The silviculture of Eastern forests in the United States

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Introduction

The forests of the Eastern United States are diverse and provide many products and amenities for people living in the area and around the world. Eastern temperate forests play an important role in determining water yield and quality. They have a tremendous potential to sequester carbon and influence air quality, and thus climate. Our standard of living is very much linked to the health and productivity of our forests. In the East, forests cover approximately 41 percent of the region, on average, but there is tremendous variability at the state level, ranging from 6 percent forest cover 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 regional syntheses of silviculture in: northern conifers, northern and central hardwoods, southern hardwoods, and southern pines (Table 1, Fig. 1). These regional 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 done at finer spatial and temporal scales. In practice, forest operations occur at the stand-scale (i.e., 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. However, restoration plans that require silvicultural treatments such as thinning and midstory reduction are usually conducted in "stand-sized" areas for their unique ability to support glade, fen, 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 represented 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 the establishment, growth, composition, structure, health, and quality of forests through the use of planned and deliberate treatments to achieve specific human objectives on a sustainable basis (Helms 1998). Silviculture is applied forest ecology, i.e., selection and implementation of treatments are 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 used to regenerate forests, or promote stand development within existing stands. The clearcutting, shelterwood and seed-tree regeneration methods are used to 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). The rotation is the

period of time an even-aged 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 throughout the stand (Table 2, Fig. 2).

Tending treatments (intermediate cuttings) may be done in conjunction with the regeneration harvest, as in the uneven-aged system, or at various times between regeneration events in the even-aged system. In tending a forest stand, some trees are deliberately removed to achieve specific responses from remaining trees, and affect stand character. The tending treatment is named according to the intended purpose or stage of stand development. For example, (1) *thinning* is done to reduce stand density and increase growth (e.g., bole diameter or crown size) of residual trees; (2) *release cuttings* are done in stands before the sapling stage to release seedlings from competing vegetation (*weeding*), to free them from overtopping, undesirable competing trees of the same age (*cleaning*), or to release them 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 insect or disease outbreaks, or wildfire.

Silvicultural System

A silvicultural system is a comprehensive program of planned treatments including regeneration and tending that are designed to manage a forest stand through its life; its name is derived from the number of age classes (e.g., even- or uneven-aged) or the

regeneration method (e.g., clearcutting, shelterwood, selection, etc.) (Fig. 3). A silvicultural prescription outlinles for each stand the timing and sequence of all treatments in the silvicultural system, including the specific regeneration method and tending treatments needed to carry the stand from its existing condition to the desired future condition that meets the needs of the landowner.

Development of the silvicultural system for a stand is based on the assessment of the current stand and site conditions, and consideration of any expected problems from insect and disease pests, damaging wildlife (i.e., white-tailed deer browsing), invasive species, and other factors. It is the final result of a thorough evaluation of how well each of a set of alternative silvicultural systems achieves the management objectives, and identifies the preferred system in light of social, economic, and ecological constraints and opportunities. The prescription also identifies the type and timing of activities needed to meet other resource objectives listed in the management plan, for example, reduce fire risk, retain trees and coarse woody debris for wildlife habitat, sustain native biodiversity, protect culturally sensitive sites, mitigate soil erosion, or maintain an ecological legacy from the previous stand. Normally, there are multiple objectives that are achieved through implementation of each silvicultural treatment. The stand prescription provides quantitative benchmarks at various key stages in stand development that must exist for the outcomes of silvicultural treatments to be desirable and sustainable.

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 regional silvicultural

systems. It is important to distinguish between acceptable, recommended methods of regeneration and practices such as diameter-limit cutting, selective cutting, and high grading that, although they are common especially on non-industrial private lands, are not recommended because their main goal is to remove commercial timber with little thought for regeneration, future productivity and value, or other objectives important to landowners.

Even-aged regeneration methods

The following methods regenerate even-aged stands:

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 can also be used by direct seeding or planting before, or more commonly after clearcutting.

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 does not modify the physical environment significantly from that which occurs in clearcuts.

shelterwood-removes the overstory in a series of harvests that are conducted over a relatively short portion of the rotation with the goal of retaining a good number of 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 done from below (i.e., trees in the smaller diameter classes and lower crown classes are 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 of reproduction 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 sustaining mast production, aesthetics, and structure for wildlife habitat. The shelterwood method may consist of three harvests:

- **preparatory cut**-removes the seed source of undesirable species and the low-quality individuals and promotes the crown expansion of seed trees. It is not necessary if the existing stand has adequate seed production potential or advance reproduction is present.
- **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.
- **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-individual or small groups of trees are harvested indefinitely on a cutting cycle that may be 5 to 25 years long. Both regeneration and tending take place simultaneously in each harvest. Trees are considered for removal from all diameter classes in the stand to establish reproduction and to allow existing trees in all size classes to recruit into larger size classes. Selection of individual trees for removal is also influenced by the quality, vigor, and growing space requirements of the tree and by considerations for wildlife habitat. Regeneration is largely from natural seedfall, existing advance reproduction, or stump sprouts and root suckers that develop after harvesting.
group selection-is used to regenerate trees in small patches in which all trees are cut creating openings that are larger than single-tree gaps, but smaller than clearcuts. Group openings vary in size depending on the requirements of the desired species for regeneration, but commonly their opening diameter is twice the height (e.g., about 125 to 250 feet) of adjacent mature trees, about 0.2 to 1.1 acres. The abundance and size of advance reproduction largely determines what reproduction will dominate forest openings, but when it 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.

Stand prescriptions for either single-tree or group selection are guided by the goal of uneven-aged management 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 selection are applied together in a stand, with group openings being opportunistically used to increase forest diversity by favoring species that are intermediately tolerant to intolerant of shade.

Northern Conifer Silviculture

Northern conifer region

Stands dominated by spruces, balsam fir, and their associates are common throughout the Laurentian Mixed Forest Province (212, Division 210) described by Bailey (1995) (Fig. 1). This province 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. In Ontario and Quebec it is called the Great Lakes-St. Lawrence Forest Region, while in New Brunswick, Prince Edward Island, and Nova Scotia it is the Acadian Forest Region (Rowe 1972). Although often called the "spruce-fir" forest, conifer stands in this province are commonly much more diverse with important components of pine (*Pinus* L.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), northern white-cedar (*Thuja occidentalis* L.) and hardwoods, especially aspen (*Populus* L.), birch (*Betula* L.), and red maple (*Acer rubrum* L.). Thus, "northern conifers" is a more apt term. The mix of species varies across the province. White spruce (*Picea glauca* (Moench) Voss) is common throughout while red spruce (*P. rubens* Sarg.), the signature species of the Acadian Forest, is rare west of the Adirondacks. Also, eastern hemlock is absent in most of Minnesota.

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

Natural disturbances

Natural stand-replacing disturbances are rare in the northern conifer forest type. Partial disturbances resulting from windthrow and isolated pockets of insects and disease are common. Spruce budworm (*Choristoneura fumiferana* (Clemens), an insect with cyclic outbreaks that causes mortality and growth suppression, has a significant impact on forest structure and composition (MacLean 1984), especially in balsam fir (*Abies balsamea* (L.) Mill.) and, to a lesser extent, spruce dominated forests. Mortality caused by spruce budworm is related to the proportion of balsam fir and poor vigor trees (McClintock and Westveld 1946, Baskerville 1975a), 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 it may not matter as many ecological and stand relationships noted at other times are simply overwhelmed.

Ecology and silvicultural systems

The spruces, balsam fir, eastern hemlock, and northern white-cedar are all shade tolerant species; even eastern white pine (*Pinus strobus* L.) is intermediate in tolerance. They also produce seed crops with regularity and on most sites 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 across the province 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 caveat is that advance reproduction is essential before harvesting the overstory; without it, regenerated stands are converted to hardwoods (Hart 1963).

The clearcutting method 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 only one year in the forest floor; consequently they are not a reliable source of natural regeneration following clearcutting (Frank and Safford 1970). The seed-tree method is also not effective for northern conifers due to competition with intolerants and, perhaps more importantly, because of the lack of windfirmness of the shallow-rooted residuals (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* (Peck)).

The most effective even-aged regeneration method for northern conifers is the shelterwood (Seymour 1995, Brissette and Swift 2006). In unmanaged northern conifer stands, the stand to be regenerated is often in the reinitiation stage of development (Oliver and Larson 1996) and will be well stocked with seedlings and saplings of desirable advance reproduction. In that case the first cut of the shelterwood may remove one-third to one-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. If there is not sufficient advance reproduction, 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 "irregular group shelterwood with reserves" or "Acadian *Femelschlag*" described by Seymour (2005). It is designed to emulate natural gap dynamic disturbances with the goal of restoring complexity to stands that have been simplified both structurally and compositionally by a century of repeated heavy partial harvests.

Historically, thinning was not common practice in northern conifers (Seymour 1999). Vast acreages of mature forest in a pulpwood market made thinning an expense that many foresters and landowners 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. Following the spruce budworm outbreak in the 1970s and 1980s, forecasted wood

shortages resulted in the nearly routine application of precommercial thinning in dense young stands as a means of reaching merchantability faster.

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 a reduction in minimum top diameter specifications and cut-to-length harvesting technology combined to make commercial thinning viable on an operational scale (McNulty 1999). The type of commercial thinning employed depends on whether the stand had previously been precommercially thinned. In stands that were precommercially thinned, crown thinning should be favored, although in some cases, or in parts of some stands selection thinning may be appropriate. 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. Thinning can open up a stand to windthrow, so density should not be reduced too much. Tree heights, crown lengths, diameters, and depth of rooting should all be considered when making thinning prescriptions.

Multi-aged northern conifer stands are not uncommon but the selection system is not often applied in a rigorous fashion. The selection system has been studied extensively for over 50 years on the Penobscot Experimental Forest (PEF) in east-central Maine (Sendak and others 2003). Some of the problems with the selection system in northern conifers has been reported by Kenefic and Seymour (2001), who showed that upper canopy trees 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; i.e., older trees in the uneven-aged stands grow less stemwood for the same amount of foliage as 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 will suppress the development of trees in the understory and may impede regeneration, although that is less of a concern (Brissette 1996). 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 is clearly related to amount and quality of overstory light (Moores 2003). Analysis of sapling ingrowth in the PEF study reveals slow growth, generating concern about the long-term sustainability of these stands (Kenefic and Brissette 2005). Thus, although it is critical not to carry too many trees in the sawtimber classes, it is also important not to let imbalances develop in other portions of the structure for two reasons: (1) to provide sufficient trees in each size class to replace those from larger classes as they grow or are cut, and (2) to influence growth of smaller trees (Arbogast 1957, Solomon and Frank 1983). Although timely regeneration of desired species is necessary to sustain uneven-aged stands it is also necessary to tend immature trees in order to accumulate quality growing stock (Hart 1963).

Because of silvics and site characteristics, managers can choose from an array of silvicultural options to manage most northern conifer stands. What silvicultural system to use 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 be used to 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 permit sustained ingrowth of trees into larger size classes.

Northern and Central Hardwood Silviculture

The Northern Hardwood Region

According to Johnson and others (2002), the northern hardwood region extends from northern Minnesota eastward through the northeastern United States (Fig. 1). Northern hardwoods in Canada (a.k.a. tolerant hardwoods working group) occur in the Deciduous, Great Lakes-St. Lawrence and Acadian Forest Regions (Rowe 1972). More than 18 Society of American Foresters' forest types (Burns and Honkala 1990) are present representing various combinations of sugar maple (*Acer saccharum* Marsh.), red maple, American beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghaniensis* Britton),

white birch (*Betula papyrifera* Marsh.), American basswood (*Tilia americana* L.), northern red oak (*Quercus rubra* L.), eastern hemlock, black cherry (*Prunus serotina* Ehrh.), aspen, and others on approximately 92 million acres of forestland in the Mixed Deciduous – Coniferous Forest (211) and Mixed Forest – Coniferous Forest – Tundra (M211b) Provinces (Bailey 1995). Northern hardwood forests are found in the following physiographic divisions (Fenneman 1938): Laurentian Upland, Appalachian Highlands (Appalachian Plateaus (Mohawk, Catskill and Southern New York Sections) and New England Provinces), and Interior Plains (Central Lowland Provinces).

The Central Hardwood Region

Johnson and others (2002) define the Central Hardwood Region as extending 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; west to central Minnesota (Fig. 1). A significant inclusion in the west-central portion of this region is the Prairie Peninsula of Iowa, northern Missouri, Illinois and Indiana, and central Ohio (Transeau 1935). The region has about 220 million acres of which 50 percent is forested today by a diversity of deciduous broadleaf species and several associated conifers (e.g., shortleaf pine (*Pinus echinata* Mill.) and eastern redcedar (*Juniperus virginiana* L.)). The oaks (*Quercus* L.) comprise the largest proportion of the regional growing stock but many species of hickory (*Carya* Nutt.), sassafras (*Sassafras albidum* (Nutt.) Nees), flowering dogwood (*Cornus florida* L.), blackgum (*Nyssa sylvatica* Marsh.), red maple, black cherry, yellow-poplar (*Liriodendron tulipifera* L.), elms (*Ulmus* L.) and other upland hardwood species

grow with the oaks. The region includes the Broadleaved forests, oceanic (221a) and the Broadleaved forests, continental (221b) Provinces of the Hot Continental Division (220); and the Deciduous or mixed forest – coniferous forest – meadow (M221) and the Broadleaf forest – meadow (M222) Provinces of the Hot Continental Mountains Division (Bailey 1995). Central hardwoods occur in the physiographic divisions of the Interior Highlands (Ozark Plateaus Province), Appalachian Highlands (Blue Ridge and Valley and Ridge Provinces, and southern sections of the Appalachian Plateaus and New England Provinces), and Interior Plains (Fenneman 1938).

Natural disturbances

In the western portion of the Northern and Central Hardwood Region, 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 eastern deciduous forests. Wherever Indians lived in the region, local forest openings, barrens, savannas and woodlands resulted from their use of fire (Pyne 1982, Guyette and others 2002). However, within decades of fire suppression in modern times, trees invaded savannas and woodlands rapidly transforming them into forests. Many fires still occur in the region, 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 epidemics can initiate stand regeneration. This may be on a scale large enough to result

in even-aged forests, but this severity of disturbance occurs infrequently, and affects relatively small areas within the Northern and Central Hardwood Regions. More common is the mortality of individual or small groups of mature trees that occur annually in each forest stand in the region. However, the probability of catastrophic forest mortality from invasive species or extreme weather events is increasing today because forests are more vulnerable as the age structure and species diversity of forests becomes more homogeneous on the landscape.

Individual tree species have been seriously affected by introduced pathogens such as the chestnut blight (*Cryphonectria parasitica* (Murrill) Barr) and Dutch elm disease (*Ophiostoma novoulmi* Brasier and *O. ulmi* (Buism.) Nannf.) that have effectively eliminated the once prominent American chestnut (*Castanea dentata* (Marsh.) Borkh.) and American elm (*Ulmus americana* L.) from eastern forests. Today, the gypsy moth (*Lymantria dispar* Linnaeus) is causing large-scale mortality and growth reductions in hardwoods throughout much of the Northeast and Lake States. Emerald ash borer (*Agrilus planipennis* Fairmaire) is threatening to eliminate ash species (*Fraxinus* L.) from eastern forests. Consequences of large-scale homogeneity in forest composition and structure across the landscape can be devastating ecological and economic loss following oak decline or outbreak of southern pine beetle (*Dendroctonus frontalis* Zimmermann).

Ecology and silvicultural systems

Natural reproduction is the primary source of regeneration in Northern and Central Hardwood forests. Current seed produced, seed stored in the forest floor, advance

reproduction, stump sprouts and root suckers are the sources of natural reproduction. Reproduction that dominates following a regeneration harvest is strongly influenced by the character of the initial stand, i.e., composition and structure of the trees in the overstory, midstory, and understory (Johnson and others 2002). All the above mentioned silviculture methods are in common use to regenerate northern and central hardwoods, with the exception of the seed-tree method. The mix of desired species, their silvical requirements, physical environment, initial stand structure and composition, and other factors affecting regeneration success (e.g., deer browsing, invasive species, competing vegetation, and insects and disease) drive the selection of the appropriate regeneration method. Often critical to the success of the regeneration method is the planning and implementation of additional treatments such as site preparation (prescribed burning, mechanical scarification, herbicide application) and vegetation management (pre- or post-harvest mechanical, chemical or fire treatments). Collectively, they are needed to ensure establishment and dominance of the desired reproduction over its major competitors.

Even-aged systems are appropriate for most of the species found in the Northern and Central Hardwood Regions. Clearcutting is a good regeneration method for shade intolerant species that are adapted to colonize highly disturbed environments and have high growth potential in open environments (Fig. 4). Aspen grows best in the open created by a clearcut, or catastrophic wildfire or blowdown. Its regeneration is primarily from root suckering because the period of seed viability is short (i.e., weeks) and young germinants are highly susceptible to moisture stress (Laidly 1990, Perala 1990). Species capable of regenerating from seed such as white birch, sweet birch (*Betula lenta* L.),

yellow-poplar, and black cherry do well in clearcuts. These species are prolific and frequent seeders and they are capable of rapid growth (Burns and Honkala 1990).

Insufficient seed supply at the time of regeneration harvesting, or unsuitable seed bed conditions due to deep litter and humus layers can result in regeneration failures. 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 understocked conditions may occur in the centers of very large clearcuts. A buffer to poor seed production or lack of dispersal into harvested areas may be seed stored in the forest floor. Seed of most tree species either germinates, or is destroyed or eaten within a year from dispersal, however, the seed of yellow-poplar can remain viable in the forest litter for 4 to 7 years, and black cherry and white ash (*Fraxinus americana* L.) for 3 to 5 years (Marquis 1975).

Many other hardwood species such as the oaks depend more on advance reproduction and can be successfully regenerated by clearcutting when this type of reproduction is present in sufficient numbers and size before harvesting. Therefore, it is the composition of large advance reproduction that determines what species will prevail after clearcutting, or share dominance with fast growing shade intolerant species.

Natural populations of oak advance reproduction are more likely to be sufficient for regeneration by clearcutting on lower quality, xeric sites (Johnson and others 2002). On high quality, mesic sites oak advance reproduction and that of other intermediate shade

tolerant species is often absent or has low regeneration potential due to its small size. Clearcutting on these sites accelerates the loss of oak and succession to either shade tolerant species such as sugar maple, red maple or American beech, or to pioneer reproduction of shade intolerant species such as yellow-poplar or aspen.

Light seeded species such as the birches, pines, and hemlock germinate best on mineral soil. Therefore, mechanical scarification or prescribed burning may be needed to provide a suitable seedbed for these species as part of the regeneration prescription (Fig. 5). Black cherry, white ash and yellow-poplar can establish seedlings in humus or light to moderate amounts of leaf litter. Seed germination of the nut producing species (e.g., black walnut (*Juglans nigra* L.), pecan (*Carya illinoinensis* (Wangenh.) K. Koch), hickory, and oaks) can occur in relatively deep litter. In fact, a covering of litter or mineral soil helps recalcitrant seed such as acorns maintain adequate moisture content, and hence seed viability (Korstian 1927).

Control of competing vegetation may be needed to favor certain species. Herbicides, mechanical cutting, mowing or disking, or prescribed burning may be required one or more times from several years before clearcutting through the first 5 years after cutting until the desired reproduction is free-to-grow (Fig. 5). Small reproduction of species that have relatively slow juvenile growth rates, and that are intolerant or intermediate in tolerance to shade, such as the oaks, hickory and pecan, can be overtopped and suppressed by rank 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 is further increased when surface soils and litter dry out rapidly during the spring and early summer in clearcuts, before tree roots are able to 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 that moderates moisture and temperature extremes in the regeneration environment improves 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 species (Fig. 6). The method is highly recommended 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 (e.g., uniform, group, strip, or irregular) of the shelterwood is managed to provide a favorable physical environment (i.e., light, and soil and atmospheric moisture and temperature) for regeneration of the desired species. Light levels under shelterwoods may range from 20 to 60 percent of full sunlight depending on the density and spatial arrangement of the shelterwood (Marquis 1973). This is sufficient light intensity 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 insufficient for the persistence or growth of any other than the more shade tolerant species (Dey and others 2008).

As with the clearcutting method, treatments to prepare a suitable seed bed or to control competing vegetation may be needed. There are many options for combining these activities before and after the preparatory, seed or removal cuts prescribed in the shelterwood method. Herbicides used to control competing woody vegetation are also lethal to the desired hardwood reproduction. Timing and method of application of herbicide can be designed to avoid exposure of desired seedlings to the chemical.

Mechanical scarification can be done to expose mineral soil and set back competing vegetation by uprooting and breaking stems of the woody understory. However, without follow-up herbicide treatment, woody shrubs and hardwood stems that are mechanically controlled have a high probability of resprouting, limiting the time of effective release of desired reproduction.

Prescribed burning is effective for controlling the density of competing woody vegetation to favor the development of fire-adapted species such as the oaks (Fig. 7). Fires are often conducted in the dormant season to reduce risk of killing the shelterwood, especially in post-harvest situations when fuel loading may be high. Dormant season fires are able to kill or cause shoot dieback in hardwood stems up to about 5 inches in diameter (Waldrop and others 1992). Many hardwood species are able to resprout after one fire, but oaks are preferentially favored by additional burning.

Finally, the density of the shelterwood can be maintained high enough to control, to some extent, the growth of competing shade intolerant species such as yellow-poplar, sassafras,

and aspen in the understory while providing enough light for more shade tolerant reproduction of species such as the oaks (Fig. 6). 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, the single-tree selection method is good for regenerating and sustaining forests dominated by shade tolerant species such as sugar maple, red maple, American beech, and eastern hemlock (Hicks 1998) (Fig. 8). Light levels in the understory of stands managed by this method are similar to those found in unmanaged, mature, closed-canopied forests, i.e., too low for any but the most shade tolerant reproduction to persist. The single-tree method is not well suited for regenerating black cherry, white ash, birch species, oak species, and other more light demanding species in the Northern and Central Hardwood Region. However, some evidence exists that the method may be able to sustainably regenerate oak forests in the Missouri Ozark Highlands (Loewenstein and others 2000, Loewenstein 2008, Iffrig and others 2008). These Ozark ecosystems lack a suite of shade tolerant competing species such as American beech and maples; here, white oak (*Quercus alba* L.) is one of the more shade tolerant species. Harvesting by the single-tree method in these ecosystems is shifting forest composition from a mix of black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), white oak and shortleaf pine toward white oak (Kabrick and others 2008).

The group selection method can be used to regenerate shade tolerant species, but more often it is used to promote that of the shade intermediate and intolerant species (Fig. 8).

The abundance and size of advance reproduction before harvesting largely determines what species will benefit. In most forest systems in the region 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 under- and midstory before or during harvesting. Group openings with diameters that are less than one to two times the height of the adjacent dominant trees favor shade tolerant species, and are more subject to closure from lateral extension of adjacent overstory crowns before reproduction is able to recruit into the overstory. However, species such as the maples and American beech can tolerate periods of suppression and eventually grow into the overstory after several releases following periodic (every 10 to 20 years) harvests in the stand.

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

Northern red oak and white ash should be present as larger advance reproduction, 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 provided by mechanical scarification during harvest operations.

Herbicide can be applied to the stump surface of cut stems, or stems by basal spray or stem injection to prevent sprouting of unwanted stems of shade tolerant species and reduce competition in group openings. Mechanical cutting alone will provide short-term release for intermediate shade tolerant or intolerant species, but sprout regrowth of maple, American beech and ironwood (*Ostrya virginiana* (Mill.) K. Koch), striped maple (*Acer pensylvanicum* L.), and flowering dogwood will be rapid and suppress desirable reproduction.

Artificial regeneration of hardwoods is done in limited situations where it is used to supplement natural populations of advance reproduction of desired species, in particular oak species, in upland forests. Johnson (1984), Johnson and others (1986), Loftis (1990), Weigel and Johnson (1998a,b and 2000), Dey and Parker (1997a,b), Spetich and others (2002), Parker and Dey (2008), and Dey and others (2008a,b), among others, have evaluated methods for underplanting oaks in shelterwoods throughout the eastern United States. Johnson and others (2002) summarize much of this work in their book on oak ecology and silviculture. Artificial regeneration of hardwoods is more common in afforestation of agricultural bottomlands and upland pastures, and a recent review of direct seeding and planting oaks in floodplains has been done by Dey and others (2008c).

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

Southern Hardwood Silviculture

The Southern Hardwood Region

Of the 535 million acres of land in the southern United States, 214.6 million acres is 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 that which existed at the onset of European colonization in 1630, and about 90 percent of that which was forested at the height of selective cutting in 1907 (Conner and Hartsell 2002). However, over the past six decades, 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 forested condition.

The southern pine and hardwood regions occur conterminously across the South, and are bounded on the north by the Central Hardwood Region, the west by the Forest-Prairie Transition Region, with the remaining boundaries the Gulf of Mexico and the Atlantic Ocean (Johnson and others 2002) (Fig. 1). The southern pine and hardwood region

includes four major physiographic regions: the Piedmont (Province 232, Division 230), the Coastal Plain (Province 231, Division 230), the Interior Highlands (Province M231, Division M230) and the lower Mississippi Valley (Riverine Intrazonal Province (R)) (Bailey 1995). The region covers approximately 270 million acres, with 60 percent of that forested.

The Cumberland Plateau and associated highlands of the Interior Highlands (Division 230) and the lower Mississippi alluvial valley contain the majority of upland and bottomland hardwood forests. Oak forests (includes white oak, scarlet oak, southern red oak (*Q. falcata* Michx.), overcup oak (*Q. lyrata* Walt.), chestnut oak, water oak (*Q. nigra* L.), Nuttall oak (*Q. texana* Buckley), willow oak (*Q. phellos* L.), northern red oak, and black oak) cover 60 percent of the region; loblolly (*Pinus taeda* L.)-shortleaf pine and longleaf (*P. palustris* Mill.)-slash pine (*P. elliottii* Engelm.) dominate the remaining forested lands. In uplands, mixed oak-pine regions exist, often consisting of mixed upland hardwood species with loblolly, shortleaf or Virginia pine (*P. virginiana* Mill.). Upland hardwoods are dominated by red and white oaks, with hickories (*Carya* spp.), yellow-poplar, sugar maple, red maple, American beech, black cherry, sassafras, sourwood (*Oxydendrum arboretum* DC.), blackgum, birch, and ash all having supporting roles. Southern bottomland forests occur on river floodplains and are most extensive in the Atlantic Coastal Plain, Gulf 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), sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), blackgum, elms, sugarberry

(*Celtis laevigata* Willd.), eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.), willow (*Salix* L.), ash, hickory, and red maple. Conifers that may grow in floodplains include loblolly pine, spruce pine (*Pinus glabra* Walt.), baldcypress (*Taxodium distichum* var. *distichum* (L.) Rich), pondcypress (*Taxodium distichum* var. *imbricarium* (Nutt.) Croom), Atlantic white-cedar (*Chamaecyparis thyoides* (L.) B.S.P.), and eastern redcedar.

Natural disturbance

Fires occur infrequently in alluvial areas because these sites are too wet and often not enough litter exists to support a fire. Natural disturbances such as severe or unseasonable flooding, drought, windstorms or animal activities provide episodic disturbances. Anthropogenic modifications include impoundments or other flood control devices, timber harvesting, and land clearing for agriculture.

Natural fires (i.e., other than human caused) have not played a major role in the landscape dynamics in southern upland hardwood forests 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. Native Americans certainly used fire to clear along water courses and to drive game, and occasionally these fires escaped to the uplands; Europeans burned for improved grazing, to control undergrowth for better visibility and accessibility, and to control insects (Komarek 1974; Van Lear and Waldrop 1989). Exploitation of coal, timber and gas resources, as well as agriculture shaped today's forests. Disturbances caused by storms, insect and disease outbreaks, and late-

season frosts continue to alter stand structure and composition. Future forest influences include increasing development, invasion by exotic species and more aggressive coal mining.

Ecology and silvicultural systems

After considering landowner goals, landscape location (physiographic, edaphic, moisture and nutrient site class) and disturbance history, as it influences current forest composition and structure, drive management decisions in southern hardwood forests. From xeric upland oak-hickory forests, to species rich mesic cove forests, to hydric bottomland forests containing oak, gum and eastern cottonwood, 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 is often limiting regeneration of desired species. However, ensuring adequate light is available to reproduction can be achieved through silvicultural treatments.

Southern hardwood forests are disturbance-dependent systems. They are also very diverse in species, many of which are desirable, and this makes controlling the final composition at maturity a challenge. Therefore, we must consider the silvic requirements of each species in selecting the type and timing of silvicultural treatments. In upland and bottomland systems, oak is a focal species group, and it is more difficult to regenerate on good sites that contain greater potential competition from other woody and herbaceous

species. Silviculture 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 lower elevation flat sites. Competition is greater on higher elevation sites than lower. Manuel (1992) developed a decision model for managing and regenerating southern bottomland hardwoods based on stand conditions according to stocking levels of desired species, tree-preference class and individual tree characteristics. Evaluation of natural regeneration of bottomland hardwoods can be done using techniques outlined by Putnam and others (1960), Broadfoot (1976), or Belli and others (1999). These techniques take into account regeneration source (seed, seedling, or sprout) and site type based on soil series and inundation regime. If regeneration is adequate, the decision model recommends using the clearcut method. If the decision is to manage but not regenerate, and adequate regeneration is present, care must be taken to provide adequate light to the forest floor 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 shade intolerant and moderately intolerant species (Clatterbuck and Meadows 1993). Light seeded species such as willow, eastern cottonwood and ash are also regenerated naturally best under clearcut conditions that exposure mineral soil. The seed tree method can be used for light seeded species but it has been shown to have no positive influence on regenerating

bottomland hardwood stands where oaks or other heavy-seeded species are desired (Johnson and Krinard 1976).

If regeneration is inadequate, or if the stand has been poorly managed and the desirable species mix is not adequate, managers should manage light by reducing stand density through harvesting to enhance the growth of individual stems, and promote establishment of regeneration. The shelterwood method can be used to promote regeneration by reducing stand density and removing undesired species by harvesting, by herbicide injection into individual stems, or a combination of both treatments. For heavy seeded species such as oak, a release harvest can be done either at the time of a bumper acorn crop, or immediately after oak seedlings establish following a good acorn crop. Final overstory removal is planned when 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 in controlling competing vegetation by pre- or post-harvest treatments.

Upland hardwood systems

Three literature sources addressing oak regeneration and management in upland systems are the proceedings from 'Oak Regeneration: Serious Problems, Practical Recommendations' (Loftis and McGee 1993), the 'Upland Oak Ecology Symposium (Spetich 2004), and the book 'The Ecology and Silviculture of Oaks' (Johnson and others 2002). Although oak-focused, research and management options include recommendations for other desirable species. Loftis (1989) provides a comprehensive method to evaluate natural regeneration of southern upland hardwoods. Currently calibrated for the southern Appalachian region, model parameters can easily be adjusted for other southern upland systems such as the Cumberland Plateau region, 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 a competition scale, and to reduce the influence of new black cherry seedlings.

Topographic position dictates management in the upland hardwood region. 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), as 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 be used that encourage more and larger oak advance reproduction while at the same time reduce competition.

Acorns that germinate after regeneration harvesting provide new seedlings, but shoot growth of these seedlings is slow, they preferentially allocate carbon to root growth, which makes them vulnerable to suppression by species that exhibit rapid shoot growth (Johnson and others 2002). Consequently, oaks rarely reach a dominant or codominant position in the new stand on productive sites (Sander 1972, Loftis 1983). Yellow-poplar is a major competitor with oaks on productive sites. In addition to regeneration from stump sprouts and advance reproduction, yellow-poplar can also regenerate successfully from new seedlings that established after harvest from current seed production or seed stored in the forest floor (Beck 1970). Yellow-poplar seedlings are often numerous and on better sites can have high shoot growth rates and thereby dominate the composition of the new stand (Fig. 9). In other upland hardwood systems, desirable species such as ash and black cherry can also regenerate from new seedlings and grow rapidly in height in sufficient light. The diversity of shade tolerances exhibited by these species contributes to the challenge of regenerating these stands.

A promising alternative regeneration method to favor oaks and other mid-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 high enough to prevent light-seeded, shade-intolerant species such as yellow-poplar from becoming established and growing. The change in canopy structure and below-canopy light conditions will also favor shade-tolerant species such as sugar maple. Treating the shade tolerant subcanopy in addition to overstory density reduction will promote the development of advance reproduction of the desired species.

Single-tree selection in upland hardwood systems consistently results in a composition shift towards shade-tolerant species over time. In mature forests that initially have a substantial component of oaks, yellow-poplar and other desirable but less shade tolerant species in the overstory, this method inhibits their regeneration and favors the recruitment of sugar maple, red maple, sourwood, dogwood (*Cornus* L.), American beech and other shade tolerant species (Fig. 10). The desirable seedlings and sprouts that do become established under single-tree cutting do not persist in the low light of the forest canopy. So, in addition to providing adequate light in the understory for development of large advance reproduction, managers may need to consider interspecific competition when manipulating stand composition and structure using this system. Creating large openings by group selection harvesting and using a herbicide to eliminate the tolerant understory may be a technique that offers promise (Della-Bianca and Beck 1985).

Many southern upland hardwood stands originated when wildfire was more prevalent than it is now. 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 Appalachians, Loftis (1990) found that one burn did not enhance oak seedling basal diameter growth, did not control the development of other competing regeneration, and had an adverse impact on survival of red oak seedlings. A disturbance regime that incorporates a high level of disturbance, such as shelterwood harvesting followed by fire, may favor oak regeneration over its competitors. Timing and intensity of these fires may also play a significant role in modifying regeneration dynamics. For

example, a single spring burn conducted several years after shelterwood harvesting produced a high intensity fire that favored oak regeneration over yellow-poplar, but less intense burns conducted in summer or winter were insufficient for control of oak's competitors (Brose et al. 1999). Single low intensity fires may have little or no effect on stand composition. Density of oak and its competitors are more affected by fire intensity than is height. Repeated burning may be necessary to favor oak over yellow-poplar where fires are low intensity. Regardless of fire timing or intensity, the competitive status of oak seedlings drives the response to disturbance.

Southern Pine Silviculture

The Southern Pine Region

About 96 million acres of timberland in the South is found in southern pine or oak-pine forest types (Smith and others 2004) (Fig. 1). 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 east Texas. Its natural range includes the Atlantic Coastal Plain, the Piedmont Plateau, parts of the Cumberland Plateau and Appalachian Mountains, and across the eastern and western Gulf Coastal Plain (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, except for the Ouachita Mountains of Arkansas and Oklahoma where the species is the only dominant naturally-occurring pine (Lawson 1990, Guldin 2007).

Slash pine has the smallest native range of the four species, found from southern South Carolina, through the hills of South Georgia and virtually all of Florida, and west along the lower Gulf 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 lower Atlantic and Gulf Coastal Plains from Virginia to east Texas; once occupying an estimated 92 million acres of the South, today it is much less widely distributed over roughly 3.2 million acres due to cutting virgin stands, fire exclusion, and reforestation of cutover areas with loblolly and slash pine (Boyer 1990, Landers and others 1995). However, earnest efforts are underway to restore longleaf pine ecosystems, especially on Federal and State lands such as national forests and lower Coastal Plain military bases.

The four southern pines are occasionally found in association with minor pine species such as spruce pine in the lower Gulf Coastal Plain, pond pine (*P. serotina* Michx.) in the lower Atlantic Coastal Plain, and the pines having a more northerly distribution that are found in the Appalachians--table mountain pine (*P. pungens* Lamb.) Virginia pine, pitch pine (*P. rigida* Mill.), and eastern white pine. And throughout the South, pines are found

in intimate mixture with hardwoods, especially the oaks and hickories that comprise the potential natural vegetation communities (Keys and others 1995) that would eventually dominate the forests of the South 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 is in the loblolly-shortleaf forest type, and 14 million acres is in the longleaf-slash forest type; another 30 million acres is classified as oak-pine forest type, in which the southern pines are found in mixtures of varying percentage with oaks (Smith and others 2004). The loblolly-shortleaf forest type includes pure stands of loblolly pine of natural or planted origin, pure stands of shortleaf pine in the Ouachita and Ozark Mountains also 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, with minor occurrence of naturally-regenerated stands with both species present. Oak-pine stands are usually of natural origin, and there is often consideration given in these mixed stands to managing either for the hardwood component or, more commonly especially on forest industry ownership, to manage for the pine component so as to simplify species composition and to increase pine growth and yield.

Natural disturbance

The southern pines are early-successional species adapted to disturbance events of varying size and scale, especially at larger scales. The climate of the South features a

variety of large-scale disturbance events, any one of which can result in the devastation of an existing stand and create open conditions for establishment of a new age cohort of pines. Wind events such as tornadoes and hurricanes can affect areas as small as a single stand to areas as large as entire states. Outbreaks of the native southern pine beetle can, if unchecked and under the proper conditions, grow to cover thousands of acres, and even if controlled can affect hundreds of acres of pines in any part of the region at any time.

Fire, whether as a result of natural or anthropogenic occurrence, is the single most important ecological element in southern pine stand dynamics and development. Presettlement descriptions of southern pine forests commonly described mature pines with virtually no midstory, and understory plant communities dominated by grasses, annuals, and perennials such that one could easily ride a horse through the woods and not be impeded by vegetation (e.g., 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 promote forage for feral and domesticated livestock. No doubt both the Native American and European cultures appreciated the benefits that understory burning provided for control of the ticks and chiggers that infest humans who live and work in southern forests.

Ecology and silvicultural systems

Fire is especially important in southern pine regeneration dynamics. Each of the four southern pine species has developed interesting and unique adaptations to prescribed fire that can result in favorable conditions for seedling establishment and development.

Shortleaf pine is the only one of the four that will reliably re-sprout if the crown of the sapling is top-killed by fire (or if mechanically severed), a trait that was described as an adaptation to fire early on (Mattoon 1915). Small shortleaf pine seedlings are extremely vulnerable to death by even low intensity surface fires, but ability to survive, or resprout after topkill increases with increasing tree diameter (Dey and Hartman 2005). Pine's ability to resprout declines as tree diameter increases above 3 inches (Dey and Fan 2008). Thus, in sapling-sized shortleaf pine stands, a new age cohort develops after fire through resprouting and some added seedfall if a seed source remains nearby. Fire frequency of less than every 8 years can keep pine regeneration from accumulating and growing into the overstory (Stambaugh and others 2007).

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 being a species that thrives naturally on moist to wet sites (Baker and Langdon 1990). However, 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 Gulf Coastal Plain is arguably the most prolific pine type in North America, producing adequate or better seed crops 4 years in 5 and having bumper crops with more than a million seed per acre (Cain and Shelton 2001). Essentially, the strategy for Coastal Plain loblolly-shortleaf pine mixtures and for slash pine are to produce enough seed on a sufficiently frequent basis to

establish seedlings within any new opening in the forest shortly after it is created, and to have those saplings grow fast enough to survive the next surface fire.

One might speculate that these respective strategies of resprouting versus reseeding work together in mixed loblolly-shortleaf pine stands of natural origin, and may suggest a reason for 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 if a surface fire occurs in a mixed pine sapling stand, the loblolly will be killed and would require an on-site or nearby seed source to reseed the area, whereas the shortleaf saplings would simply resprout--a dynamic that might confer an adaptive advantage to shortleaf in circumstances where loblolly would normally outgrow shortleaf.

Longleaf pine has a different strategy entirely, featuring extended irregularity in seed crops and the famous seedling grass stage. While in the grass stage, the seedling emphasizes root growth rather than shoot growth, and the terminal bud is protected from surface fire by the physiognomic pattern of bud scales and needle architecture. Those early years in the grass stage require occasional surface fires to prevent grasses and other understory herbaceous and woody vegetation from suppressing the pines. Those fires also serve to control brown spot needle blight (*Mycosphaerella dearnessii* Barr.) that infects pine needles and which, if uncontrolled, can prevent seedling emergence from the grass stage (Boyer 1979). After several years and under proper conditions, longleaf seedlings break the grass stage and initiate height growth 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 shortleaf pine, both of which can tolerate more overstory shade when young than can longleaf and especially 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 the pines to maintain site occupancy under partial disturbance events such as ice storms or wind events. The four species also show good ability to differentiate in height, which helps minimize extended periods of sapling stagnation even though that can occur to a certain degree in densely-stocked naturally-regenerated sapling stands.

Excellent 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. Agriculture Handbook 445, Silvicultural Systems for the Major Forest Types of the United States (Burns 1983), includes general discussions for most of the important forest types in North America, including the southern pines. Overviews of the general principles of plantation silviculture and silviculture of naturally-regenerated stands were recently published (Guldin 2004, Fox and others 2007). 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 with 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 prominent 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 to 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 scientific advances and technologies were optimally applied in stands that were clearcut and site prepared using an array of site-specific intensive methods, and then planted with careful attention to the origin and quality of planting stock. As a result, clearcutting and planting became the standard prescription for intensive pine silviculture, and the millions of acres of plantations created using the many variations of clearcutting, planting, and subsequent intermediate treatments have been the mainstay of the Southern pulp and paper industry for the past four decades (Fig. 11).

Because of the plasticity and success of intensive pine plantation silviculture for rapid fiber production, the southern pine forest types are the focus of the most intensive forest management activity in the South if not the Nation. Recent data suggest that of the 66 million acres in the two pine-dominated forest types, 34 million acres is in pine stands of natural origin, and 32 million acres is planted (Smith and others 2004). The plantation area in these two pine-dominated cover types by ownership varies from 1 million acres (24 percent) on National Forest lands and 750,000 acres (20 percent) on other public

lands, to roughly 15 million acres (40 percent of the total pine-dominated area in this ownership) on the non-industrial private forest 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 total in planted pine-dominated forest types represents 84 percent of the total area of planted stands in the South

Wear (2002) suggested that by the year 2050, one in four acres of the southern forest—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 from natural pine-dominated forests to planted pines in the next four decades. Given the current political environment, it's not likely 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 forest types. The trend is likely to be found in one of several areas—increases in planted forest area in the non-industrial private forest ownership sector, or increases in converting hardwood-dominated forest types to pine plantations on forest industry and non-industrial private forest lands. And because planting with containerized planting stock is an important tool in the restoration of longleaf pine stands on the lower Atlantic and Gulf Coastal Plains, there may also be significant area planted for a restoration goal on public lands as well.

Other even-aged methods

However, that portion of the southern pine forest types not managed using plantations can be very effectively managed using even-aged and uneven-aged methods that rely on natural regeneration. Four spheres of application have been suggested (Guldin 2004).

First, plantation silviculture is costly, especially in the initial capital investment in 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. Second, some landowners seek large-diameter pine trees of high quality, to take advantage of larger product sizes and the higher unit value that sawtimber brings relative to pulpwood when trees are harvested. Third, there is a middle ground of silvicultural activity within streamside management zones (SMZs) that falls between the extremes of 'hands off' or 'high-grading', and regeneration methods that retain some overstory trees may be a more robust way to manage SMZs sustainably in the future. Finally, the shift away from clearcutting on public lands has been coupled with increased reliance on other even-aged and uneven-aged regeneration methods that provide ecosystem values unable to be satisfied using clearcutting.

A key to success in using natural regeneration in southern pines is to pay attention to the fruitfulness of individual pines. Seed production is a highly inherited genetic trait in the pines, so foresters must pay attention to the inherent fruitfulness of trees being retained as seed producers. This is easy to do with shortleaf pine, because of the habit this species has for old cones to persist in the crown. For the other three southern pines, one should look for cones at the base of the tree or use binoculars to look for developing cones to assess fruitfulness.

The seed tree method reserves 4 to 10 dominant or codominant pines per acre, with a corresponding residual basal area from 5 to 15 square feet per acre (Fig. 12). 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 of a recent seed-tree method. Shortleaf pine can also be managed using the method, if attention is given to retaining effective seed producers and properly preparing the site. An excellent description of the seed-tree method is found in Zeide and Sharer (2000), which outlines the typical seed-tree prescriptions in mixed loblolly-shortleaf pine stands in the upper west Gulf Coastal Plain as practiced by forest industry in south Arkansas in the last three decades of the 20th century.

Application of the seed-tree method starts with late-rotation thinning or preparatory cutting that encourages crown development in trees likely to be retained as seed trees. The seed cut then removes all but the few residual trees per acre, and should be associated with effective site preparation treatments to dispose of logging slash and to 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 germination and establishment of the pines. A properly-timed prescribed fire can help with this, especially with shortleaf pine. Several years after the new age cohort is well-established, the seed trees can be removed using a removal 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 will include commercial thinning on a 7- to 10-year cycle, a decennial herbicide application 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 from 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 more uncertain. The extra trees retained in the shelterwood compared to the seed-tree method provide added seed production potential and help to modify the microclimate in the regeneration zone to favor pine seedling survival, and this can be an important difference between marginal and adequate stocking.

The best example of shelterwood method in southern pines is the famous work done in the 1970s with longleaf pine in southern Alabama (Croker and Boyer 1975, Boyer 1979). 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 being optimal (Maple 1977). Second, prescribed fires were used to control brown-spot needle blight. The shelterwood optimized the relationship between seed production and needlefall required to support regular prescribed burning. This is essentially a silvicultural application of the stored seedling bank beneath the seed trees, which can then develop into the succeeding age cohort as seedlings break from the grass stage ideally in three to five years after germination (Fig. 13).

As was the case 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. Again, effective site preparation treatments should be conducted in association with the seed cut to dispose of logging slash and to remove competing vegetation, and the logging and site preparation activities should be sufficient to prepare the seedbed. Prescribed fire should be implemented shortly after the seed cut, especially in longleaf pine for reasons mentioned above. Several years after the new age cohort is well-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 can actually be an advantage to the removal cut, because they provide harvest volumes sufficient to attract a logger. On the other hand, the larger number of pines to remove in the shelterwood may result in unacceptable logging damage to the regeneration cohort, especially if stocking is marginal. Some managers plan 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, a decennial herbicide application to control encroaching hardwoods, and reintroduction of prescribed fire on a 3- to 5-year cycle to retain open understory conditions.

Applying uneven-aged regeneration methods in species that are intolerant seems counterintuitive, but the earliest successful examples of the selection method were in

pines--the Dauerwald in Germany (Troup 1952) applied to Scots pine (*P. sylvestris* L.) and the improvement selection in Arizona (Pearson 1950) applied to ponderosa pine (*P. ponderosa* Dougl. ex Laws.). In the South, the longest record of success with the method has been in west Gulf Coastal Plain loblolly-shortleaf pine stands in southeastern Arkansas (Baker 1986, Reynolds and others 1984, Baker and others 1996, Guldin and Baker 1998, Guldin 2004), 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 in longleaf pine in Florida and Alabama (Farrar 1996, Brockway and Outcalt 1998, Mitchell and others 2006), and in shortleaf pine stands in the Ouachita Mountains (Lawson 1990, Guldin and Loewenstein 1999). There has been virtually no research on uneven-aged regeneration methods in slash pine, but the group selection method has been suggested (Langdon and Bennett 1976) and other methods suitable for longleaf pine should also work with 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. The openings created using group selection can be made without residual trees, relying on existing advance growth or natural seedfall from adjacent trees or by supplemental planting within the group opening. Retaining some residual trees at shelterwood basal areas within group openings is also an option for longleaf pine (Farrar 1996, Guldin 2006), and would probably work nicely in shortleaf pine as well. Once the pine seedlings are established, the relatively open conditions that

occur within group openings resemble the early seral conditions that are best for the southern pines, which would be more favorable with larger group openings rather than smaller ones. Administratively, followup treatments such as cleaning or precommercial thinning should be targeted specifically to the openings, an easy process to work into operational contracts using maps or geographic locations of the openings where treatments are to be conducted.

The major disadvantage to group selection is that the methods works well early in the installation of group openings, but is difficult to maintain over repeated cutting cycles without strictly adhering to an area-based regulation system—which may fall more into the realm of an even-aged patch clearcutting system rather than an uneven-aged selection system. That is not important to the trees, but might be important to managers if commitments have been made about the proportions of even-aged versus uneven-aged area being managed across an area, as is often the case in National Forest management plans.

The single-tree selection method also offers advantages and disadvantages. The standout experience over seven decades with the Farm Forestry Forty demonstrations at the Crossett Experimental Forest in south Arkansas (Fig. 14) 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. Over time, stands that had initially been understocked recovered to full stocking within 2 decades. Details of the implementation of the selection method

in these mixed loblolly-shortleaf pine stands have been outlined elsewhere (Baker and others 1996, Guldin and Baker 1998, Guldin 2002), and serve as appropriate mensurational guidelines for any of the intolerant southern pines managed using either volume regulation with a guiding diameter limit, or structural regulation using the BDq method.

But the biggest disadvantage of the selection method in intolerant southern pines is the management commitment required to maintain proper stand structure, especially with single-tree selection. The concept 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. Most uneven-aged stands of southern pines grow between 2 and 3 square feet of basal area per acre annually, and regeneration becomes suppressed beneath a stand carrying roughly 75 square feet per acre or more. Cutting cycle harvests usually leave between 45 to 60 square feet per acre immediately after harvest, which suggests that cutting cycle of 10 years or less will be needed to maintain acceptable understory development. If timely cutting cycle harvests are not repeatedly maintained, the understory development needed to maintain stand structure will be lost. This will lead to a reversion of the midstory and overstory crown classes 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.

Conclusion

Managers have many silvicultural options for managing forests to provide the mix of commodities and amenities desired by society because of the diversity of tree species in the eastern United States, the large ecological amplitude 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 attainment of forest goals with a degree of certainty.

Rarely do we treat stands for singular reasons for short-term goals such as fuels management. However, agency or organizational funding initiatives often drive on-the-ground management operations, and the failure in implementation of forest management plans comes when well-funded activities are not integrated with other disciplines to meet forest management 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 efficiently and effectively achieve the desired management outcomes. This integrated planning to achieve a common mission increases the probability that when treatments are applied that they maximize attainment of goals and objectives, give the biggest bang for the dollar, and minimize the times that treatments

produce outcomes contrary to other resource goals. Silvicultural systems are dynamic and can be adapted as better knowledge is gained, management goals change, and stochastic events occur that alter forest condition and succession from the desired pathways.

The best long-term strategy to combat the certain future attack by invasive species, thwart outbreaks of native species, and prepare for the inevitable environmental extreme events is the proper application of silviculture within the framework of sound forest and regional planning. Silvicultural prescriptions can be developed to treat current stand conditions, to manage composition, and promote tree vigor and forest health. Healthy forests are less susceptible to attack by insects and pathogens, are less vulnerable when attacked, and are more resilient to survive and recover from the biotic attack or stress from environmental extreme. Forest plans should seek to diversify composition and structure of forests, woodlands and savannas across the landscape to buffer the effects of pest outbreaks and harsh climates.

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Table 1. Forest regions and Bailey's (1995) ecological Divisions (based on Johnson and others (2002), Hicks (1998) and Braun (1950)).

Forest Region	210 Warm Continental	220 Hot Continental	230 Subtropical	M210 Warm Continental Mountains	M220 Hot Continental Mountains	M230 Subtropical Mountains
Northern Conifer	X			X		
Northern Hardwood	X			X		
Central Hardwood		X	X		X	X
Southern Hardwood			X			
Southern pine			X			

Table 2: Silvicultural treatments for stand regeneration or intermediate tending.

Treatment Category		
Regeneration	**Age Structure**	**Regeneration Method**
	Even-Age	Clearcut
		Seed Tree
		Shelterwood
	Uneven-Age	Single Tree Selection
		Group Selection
Intermediate Tending	Thinning	
	Release	Weeding
		Cleaning
		Liberation
	Pruning	
	Sanitation	
	Sanitation	

Figure Captions

Figure 1. Major forest regions of the eastern United States (adapted from Fig. 1.6 of Johnson et al. 2002).

Figure 2. Stands regenerated by one of the even-aged methods progress through a sequence of stages from Stand initiation to the Complex Stage if left to develop on their own. Stands in all developmental stages are subject to gap-scale disturbances within the stand that originate from the natural mortality of individual trees, or from tending and intermediate cutting (dotted arrows). As average tree size (and thus gap size) increases with increasing stand age, stands progress toward the uneven-aged state (Complex Stage) via the gap-wise replacement of main canopy trees by subcanopy trees and reproduction. In uneven-aged management, the Complex Stage can be sustained using single-tree and group selection harvesting. However, stand-initiating disturbances can occur at any stage of stand development (solid arrows). Disturbances that eliminate only a fraction of the overstory, but leave a significant number of trees standing, are termed incomplete stand-scale disturbances. These disturbances produce a mixed stage of stand development comprised of both new and older trees that develop into multi-tiered stands of irregular age structure (dashed arrows). The group selection method, or shelterwood harvesting with long-term retention of a portion of the overstory may result in structure represented by the Mixed Stage. The Mixed Stage may (1) advance to the Complex Stage in the absence of further stand-initiating or incomplete stand-scale disturbances, (2) return to the stand initiation stage after a stand-scale disturbance, or (3) remain in the Mixed Stage

as a result of further incomplete stand-scale disturbances. (Courtesy of Steve Shifley and Paul Johnson).

Figure 3. (A) Chronosequential application of individual practices of a silvicultural system in an even-aged stand. During the rotation age (r), treatments are applied across the entire stand to meet silvicultural objectives that are related to tree age. (B) Concurrent application of individual practices of an uneven-aged silvicultural system during a cutting cycle (C_i) harvest in a balanced uneven-aged stand. Each cutting cycle harvest will support similar treatments (Guldin 2006).

Figure 4. Clearcutting is a good 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 the Northern and Central Hardwood Regions, as shown here in a progression of photos taken from several stands in the Ozark Highlands of Missouri (photos by Dan Dey).

Figure 5. Site preparation is often required as part of the regeneration prescription to provide a suitable seedbed and to control competing vegetation. Mechanical scarification (A and B) or prescribed burning (C) are effective methods for exposing mineral soil needed especially by light seeded species such as yellow birch, white pine, red pine, and shortleaf pine. Ground can be scarified by anchor chains dragged behind rubber-tired skidder (A) or by dozers with brush blades (B). Prescribed fires can consume fine litter

and expose duff or mineral soil depending on fire intensity as depicted in (C), which shows the immediate results of a low intensity spring burn in an Ontario northern hardwood stand. Low intensity fires are able to reduce competition from woody species up to about 5 inches in diameter, and many herbaceous species. With either method, benefits of competition control are ephemeral and treatments may need to be applied again. Conversely, logging in the winter over frozen and snow covered ground can minimize the disturbance to soil, existing seedlings, and other desirable ground cover (D) (photos by Dan Dey).

Figure 6. The seed-tree (A) and shelterwood (B and C) methods are even-aged systems for regenerating a variety of hardwood and conifer species. Seed-trees, often less than 15 trees per acre, are left in the stand to provide a uniform dispersal of seed after the harvest. The method is most often used to promote light seeded species that can regularly produce good seed crops such as eastern white pine in Ontario (A). In the shelterwood system, enough overstory trees are left after harvest to moderate the microenvironment in the regeneration zone. There is much flexibility in applying this method by varying the amount of residual overstory, and the rate at which the overstory is further reduced once regeneration of desired species is established. Shelterwoods may have only 30 to 50 percent of the original basal area (B), or be more heavily stocked (C). Species specific thresholds for water, nutrients and light determine the optimal range of shelterwood density that promotes survival and good growth of the desired reproduction. Typically, shelterwoods are created by removing trees from the smaller size classes first, otherwise known as thinning or harvesting from below. Management of the shelterwood must be

done also to control growth of aggressive woody competitors. The need for this varies with site quality (photos by Dan Dey).

Figure 7. Prescribed burning is done to: (1) restore and manage savanna (A) and woodland (B) ecosystems by frequent burning and perhaps tree harvesting, and (2) promote oak and pine regeneration in forest management by judicial and very targeted use of fire as part of the regeneration prescription (photos by Dan Dey).

Figure 8. Uneven-aged systems include single-tree and group selection methods. The single-tree method favors shade tolerant species such as sugar maple and American beech. Harvest of individual trees (A and B) throughout the stand creates small gaps in the canopy (C). [Circles in photo A show individual trees that were harvested in the stand]. Increases in understory light are slight and benefit only the most shade tolerant advance reproduction. Group selection openings (D) are used to favor shade intolerant or intermediately tolerant species and are usually located within an area being managed by single-tree selection. Group openings differ from clearcuts in that the adjacent forest influences much of the group opening (photos by Dan Dey).

Figure 9. Yellow-poplar is a major competitor of oak and often dominates after regeneration by even-aged methods if nothing is done to control its development. In the Cumberland Plateau Region of Alabama, density of large yellow-poplar, sugar maple and ash reproduction increased substantially compared to slight increases in large oak seedling density 5 years after shelterwood harvesting, where 50 percent of the basal area

was removed (WO = white oak, RO = red oak, SM = sugar maple, RM = red maple, YP = yellow-poplar, HIC = hickory, ASH = ash, BG = blackgum, BC = black cherry).

Figure 10. 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 Schweitzer).

Figure 11. A loblolly pine plantation on a good 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).

Figure 12. Mixed loblolly-shortleaf pine stand in the upper West Gulf Coastal Plain managed using the seed tree method (photo by James M. Guldin).

Figure 13. Longleaf pine stand in the lower Atlantic Coastal Plain managed using the shelterwood method (photo by D. Wilson).

Figure 14. Mixed loblolly-shortleaf pine in the upper West Gulf Coastal Plain managed using the selection method (photo by James M. Guldin).