter of a group opening is smaller than one-to-two times the height of the adjacent dominant trees, it will favor shade-tolerant species and will be more vulnerable to closure from lateral extension of adjacent overstory crowns before reproduction can recruit into the overstory. However, species such as maple and American beech can tolerate periods of suppression and eventually grow into the overstory, provided they are released by several periodic (every 10 to 20 years) stand harvests.

Larger openings are needed for black cherry, white ash, yellow birch, northern red oak, eastern white pine, and yellow-poplar. If the diameter of the opening equals the height of one tree (75 to 100 feet), light levels in the center can range from 20 percent on moderate north slopes to 30 percent on moderate south slopes (Fischer 1981). Increasing the diameter to two tree heights provides almost 50 percent of full sunlight on moderate north slopes and >60 percent on similarly steep south slopes, adequate for robust growth of most species of intermediate shade tolerance. Larger openings are even more beneficial to shade-intolerant species that require nearly full sunlight to achieve maximum growth.

Northern red oak and white ash should be present as large advance reproduction for successful regeneration, but black cherry, yellow birch, and yellow-poplar can regenerate from seed (Marquis 1990, Weigel and Parker 1997). Yellow birch and other light-seeded species germinate best on mineral soil, which can be exposed by mechanical scarification during harvesting.

Herbicides can be sprayed on the fresh stumps or injected into stems to prevent sprouting of unwanted shade-tolerant species, thereby reducing competition in group openings. Mechanical cutting alone will provide short-term release for intermediately tolerant–to-intolerant species, but sprouting of maple, American beech, hophornbeam

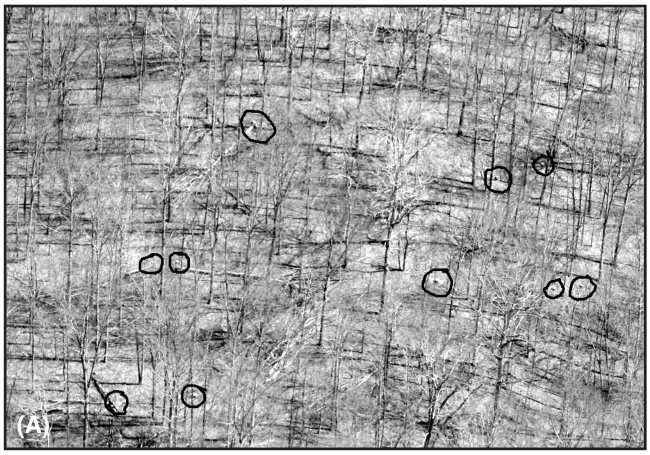

Figure 7. Various perspectives on uneven-aged systems including single-tree selection in an upland oak-hickory stand in Missouri showing (A) aerial view and (B) a harvested tree and stand structure, and (C) overstory canopy in northern hardwoods; and (D) aerial of group selection openings. Circles in (A) show where individual trees were harvested. (Photos by Daniel C. Dey)

(*Ostrya virginiana*), striped maple (*Acer pensylvanicum*), and flowering dogwood will be rapid, with new stems quickly suppressing desirable reproduction.

Artificial regeneration of hardwoods limited to situations where it is needed to supplement natural advance reproduction of desired species (in particular oaks) in upland forests. As summarized by Johnson and others (2009), a number of researchers have evaluated methods for underplanting oaks in shelterwoods in the Eastern United States, including Dey and Parker (1997a, 1997b), Dey and others (2009, 2008a), Johnson (1984), Johnson and others (1986), Loftis (1990), Parker and Dey (2008), Spetich and others (2002), and Weigel and Johnson (1998a, 1998b, 2000). Artificial regeneration of hardwoods is more common in afforestation of agricultural bottomlands and upland pastures; and, in combination with direct seeding, for oaks in floodplains (Dey and others 2008a).

Once regeneration is established, sustaining the stocking of desired species to maturity may require one or more tending treatments. Crop tree release is effective for improving the survival, growth, and quality of individual trees and maintaining the stocking of desired species to maturity (Dey and others 2008b, Miller and others 2008). Maintaining shade-intolerant and intermediately tolerant species in young stands requires early crop tree release, beginning about the time of crown closure.

Southern Hardwood Silviculture

Of the 535 million acres of land in the Southern United States, 214.6 million acres are classified as forest land, the majority (95 percent) of which is commercial timberland (Smith and others 2004). This area of forest is about 60 percent of what existed at the onset of European settlement in 1630, and about 90 percent of forest acreage at the height of selective cutting in 1907 (Conner and Hartsell 2002). Over the past six decades, however, the area of commercial timberland in the South has remained more or less constant, with areas going out of timberland primarily to agriculture and urbanization balanced by a reversion of abandoned agricultural land back into forests.

Southern pines and hardwoods occur conterminously across the South (fig. 1), and are bounded on the north by central hardwood forests and on the west by the Prairie Division (250), with the remaining boundaries being the Gulf of Mexico and the Atlantic Ocean (Johnson and others 2009). Within this area are four major ecoregions in Bailey's (1995) Subtropical Division (230 and M230)—the Piedmont [Southern Mixed Forest Province (231)], the Coastal Plain [Outer Coastal Plain Mixed Province (232)], the Interior Highlands [Ouachita Mixed Forest–Meadow Province (M231)], and the lower Mississippi Alluvial Valley [Lower Mississippi Riverine Forest Province (234)]—all covering approximately 270 million acres, 60 percent of which are forested.

The Cumberland Plateau [Hot Continent Division (220)], and associated highlands of the Interior Highlands and lower Mississippi Alluvial Valley [Subtropical Division (230)] contain the majority of upland and bottomland hardwood forests. Oak forests—including white oak, scarlet oak, southern red oak (*Q. falcata*), overcup oak (*Q. lyrata*), chestnut oak (*Q. prinus*), water oak (*Q. nigra*), Nuttall oak (*Q. nuttallii*), willow oak (*Q. phellos*), northern red oak, and black oak—cover 60 percent; loblolly pine (*Pinus taeda*), shortleaf pine, longleaf pine (*Pinus palustris*), and slash pine (*Pinus elliottii*) dominate the remaining forested lands.

In uplands are mixed oak-pine stands, often consisting of mixed upland hardwood species with loblolly, shortleaf, or Virginia pine (*Pinus virginiana*). Upland hardwoods are dominated by red and white oaks, with frequent occurrences of hickory, yellow-poplar, sugar maple, red maple, American beech, black cherry, sassafras, sourwood (*Oxydendrum arboreum*), blackgum, birch, and ash.

Southern bottomland forests occur on river floodplains and are most extensive in the Coastal Plain and Mississippi Alluvial Valley. Species compositions are complex and influenced by site conditions. Bottomlands are dominated by oaks (overcup oak, Nuttall oak, willow oak and water oak), American sycamore (*Platanus occidentalis*), sweetgum (*Liquidambar styraciflua*), blackgum, elm, sugarberry (*Celtis laevigata*), eastern cottonwood (*Populus deltoides*), willow (*Salix* spp.), ash, hickory, and red maple. Conifers that may grow in floodplains include loblolly pine, spruce pine (*Pinus glabra*), baldcypress (*Taxodium distichum*), pondcypress (*Taxodium distichum* var. *nutans*), Atlantic white-cedar (*Chamaecyparis thyoides*), and eastern redcedar.

Natural Disturbances

Fires occur infrequently in alluvial areas because these sites are too wet and often lacking enough litter to support combustion. More common are natural and episodic disturbances, such as severe or unseasonable flooding, drought, windstorms, and animal activities; or human modifications such as impoundments or other flood control devices, timber harvesting, and land clearing for agriculture.

In southern upland hardwood forests, natural fires (those not set by humans) have not played a major role in landscape dynamics because the climate is dominated by long, hot growing seasons and abundant rain. Conflicting opinions exist over the role and extent that human use of fire had as an ecological force in upland forests. Native Americans certainly used fire to clear along watercourses and to drive game, and occasionally these fires escaped into higher elevations. Europeans burned to improve grazing, reduce undergrowth for better visibility and accessibility, and control insects (Komarek 1974, Van Lear and Waldrop 1989).

In addition to fire, the most important shapers of today's southern hardwood forests were agriculture and extraction of coal, timber, and gas resources. Disturbances caused by storms, insect and disease outbreaks, and late-season frosts continue to alter stand structure and composition. Likely future forest influences include increasing development, invasion by nonnative species, and more aggressive coal mining.

Ecology and Silvicultural Systems

In addition to landowner goals, the key factors driving management decisions in southern hardwood forests are landscape location (physiographic, edaphic, and moisture and nutrient site class) and the influences of past disturbances on current forest composition and structure. From xeric upland oak-hickory forests to species rich mesic cove forests to mixtures of oak, gum, and eastern cottonwood in hydric bottomland forests, site factors—primarily moisture and fertility—dictate the range of appropriate silvicultural prescription options. Also important is managing competition to achieve desired forest composition and structure. Regenerating desirable species is more difficult on the most productive sites, where competition is great and light availability often limits regeneration of desired species. However, ensuring that adequate light is available to reproduction can be achieved through silvicultural treatments.

Southern hardwood forests are disturbance-dependent systems. They are also diverse in species, many of which are desirable, challenging efforts to control the final composition at maturity. Therefore, we must consider the silvic requirements of each species when selecting the type and timing of silvicultural treatments. In upland and bottomland systems, oak is a focal species group—more difficult to regenerate on high-quality sites, where potential competition from other woody and herbaceous species is greater. Silvicultural prescriptions for regenerating southern hardwoods are primarily even-aged based; scant information exists on the long-term effects of uneven-aged management.

Bottomland Hardwood Systems

In bottomlands, higher elevation sites on fronts and ridges of major streams have better drainage and lower soil clay content than the lower elevation flat sites. Competition is greater on higher elevation sites than lower. Manuel's (1992) decision model for managing and regenerating southern bottomland hardwoods is based stocking levels of desired species, tree-preference class, and individual tree characteristics. Belli and others (1999), Broadfoot (1976), and Putnam and others (1960) outline techniques for evaluating natural regeneration of bottomland hardwoods. These techniques take into account regeneration source (seed, seedling, or sprout) and site type based on soil series and inundation regime. If the regeneration source is adequate, the decision model recommends using the clearcut method. If the decision is to manage but not harvest and if adequate regeneration is present, care must be taken to provide the forest floor with enough light to maintain that regeneration.

Clearcutting is the most widely proven method of regenerating bottomland hardwoods because it allows for full sunlight to reach the forest floor, promoting the growth of species that are shade-intolerant and moderately shade-intolerant (Clatterbuck and Meadows 1993). Light-seeded species such as willow, eastern cottonwood, and ash also thrive under clearcutting operations that exposure mineral soil. The seed tree method can also be used for light-seeded species in bottomland hardwood stands, but it has been shown to have no benefit for regenerating oaks or other desired heavy-seeded species (Johnson and Krinard 1976).

If the regeneration is inadequate or the stand lacks an adequate mix of desirable species, managers can enhance the growth of individual stems and promote establishment of regeneration by increasing light through density-reducing harvests. The shelterwood method can promote regeneration by harvesting to reduce stand density and remove undesired species, by herbicide injection into individual stems of undesired species, or by a combination of both treatments. Oaks and other heavy-seeded species benefit from a release harvest, either at the time of a bumper acorn crop or immediately after the establishment of seedlings from a bumper crop. Final overstory removal is postponed until the desired advance reproduction is large enough to be competitive after release.

Single-tree selection, practiced in the bottomlands in the 1950s and 1960s, favored the development of shade-tolerant species and resulted in forest composition shifts towards lower-valued timber species (Hodges 1997). Group selection may also result in species composition shifts towards more shade-tolerant species; groups must be large enough to meet the regeneration needs of shade-intolerant species. Patch cutting, which combines clearcutting and group selection to create larger openings, is becoming increasingly more common in bottomlands (Meadows and Stanturf 1997). Key to success is the development of large advance reproduction before final regeneration harvesting and the control of competing vegetation by preharvest or postharvest treatments.

Upland Hardwood Systems

Although primarily focused on oaks, Johnson and others (2009), Loftis and McGee (1993), and Spetich (2004) provide an overview of silvicultural options and recommendations that can be applied to other desirable species in upland hardwood forests. Loftis' (1989) comprehensive model for evaluating natural regeneration of southern upland hardwoods is calibrated for the Southern Appalachian Mountains, but it can easily be adjusted for other southern upland systems. For example, in the Cumberland Plateau, which differs by having abundant sugar maple and a scarcity of black cherry, users can alter the model parameters to increase sugar maple ranking on the competition scale and reduce the influence of new black cherry seedlings.

Topographic position dictates upland hardwood management. In general, clearcutting regenerates oak stands on higher elevation sites (for example, the tabletops of the Cumberland Plateau and upper ridges of the Southern Appalachian Mountains), where lower site quality, less competition from other species, and relatively high numbers of oak advance reproduction contribute to a desirable species composition in the next stand. If the preservation of the oak component for more productive stands is desired, silvicultural techniques can encourage more and larger oak advance reproduction while at the same time reducing competition.

After a regeneration harvest, germinating acorns provide new seedlings; but because oak seedlings preferentially allocate carbon to root growth, their shoot growth is slow, making them vulnerable to suppression by species (fig. 8) that exhibit rapid shoot growth (Johnson and others 2009). Consequently, regenerating oak rarely reaches a dominant or codominant position on productive sites (Loftis 1983, Sander 1972), where yellow-poplar is its major competitor. In addition to regeneration from stump sprouts and advance reproduction, yellow-poplar can also regenerate successfully from often-numerous seedlings that grow rapidly after harvesting, either from current seed production or seed stored in the forest floor (Beck 1970). In other upland hardwood systems, desirable species such as ash and black cherry can also regenerate from new seedlings and grow rapidly if given sufficient light. The diversity of shade tolerances that these species exhibit contributes to the challenge of regenerating southern upland hardwood stands.

A promising alternative regeneration method to favor oaks and other intermediately shade-tolerant species, the shelterwood requires a sequence of cuttings over a 5- to 20-year interval and multiple entries into the stand. The residual basal area in a shelterwood must be large enough to prevent light-seeded, shade-intolerant species such as yellow-poplar from growing and becoming established. The change in canopy structure and below-canopy light conditions will also favor sugar maple and other shade-tolerant species. Treating the shade-tolerant subcanopy, in addition to reducing overstory density, will promote the development of advance reproduction of the desired species.

Over time, single-tree selection in upland hardwood systems consistently results in a composition shift towards shade-tolerant species. In mature forests that initially have

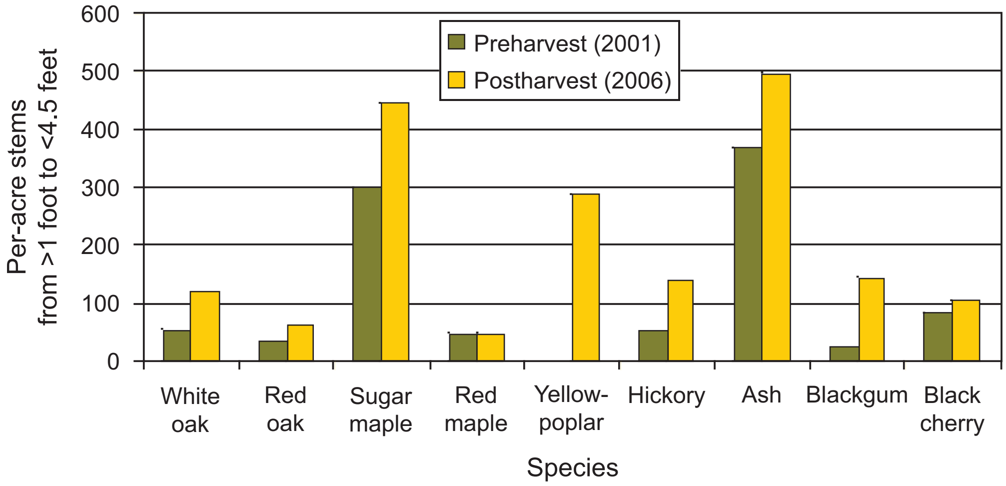

Figure 8. Species density in the Cumberland Plateau of Jackson County, AL, where large yellow-poplar, sugar maple, and ash reproduction increased substantially compared to slight increases in large oak reproduction, 5 years after a shelterwood harvest that removed 50 percent of the basal area.

a substantial overstory component of oaks, yellow-poplars, and other desirable but less shade-tolerant species, this method inhibits their regeneration and favors the recruitment of sugar maple, red maple, sourwood, flowering dogwood, American beech, and other shade-tolerant species (fig. 9). The desirable seedlings and sprouts that do become established will not persist in the low light of the forest canopy. This means that managers may need to consider interspecific competition when manipulating stand composition and structure in addition to ensuring sufficient light in the understory for development of large advance reproduction. Creating large openings by group selection harvesting and applying herbicides to eliminate the tolerant understory is a technique that may offer promise (Della-Bianca and Beck 1985).

Many southern upland hardwood stands originated when wildfire was more prevalent. Burning to regenerate oak most likely will require multiple fires over a decade or more. In an early study testing the use of prescribed fire on oak regeneration in the Southern Appalachian Mountains, Loftis (1990) found that one burn not only failed to increase oak-seedling growth and control the development of other competing regeneration, but it also reduced the survival rate of red oak seedlings. A regime that incorporates a high level of disturbance, such as shelterwood harvesting followed by prescribed burning, may favor oak regeneration over its competitors.

Figure 9. Shade tolerant species such as sugar maple are dominant in the understory of many mature hardwood forests in the Eastern United States. Single-tree and group selection favors the recruitment of these species into the overstory and the replacement of the oaks and other less shade tolerant species. Even-aged systems that fail to control the shade-tolerant competitors also accelerate successional replacement of the oak species. (Photo by Callie J. Schweitzer)

The timing and intensity of burning may also play a significant role in modifying regeneration dynamics. For example, a single spring burn several years after shelterwood harvesting produced a high-intensity fire that favored oak regeneration over yellow-poplar, compared to less-intense summer or winter burns that were insufficient for competition control (Brose and others 1999). Fire intensity affects stand density more than the height of oak and its competitors. Because a single, low-intensity fire may have little or no effect on stand composition, repeated burning may be necessary to favor oak over yellow-poplar. But regardless of fire timing or intensity, the competitive status of oak seedlings drives the response to disturbance.

Southern Pine Silviculture

About 96 million acres of timberland in the Southern United States (fig. 1) are found in southern pine or oak-pine forests (Smith and others 2004). The southern pines consist of four major species: loblolly pine, shortleaf pine, slash pine, and longleaf pine.

Loblolly pine is found in 14 States, growing from southern New Jersey to eastern Texas. Its natural range is along the Atlantic Ocean and Gulf of Mexico, in the Piedmont Plateau, and in parts of the Cumberland Plateau and Appalachian Mountains (Baker and Langdon 1990). Loblolly is the preferred species for plantation forestry in the South, and millions of acres of native mixed pine, pine-hardwood, and hardwood-pine stands across the South have been converted to genetically improved and intensively managed loblolly pine plantations for use in timber and fiber production.

Shortleaf pine is the most widely distributed of the four southern pines. It is found in 22 States, typically in mixture with other pines (especially loblolly) or hardwoods; but in the Ouachita Mountains of Arkansas and Oklahoma, it is the only dominant naturally occurring pine (Guldin 2007, Lawson 1990).

Slash pine has the smallest native range of the four species, found from southern South Carolina through the hills of southern Georgia and virtually throughout Florida, and west along the Coastal Plain to southern Louisiana. Outside of its native range, it has been widely planted and direct-seeded in western Louisiana and eastern Texas on cutover longleaf pine sites (Lohrey and Kossuth 1990).

Longleaf pine is native along the Coastal Plain from Virginia to eastern Texas. Once occupying an estimated 92 million acres of the South, today it is much less widely distributed over roughly 3.2 million acres—the result of virgin-stand harvests, fire exclusion, and reforestation of cutover areas with loblolly and slash pine (Boyer 1990, Landers and others 1995). Efforts are underway to restore longleaf pine ecosystems, especially on Federal and State lands such as national forests and lower Coastal Plain military bases.

These four southern pines are occasionally found in association with minor pine species such as spruce pine along the Gulf of Mexico and pond pine (*Pinus serotina*) along the lower Atlantic coast; in the Appalachian Mountains are found the pines that have a more northerly distribution, such as Table Mountain pine (*Pinus pungens*), Virginia pine, pitch pine (*Pinus rigida*), and eastern white pine. Throughout the South, pines are found side-by-side with hardwoods, especially the oaks and hickories (Keys and others 1995) that would eventually dominate in the absence of disturbance.

Thirty percent of the forest land area in the South—some 66 million acres—is dominated by two southern pine forest types. About 52 million acres are in the loblolly-shortleaf forest type, and 14 million acres are in the longleaf-slash forest type; another 30 million acres are classified as the oak-pine forest type, in which pines and oaks are found in mixtures of varying percentages (Smith and others 2004):

- The loblolly-shortleaf forest type includes pure stands of loblolly pine throughout the South and pure stands of shortleaf pine in the Ouachita and Ozark Mountains—both of natural or planted origin—and mixed stands of loblolly and shortleaf pine that are typically of natural origin.

- The longleaf-slash pine forest type is generally found in pure stands of either slash or longleaf pine of natural or planted origin; only occasionally are both species present in naturally regenerated stands.
- Oak-pine stands are usually of natural origin; landowners often to manage them either for the hardwood component or—more commonly, especially on forest industry ownership—for the pine component so as to simplify species composition and increase pine growth and yield.

Natural Disturbances

The southern pines are early successional species adapted to a range of disturbance events, most especially at larger scales. The climate of the South features a variety of large-scale disturbance events, any one of which can destroy an existing stand and create open conditions for establishing a new age cohort of pines. Wind events such as tornadoes and hurricanes can affect areas as small as a single stand or as large as an entire State. Under certain conditions, outbreaks of the native southern pine beetle can spread to cover thousands of acres if unchecked; even if controlled, they can affect hundreds of acres anywhere in the South at any time.

Fire, whether as a result of natural or human causes, is the single most important ecological determinant in southern pine stand dynamics and development. Presettlement accounts of southern pine forests commonly described mature pines with virtually no midstory and with an understory dominated by grasses, annuals, and perennials—where one could easily ride a horse and not be impeded by vegetation (Hedrick and others 2007). Native Americans used understory burning to promote hunting and community defense (Guyette and others 2006). Early settlers adopted the practice as well to attract game and provide forage for domesticated livestock. No doubt, both the Native American and European cultures appreciated the benefits that understory burning provided in controlling the ticks and chiggers that still torment those who live and work in southern forests.

Ecology and Silvicultural Systems

Fire is especially important in southern pine regeneration dynamics. The four southern pine species have each developed interesting and unique adaptations to fire that improve the likelihood of seedling establishment and development. A shortleaf pine sapling is the only one of the four that will reliably resprout if its crown is topkilled by fire (or if mechanically severed), a fire adaptation trait that was described early on (Mattoon 1915). Small shortleaf seedlings are extremely vulnerable to even low intensity surface fires, but their ability to survive or resprout after topkill increases with increases in stem diameter (Dey and Hartman 2005), up to a maximum d.b.h. of 3 inches (Dey and Fan 2009). Thus, in sapling-sized shortleaf pine stands, a new age cohort develops through resprouting and some added seedfall if a seed source remains nearby. To prevent regeneration from accumulating and growing into the overstory, the frequency of burning must be 8 years or less (Stambaugh and others 2007).

In contrast to shortleaf, loblolly and slash pine saplings are quickly and effectively killed by fire, which may explain why these species are thought to be the more mesic of the southern pines. For example, slash pine is found naturally only in the wetter areas of the Atlantic Coastal Plain (Lohrey and Kossuth 1990), and loblolly pine has a reputation of thriving naturally on moist to wet sites (Baker and Langdon 1990). Both species are abundant and regular seed producers, producing adequate-or-better seed crops at least half the time. The loblolly-shortleaf pine type in the western Coastal Plain is arguably the most prolific pine type in North America, producing adequate-or-better seed crops 4 years in 5 and bumper crops with >1 million seeds per acre (Cain and Shelton 2001). Essentially, the adaptation strategy for Coastal Plain loblolly-shortleaf pine mixtures and slash pine is to produce enough seed on a sufficiently frequent basis to establish seedlings within any new forest opening shortly after it is created, and to grow to the sapling stage fast enough to survive the next surface fire.

One might speculate that the two strategies—resprouting and reseeding—work together in mixed loblolly-shortleaf pine stands of natural origin, and that this may explain why shortleaf is retained in the mixture. If a newly established loblolly-shortleaf pine cohort has the opportunity to grow fast enough to escape the next fire, the species mixture would favor loblolly pine, whose saplings grow faster than shortleaf pine. But a surface fire in a mixed sapling stand would kill the loblolly—requiring reseeding onsite or from a nearby seed source—whereas the shortleaf saplings would simply resprout: a dynamic that might confer an adaptive advantage to shortleaf in circumstances that would normally favor loblolly.

Longleaf pine has a different strategy entirely, featuring extended irregularity in seed crops and a distinctive seedling grass stage. While in the grass stage, the seedling builds root growth rather than shoot growth, and the terminal bud develops a pattern of bud scales and needle architecture that protects it from surface fire. Those early years in the grass stage require occasional surface fires to prevent suppression by grasses and other understory herbaceous and woody vegetation. Fires also control brown spot needle blight (*Mycosphaerella dearnessii*), which can prevent seedling emergence from the grass stage (Boyer 1979). After several years and under proper conditions, longleaf seedlings break through the grass stage and begin to grow rapidly.

All four species are generally considered intolerant of shade as mature trees, but shade tolerance is more pronounced at younger ages—especially in loblolly and short-leaf pine, both of which can tolerate somewhat more overstory shade than longleaf and much more than slash pine. All of the southern pines also have the interesting attribute of being able to respond to release from adjacent or overtopping competition at relatively advanced ages, which enables them to maintain site occupancy under partial disturbance events such as ice storms or wind events. The four species also show good ability to segregate into crown classes, which helps minimize extended periods of sapling stagnation even though poor growth can occur to a certain degree in densely stocked sapling stands.

Summaries of the silviculture of southern pines have been developed over the past four decades and are still appropriate references for landowners and the foresters who advise them. Burns (1983) describes most of the important forest cover types in North America, including the southern pines. More recently, Fox and others (2007) and Guldin (2004) have published overviews of the general principles of plantation silviculture and silviculture of naturally regenerated stands. State-of-the-art summaries of the selection method are also available, one for longleaf pine (Farrar 1996) and the other for loblolly and shortleaf pines (Baker and others 1996).

Clearcutting and planting

Even-aged plantation silviculture is effective for all four of the southern pines, but has been most widely practiced with loblolly and slash pine. One can argue convincingly that the two most important silvicultural advancements in the 20th century were responsible for the widespread practice of plantation silviculture. First was the development of genetically improved planting stock, which was pioneered with loblolly pine and applied with varying intensities in all four species. Second was the development of chemical amendments such as fertilizers for site amelioration and herbicides for woody and herbaceous competition control. These technologies were optimally applied in association with clearcutting and intensive customized site preparation, followed by planting with careful attention to the origin and quality of planting stock. As a result, clearcutting, planting, and subsequent intermediate treatments became the standard prescription for intensive pine silviculture. The millions of acres of plantations that were created using the many variations of this practice have been the mainstay of the southern pulp and paper industry for the past four decades (fig. 10).

Because of the plasticity and success of pine plantation silviculture for rapid fiber production, southern pine forests have become the focus of the most intensive forest management activity in the South, if not the Nation. Recent data suggest that of

Figure 10. A loblolly pine plantation on a high-quality site in the western Ouachita Mountains; the stand is between 15 and 20 years in age, and recent treatments consisted of prescribed burning and thinning. (Photo by James M. Guldin)

the 66 million acres in the two pine-dominated forest types, 34 million acres are in stands of natural origin and 32 million acres are planted (Smith and others 2004). Most pine plantation area is in private ownership, with only 1 million acres (24 percent) on national forest lands and 750,000 acres (20 percent) on other public lands; compared to roughly 15 million acres (40 percent of the total pine-dominated area in this ownership) on nonindustrial private lands, and 15 million acres (75 percent of the pine-dominated forest area) on forest industry lands (Smith and others 2004). And the 32 million acres of forests dominated by planted pines represents 84 percent of the total plantations in the South.

Wear (2002) suggested that by 2050, a quarter of all southern forest land—50 million acres—will be planted. With 85 percent of current plantations coming from the two southern pine forest types, an additional 11 million acres, roughly, are likely to be converted to planted pines. It is unlikely that these additional planted acres will come from forest industry, which has only 5 million acres of natural stands remaining in its 20 million acres of pine-dominated forests. Instead, we are likely to see the increases come from natural pine stands on nonindustrial private land or from converting hardwood-dominated forests on forest-industry and nonindustrial private lands. And because planting with containerized planting stock is an important tool in the restoration of longleaf pine stands on the southern Coastal Plains, longleaf restoration goals may involve significant planting on public lands as well.

Other even-aged methods

That portion of the southern pines not managed using plantations can be very effectively managed using even-aged and uneven-aged methods that rely on natural regeneration. Four areas of continuing or expanding application have been suggested (Guldin 2004):

- Plantation silviculture is costly, especially the initial capital investment into stand establishment; many landowners seek regeneration methods that have lower initial establishment costs and that retain some degree of canopy cover on their forest land.

- Some landowners seek high-quality, large-diameter pine trees to take advantage of the larger product sizes and higher unit values that sawtimber brings compared to pulpwood.
- The middle ground of silvicultural activity within streamside management zones falls between the two extremes of hands-off or high-grading; regeneration methods that retain some overstory trees may be a more robust way to manage these areas sustainably in the future.
- The shift away from clearcutting on public lands has been coupled with increased reliance on other even-aged and uneven-aged regeneration methods, which meet ecosystem needs that cannot be satisfied by clearcutting.

A key to successful natural regeneration of southern pines is in the wide range of fruitfulness among individual trees. Seed production in the pines is a highly inherited genetic trait, so foresters must pay attention to the inherent differences in capacity when selecting trees being retained as seed producers. This is easy to do with shortleaf pines, because their cones persist in the crown. For the other three southern pines, one should examine cones at the base of the tree or use binoculars to scrutinize developing cones.

The seed tree method reserves 4 to 10 dominant or codominant pines per acre, with a corresponding residual basal area of 5 to 15 square feet per acre (fig. 11). The method is most easily applied in loblolly and slash pine; both are abundant seed producers, and seedlings thrive in the open conditions found in the understory after a recent seed-tree harvest. Shortleaf pine can also be managed using this method, if attention is given to retaining effective seed producers and properly preparing the site. Zeide and Sharer (2000) outline the typical seed-tree prescriptions for mixed loblolly-shortleaf stands in

Figure 11. A mixed loblolly-shortleaf pine stand in the upper western Coastal Plain (Gulf of Mexico), managed using the seed tree method. (Photo by James M. Guldin)

the upper western Coastal Plain as practiced by forest industry in southern Arkansas over the last three decades of the 20th century.

Application of the seed-tree method starts with late-rotation thinning or preparatory cutting to encourage crown development in trees likely to be retained for seed production. The seed cut then removes all but a few residual trees per acre, in association with site preparation treatments to dispose of logging slash and remove competing vegetation. Frequently, the normal scarification of the site associated with logging is sufficient to expose mineral soil, which is the best seedbed for germinating and establishing the pines. A properly timed prescribed fire can help with this, especially when regenerating shortleaf pine. Several years after the new age cohort is established, the seed trees can be cut. Subsequent treatments in the first decade after the seed cut are likely to include chemical release of the pines from competing hardwoods and precommercial thinning to control pine stem density. In the second decade and beyond, a typical prescription includes commercial thinning on a 7- to 10-year cycle, an herbicide application every 10 years to control encroaching hardwoods, and reintroduction of prescribed fire on a 3- to 5-year cycle to retain open understory conditions.

The shelterwood method reserves 15 to 30 dominant or codominant pines per acre, with a corresponding residual basal area of 20 to 40 square feet per acre. The most practical use of the shelterwood method is to regenerate species that have erratic or unreliable seed production, and thus for which the seed tree method is uncertain. The extra trees retained in the shelterwood can make an important difference between marginal and adequate stocking by providing added seed production potential and helping modify the microclimate in the regeneration zone to favor pine seedling survival.

A classic example of shelterwood method in southern pines is the work done in the 1970s with longleaf pine in southern Alabama (Boyer 1979, Croker and Boyer 1975). The limitations of seed production were overcome through careful attention to the fruitfulness and the basal area of residual trees, with 30 to 40 square feet per acre of basal area deemed optimal (Maple 1977). Prescribed fires were used to control brown-spot needle blight. The shelterwood optimized the relationship between seed production and the amount of needlefall required to support regular prescribed burning. This example is essentially a silvicultural application of the stored seedling bank beneath the seed trees, which develops into the succeeding age cohort as seedlings break from the grass stage, ideally in 3 to 5 years after germination (fig. 12).

Figure 12. A longleaf pine stand in the lower Atlantic Coastal Plain, managed using the shelterwood method. (Photo by Dan Wilson)

As with the seed-tree method, the shelterwood method starts with late-rotation thinning or preparatory cutting that encourages crown and cone development. The seed cut then removes those trees not marked for retention, and site preparation treatments dispose of logging slash and remove competing vegetation—with logging and site preparation activities also preparing the seedbed. Prescribed fire is implemented shortly after the seed cut, especially important for longleaf pine. Several years after the new age cohort is established, the seed trees can be harvested using a removal cut. The added number of seed trees in the shelterwood (compared to the seed-tree method) can actually benefit the removal cut, because they provide harvest volumes sufficient to attract a logger. Conversely, removing the larger number of pines may result in unacceptable logging damage to the regeneration cohort, especially if stocking is marginal. Some managers may want to retain the seed trees through the subsequent rotation for reasons related to structural diversity, but this comes at a cost of reduced volume growth in the new age cohort. Subsequent treatments after the seed cut are similar to those in the seed-tree method: chemical release of the pines from competing hardwoods, precommercial thinning to control pine stem density, commercial thinning on a 7- to 10-year cycle, an herbicide application every 10 years to control encroaching hardwoods, and reintroduction of prescribed fire on a 3- to 5-year cycle to retain open understory conditions.

Uneven-aged methods

Applying uneven-aged regeneration methods in species that are shade-intolerant seems counterintuitive, but the earliest successful examples of the selection method were in pines, for example the German Dauerwald method of forest management, patterned after nature, promoting sustainably productive, profitable, environmentally stable, biologically diverse, socially responsive forests (Troup 1952) as applied to Scots pine (*Pinus sylvestris*); and the improvement selection in Arizona (Pearson 1950) as applied to ponderosa pine (*Pinus ponderosa*). In the South, the longest record of success with uneven-aged management has been in Coastal Plain loblolly-shortleaf pine stands of southeastern Arkansas (Baker 1986, Baker and others 1996, Guldin 2004, Guldin and Baker 1998, Reynolds and others 1984), with other long-term demonstrations reported in Mississippi (Farrar and others 1989) and southwestern Arkansas (Farrar and others 1984). Uneven-aged methods have also been used for longleaf pine in Florida and Alabama (Brockway and Outcalt 1998, Farrar 1996, Mitchell and others 2006) and shortleaf pine in the Ouachita Mountains (Guldin and Loewenstein 1999, Lawson 1990). Research on uneven-aged regeneration methods in slash pine is virtually nonexistent, but results from Langdon and Bennett (1976) suggest that the group selection method may show some promise, and other methods suitable for longleaf pine should also be effective for slash pine. In short, the selection method can be used in southern pines if attention is paid to marking, regeneration, and stand structure (Guldin and Baker 1998).

The group selection method offers ecological and administrative advantages in managing the intolerant southern pines. Openings can be made without leaving seed trees, instead relying on existing advance growth, natural seedfall from adjacent trees, or supplemental planting. Retaining some residual trees at shelterwood basal areas within group openings is also an option for longleaf pine (Farrar 1996, Guldin 2006), and probably shortleaf pine as well. Once the pine seedlings are established, the relatively open conditions within group opening resemble the conditions that are most favorable for the southern pines—more so with larger group openings than with smaller ones. Administratively, followup treatments such as cleaning or precommercial thinning are targeted specifically to the openings, an easy process to work into operational contracts using maps or geographic locations.

The group selection method has one major disadvantage: although easy to initiate, group openings are difficult to maintain over repeated cutting cycles without strictly adhering to an area-based regulation system, which can eventually become an even-aged patch clearcutting system rather than an uneven-aged selection system. That is not important to the trees, but might be important for managers who have committed to specific proportions of even-aged versus uneven-aged acreages, as is often true for national forest management planning.

The single-tree selection method also offers advantages and disadvantages. The seven-decade experience with the Farm Forestry Forty demonstrations at the Crossett Experimental Forest in south Arkansas (fig. 13) had its origins in the rehabilitation of understocked stands (Baker and Shelton 1998) and was imposed using a simple marking rule—cut the worst trees and leave the best, regardless of diameter or pattern of occurrence. Stands that had initially been understocked recovered to full stocking within two decades. Details of the implementation of the selection method in these mixed loblolly-shortleaf pine stands (Baker and others 1996, Guldin 2002, Guldin and Baker 1998) serve as appropriate mensurational guidelines for any of the intolerant southern pines that are managed using volume regulation with a guiding diameter limit, or structural regulation (BDq method) using preset targets for residual basal area (B), a maximum retained diameter (D), and the rate of change in density in adjacent size classes classes (q).

The biggest disadvantage of the selection methods in intolerant southern pines is the management commitment required to maintain proper stand structure, especially with single-tree selection. The concept behind single-tree selection is to manage size classes rather than age classes, relying on the assumption that diameter approximates age in stands with three or more age classes. To maintain adequate sunlight in the understory for development of the seedling and sapling classes, the overstory and midstory diameter classes of the stand must be deliberately maintained in a slightly understocked condition (less than 75 square feet per acre, assuming that annual growth of most uneven-aged southern pine stands is 2 to 3 square feet per acre). Cutting-cycle harvests usually leave from 45 to 60 square feet per acre, which suggests that the cutting cycle must be 10 years or less to maintain acceptable understory development. If

Figure 13. A mixed loblolly-shortleaf pine stand in the upper west Coastal Plain (Gulf of Mexico), managed using uneven-aged methods. (Photo by James M. Guldin)

timely cutting-cycle harvests are not repeatedly maintained, the understory development needed to maintain stand structure will be lost. Midstory and overstory crown classes will revert to a homogeneous canopy profile more typical of a late-rotation even-aged stand, rather than the heterogeneous canopy profile that characterizes a well-regulated uneven-aged stand.

Conclusions

Forest managers have many options for providing the mix of commodities and amenities desired by society thanks to the diversity of tree species in the Eastern United States, the large ecological breadth and geographic distribution that most species exhibit, and the variety of uneven- and even-aged silvicultural systems available. Silvicultural systems are designed to achieve multiple resource objectives—often simultaneously—within ecological, social, and economic constraints. Silvicultural stand prescriptions integrate resource objectives, apply ecological principles, and identify the system of treatments that are effective and efficient in achieving forest goals with a degree of certainty.

Rarely do foresters treat stands for a single reason or for a short-term goal, such as fuels management. However, available funding often drives on-the-ground management operations, and the failure of forest management plans comes when implementation of newly funded activities is not integrated with already established forest plan goals and silvicultural prescription objectives. The process of developing forest plans and silvicultural prescriptions provides an opportunity to integrate all management activities before implementation, and to coordinate and schedule treatments to achieve the desired management outcomes efficiently and effectively. This integrated planning to achieve a common mission increases the probability that treatments maximize attainment of goals and objectives, give the biggest bang for the dollar, and minimize the likelihood of outcomes that are in conflict with other resource goals. This is possible because silvicultural systems are dynamic and can be adapted as new knowledge accumulates, management goals change, and stochastic events alter forest condition and succession from the desired pathways.

Preparing for the certain future attack by nonnative invasive species, periodic outbreaks of native species, and the inevitable environmental extreme events requires the proper application of silviculture within the framework of sound forest and regional planning. Silvicultural prescriptions can be developed to treat current stand conditions, manage composition, and promote tree vigor and forest health. Healthy forests are less susceptible to attack by insects and diseases, less vulnerable when attacked, and more able to survive and recover from the biotic attacks or stress from environmental extremes. The most effective forest plans seek to diversify composition and structure of forests, woodlands, and savannas across the landscape and thereby buffer the effects of pest outbreaks and harsh climates.

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