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Silvicultural systems for southern bottomland hardwood forests

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Abstract

Silvicultural systems integrate both regeneration and intermediate operations in an orderly process for managing forest stands. The clearcutting method of regeneration favors the development of species that are moderately intolerant to intolerant of shade. In fact, clearcutting is the most proven and widely used method of successfully regenerating bottomland oak species in the South. The seed-tree method of regeneration favors the establishment of light-seeded species. Mechanical soil scarification may be necessary if the desired species requires bare mineral soil for establishment. The shelterwood method of regeneration can provide for the development of heavy-seeded species, but has produced highly variable results with southern bottomland oaks. The single-tree selection method of regeneration favors the development of shade-tolerant species. When single-tree selection is applied repeatedly to stands containing commercially valuable shade-intolerant species, composition will gradually shift to less-valuable, more-tolerant species. Consequently, the single-tree selection method of regeneration is not recommended for any commercially valuable bottomland hardwood tree species. Group selection, in its strictest application, creates only small openings that usually fail to allow sufficient light to the forest floor for satisfactory establishment and development of shade-intolerant bottomland species. Patch cutting, a combination of uneven-aged (group selection) and even-aged (clearcutting) silviculture, designed to create larger openings, has been successfully used to produce an uneven-aged stand that consists of many small, irregularly shaped, even-aged groups. Silvicultural systems should include a planned program of intermediate operations designed to enhance the growth and development of those species favored during the regeneration process. Improvement cutting and commercial thinning are increasingly common in southern bottomland hardwood forests. Other partial cuttings employed today in bottomland hardwood forests typically involve some form of crop-tree release. Specific recommendations for the selection of silvicultural systems are presented for the eight most important species groups found in southern bottomland hardwood forests.

Keywords: Even-aged regeneration; Uneven-aged regeneration; Partial cuttings; Patch cutting; *Quercus*

1. Introduction

Southern bottomland hardwoods are found on about 13 Mha of forest land in river bottoms, minor stream bottoms and swamps from Virginia to east Texas (McKnight and Johnson, 1980). These ecosystems support a wide diversity of tree species, each of which is unique in terms of its biological requirements, silvical characteristics and pattern of growth over time. Successful management of these diverse ecosystems is necessarily complex. This paper describes the various silvicultural systems and their general utility in southern bottomland hardwood forests, provides general guidelines for a planned program of intermediate silvicultural operations in

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those forests, and discusses silvicultural systems recommended for specific species groups.

Silvicultural systems integrate both regeneration and intermediate operations in an orderly process for managing forest stands (Clatterbuck and Meadows, 1993). Silvicultural practices can be designed for any management objective, such as timber, wildlife, or biological diversity. The key to successful regeneration of most bottomland hardwood species is not the development of some radically new method of harvesting, but recognition that all cutting operations, including partial cuts associated with intermediate silvicultural practices, should have as one of their objectives the creation of environmental conditions favorable for the establishment of desirable reproduction (Hodges, 1989). Although the major objective of intermediate cutting is usually to improve growth and quality of residual trees, cuttings can be designed to simultaneously create suitable conditions for the establishment of advance reproduction of desirable species. Subsequent partial cuttings not only serve to further improve growth and quality of residual trees, but may also nurture the development of previously established advance reproduction. The key to success is to recognize that regeneration and intermediate operations are integral parts of an orderly process to manage forest stands, rather than separate, unrelated activities. All operations conducted over the life of any forest stand should be designed and implemented to follow the direction of the chosen silvicultural system.

Species favored under any silvicultural system can support numerous management objectives. In most southern bottomland hardwood forests, maintaining a viable oak component is very desirable for timber, wildlife and biodiversity values, but presents the greatest difficulty for achieving successful regeneration. However, most forests can be managed without an oak component and still yield multiple benefits. Species suitability for timber production is listed in Table 1, while species tolerance to shade is categorized in Table 2. Similar listings of species suitabilities could be constructed for wildlife habitat or other non-timber objectives.

Silvicultural practices are traditionally divided into two broad categories: even-aged and uneven-aged. The regeneration methods employed under even-aged silviculture include clearcutting, seed-tree and shel-

Table 1
Suitability of common southern bottomland hardwood tree species for timber production

Common name	Scientific name
Preferred species	
Sweet pecan	*Carya illinoensis* (Wangenh.) K. Koch
Green ash	*Fraxinus pennsylvanica* Marsh.
Eastern cottonwood	*Populus deltoides* Bartr. ex Marsh.
White oak	*Quercus alba* L.
Cherrybark oak	*Quercus falcata* var. *pagodifolia* Ell.
Swamp chestnut oak	*Quercus michauxii* Nutt.
Nuttall oak	*Quercus nuttallii* Palmer
Shumard oak	*Quercus shumardii* Buckl.
Other desirable species	
Sugarberry	*Celtis laevigata* Willd.
Common persimmon	*Diospyros uirginiana* L.
Sweetgum	*Liquidambar styraciflua* L.
Yellow-poplar	*Liriodendron tulipifera* L.
Water tupelo	*Nyssa aquatica* L.
Sycamore	*Platanus occidentalis* L.
Water oak	*Quercus nigra* L.
Willow oak	*Quercus phellos* L.
Black willow	*Salix nigra* Marsh.
Baldcypress	*Taxodium distichum* (L.) Rich.
Acceptable species	
Red maple	*Acer rubrum* L.
Bitter pecan	*Carya aquatica* (Michx. f.) Nutt.
Bittemut hickory	*Carya cordiformis* (Wangenh.) K. Koch
Shagbark hickory	*Caryu ovata* (Mill.) K. Koch
Mockemut hickory	*Carya tomentosa* (Poir.) Nutt.
American beech	*Fagus grandifolia* Ehrh.
Waterlocust	*Gleditsia aquatica* Marsh.
Honeylocust	*Gleditsia triacanthos* L.
Southern magnolia	*Magnolia grandiflora* L.
Black tupelo	*Nyssa sylvatica* Marsh.
Laurel oak	*Quercus laurifolia* Michx.
Overcup oak	*Quercus lyrata* Walt.
Winged elm	*Ulmus alata* Michx.
American elm	*Ulmus americana* L.
Cedar elm	*Ulmus crassifolia* Nutt.
Slippery elm	*Ulmus rubra* Muhl.
Undesirable species	
Boxelder	*Acer negundo* L.
River birch	*Betula nigra* L.
American hornbeam	*Carpinus caroliniana* Walt.
Roughleaf dogwood	*Cornus drummondii* C.A. Meyer
Hawthorn	*Crataegus* L. spp.
Swamp-privet	*Forestiera acuminata* (Michx.) Poir.
Carolina ash	*Fraxinus caroliniana* Mill.
Deciduous holly	*Ilex decidua* Walt.
American holly	*Ilex opaca* Ait.
Red mulberry	*Morus rubra* L.
Eastern hophornbeam	*Ostrya uirginiana* (Mill.) K. Koch
Water-elm	*Planera ayuatica* J.F. Gmel.

Table 2
Shade tolerance of common southern bottomland hardwood tree species

Very intolerant	
Yellow-poplar	Black willow
Eastern cottonwood	
Intolerant	
River birch	Sycamore
Carolina ash	Cherrybark oak
Waterlocust	Water oak
Honeylocust	Nuttall oak
Sweetgum	Willow oak
Water tupelo	Shumard oak
Moderately intolerant	
Sweet pecan	Overcup oak
Hawthorn	Swamp chestnut oak
White oak	Baldcypress
Laurel oak	
Moderately tolerant	
Boxelder	Green ash
Bitter pecan	Black tupelo
Bittemut hickory	American elm
Mockemut hickory	Cedar elm
Tolerant	
Red maple	Water-elm
Shagbark hickory	Winged elm
Swamp-privet	Slippery elm
Southern magnolia	
Very tolerant	
American hornbeam	Deciduous holly
Sugarberry	American holly
Roughleaf dogwood	Red mulberry
Common persimmon	Eastern hophombeam
American beech	

Source: Putnam et al. (1960) and Bums and Honkala (1990).

terwood. Single-tree selection and group selection are regeneration methods used under uneven-aged silviculture.

2. Even-aged silvicultural systems

2.1. Clearcutting

The clearcutting method of regeneration, because it provides full sunlight to the forest floor, favors the growth and development of moderately intolerant to intolerant species (see Table 2). In fact, clearcutting is the most proven and widely used method of successfully regenerating bottomland oak species in the South (Clatterbuck and Meadows, 1993). However, successful regeneration of oak through clearcutting is normally contingent upon three important requirements: (1) presence of adequate oak advance reproduction in the stand prior to clearcutting, (2) adequate sprouting potential of stumps from severed oak stems and (3) cutting of all stems, both merchantable and non-merchantable, during the harvest operation.

If large seedlings of oak advance reproduction are not present in the stand at the time of complete harvest, clearcut stands will typically regenerate to shade-intolerant, fast-growing, light-seeded species. New oak seedlings that become established after the harvest commonly cannot compete with faster-growing species, and generally do not develop into the overstory of the new stand. Exceptions to this general rule do occur, but oaks that originate from new seedlings established after harvest generally do not comprise a major proportion of the total oak component in the mature stand.

Sprouts from severed oak stems constitute a second major source of oak reproduction in clearcut stands. Sprouts from severed trees less than 30 cm diameter are an excellent source of regeneration because of their well-established root systems and vigorous growth potential (Janzen and Hodges, 1987; Hodges, 1989). However, sprouting potential declines markedly in trees greater than 30 cm diameter, such that large trees should not be relied upon to contribute significantly to the oak component of the new stand. Severed stems of oak seedlings and saplings present in the stand at the time of harvest will sprout vigorously. Creation of these oak "seedling sprouts" during the harvest operation should be encouraged.

The third requirement for successful oak regeneration through the clearcutting method is that all stems larger than seedlings must be cut or deadened during the harvest operation. This complete removal of stems from the existing stand will provide full sunlight to the forest floor and will enable the oak reproduction to successfully compete in the new stand.

In fact, most oak regeneration failures following clearcutting result from the inability to achieve one or more of these three important requirements. The number of oaks in the new stand is directly related to the number of large, well established oak seedlings present in the stand prior to harvest and to the sprouting potential of severed oak stems (Hodges, 1989; Clatterbuck and Meadows, 1993). Additionally, the presence of residual stems from the previous stand will greatly impair the development of oak reproduction in the new stand.

One of the most important aspects of any regeneration method is to understand how the new stand develops and matures after the regeneration cut is made. In southern bottomland hardwood stands, clearcutting initially favors the growth and development of shade-intolerant, fast-growing, light-seeded species, such as sweetgum and river birch. During the early stages of development, the new stand is dominated by these pioneer species; oaks may be present in the stand, but are few in number and relatively inconspicuous (Meadows, 1994). However, studies on oak stand development have shown that bottomland oaks can eventually outgrow the more numerous and initially dominant sweetgum and form the dominant canopy of the mature stand (Johnson and Krinard, 1976; Johnson and Krinard, 1983; Johnson and Krinard, 1988; Clatterbuck and Hodges, 1988).

In the study reported by Johnson and Krinard (1976, 1983, 1988), two red oak-sweetgum stands in southeastern Arkansas were harvested in the winter of 1956-57, and the growth and development of the new stands were followed over time. Through the first 9 years of development on one of the sites, the new stand was dominated, both in number and size of stems, by sweetgum, river birch and American hornbeam. Densities of the three species were 1166, 1149 and 922 trees ha-‘, respectively. Collectively, these three species accounted for 76% of the stems in the new stand at age 9 years.

However, between the ages of 9 and 29 years, mortality of river birch was very high, and the species essentially dropped out of the stand. By age 29 years, the density of river birch in the upper canopy had declined to only 27 trees ha-’ and 0.8 m^2 ha-’ of basal area. The total number of American hornbeam stems remained high (833 trees ha-‘), but the species lost its early dominance, was relegated to an understory position and accounted for only 0.1 m^2 ha-’ of basal area in dominant or codominant trees. Sweetgum, during the same period of time, maintained both its relatively high density and its dominance within the stand. By age 29 years, the density of sweetgum in the upper canopy was 237 trees ha-’ and 9.0 m^2 ha-’ of basal area, accounting for about 57% of the stems and 53% of the basal area of dominant or codominant trees. However, recent measurements of the stand at age 37 years showed that sweetgum mortality increased significantly and that dominance of the stand by sweetgum declined [1]. The number of dominant or codominant sweetgum stems dropped to 143 trees ha-^{1}, while basal area remained nearly constant at 9.3 m^2 ha-‘.

In contrast, there were only 190 red oaks ha-’ (4% of the total) at age 9 years. Principal red oak species were cherrybark, water and willow oaks. Red oaks were far less numerous than the three initially dominant species and were quite inconspicuous during the early stages of stand development. However, the oaks gradually developed into an increasingly greater component of the stand and by age 29 years there were 79 dominant or codominant red oaks ha-’ which accounted for a basal area of 3.7 m^2 ha-’ in that upper canopy. By age 37 years, the number of red oaks in the upper canopy remained constant at 79 trees ha-‘, but basal area increased to 5.6 m^2 ha-^{1}. Consequently, between the ages of 29 and 37 years, the red oak component of the upper canopy of the stand increased from 19 to 29% of the trees and from 22 to 31% of the basal area, while the sweetgum component decreased during that same time period. These recent measurements indicated that red oak will eventually dominate the stand.

Even though it is apparent that red oaks will eventually dominate this stand, it will have taken many years of slow growth for the oaks to naturally reach this stage of development. It may be possible to hasten this process through some type of precommercial partial cutting. Removal or deadening of

[1] Meadows, James S. and Goelz, J.C. 1993. Unpublished data. On file with: USDA Forest Service, Southern Hardwoods Laboratory, Stoneville, MS.

faster-growing, non-oak species has been shown to release Nuttall oak stems from larger competitors and to increase the relative proportion of Nuttall oaks in the upper crown classes (Meadows, 1993a). However, Johnson and Krinard (1988) reasoned that, because the red oaks were allowed to develop naturally alongside the initially faster-growing sweetgums in the absence of disturbance, the red oaks developed the maximum length and quality of merchantable bole allowed by the productivity of the site. Consequently, precommercial partial cutting in red oak-sweetgum stands prior to the emergence of the oaks as the dominant component of the stand may succeed in increasing the relative proportion of oaks in the upper canopy, but may also effectively reduce the length and quality of the merchantable bole. More research is needed to fully understand the complex nature of natural stand development in red oak-sweetgum stands.

The important lesson to be learned from this research is that bottomland red oaks, even though they may be greatly outnumbered and essentially inconspicuous in young, even-aged stands, can gradually out-compete the initially dominant pioneer species and eventually dominate the mature stand. A thorough understanding of stand development in red oak-sweetgum stands may prevent incorrect, premature assessments of species composition, dominance and regeneration success or failure.

2.2. Seed-tree

The seed-tree method of regeneration favors the establishment of light-seeded species, such as sweetgum and yellow-poplar. However, retention of seed trees to successfully regenerate either sweetgum or yellow-poplar may not be necessary. Most sweetgum regeneration originates as stump sprouts or root suckers, whereas most yellow-poplar regeneration develops from seed stored in the forest floor rather than from freshly fallen seed from residual seed trees. Mechanical soil scarification may be necessary if the desired species requires bare mineral soil for establishment, as for eastern cottonwood and black willow. Retention of seed trees to establish new oak seedlings is unnecessary because most successful oak regeneration develops from advance reproduction or from stump sprouts (Johnson and Krinard, 1976).

2.3. Shelter-wood

The shelterwood method of regeneration can provide for the development of heavy-seeded species, such as oaks and hickories, but may also promote excellent seed dissemination and establishment of many light-seeded species. It has been used to successfully regenerate oak in the southern Appalachian Mountains (Loftis, 1990), but has produced highly variable results when used to regenerate southern bottomland oak species. The shelterwood method is the most flexible of the even-aged regeneration methods, but also the most difficult of these to implement.

One of the keys to the successful use of the shelterwood method to regenerate oak is the intensity of the establishment cutting. Hodges (1989) concluded that heavy establishment cuts actually favor the development of fast-growing, shade-intolerant species rather than the oaks, whereas light cuts may encourage the development of less-desirable, shade-tolerant species commonly present in the midstory and understory of mature bottomland hardwood stands (see Table 2). Designing the intensity of the establishment cutting to favor oaks rather than either of the other two groups of species is a difficult task in southern bottomland hardwood forests. In general, establishment cuttings that retain more than 12 m^2 ha-' of basal area will tend to favor the development of shade-tolerant species. However, more research is needed to adequately define the optimum residual density necessary to successfully regenerate bottomland oak species through the shelterwood method. As a general rule, the intensity of the establishment cutting should be designed to create environmental conditions on the forest floor that are restricted as much as possible to those which are optimum for germination and establishment of the desired species.

As with all regeneration methods, successful implementation of the shelterwood method can be enhanced through carefully planned manipulations in the stand prior to the regeneration stage. Thinnings and other partial cuttings can be designed to not only improve the growth and quality of residual trees, but also to create and maintain environmental conditions on the forest floor favorable for the germination, establishment and continued development of desired species. These partial cuttings can also be designed to control species composition in such a way that seed sources of less-desirable species are reduced as much as feasible. Most partial cuttings, particularly those in older stands, should be performed with future regeneration in mind, such that cuttings are designed to create environmental conditions favorable for regeneration of desirable species and unfavorable for regeneration of undesirable species. In this way, partial cuttings performed late in the rotation should prepare the stand for regeneration and render the need for a separate preparatory cutting unnecessary.

Establishment cuttings should be designed to create environmental conditions favorable for the establishment of desired reproduction and to promote the continued development of previously established reproduction of desired species. Trees removed in the establishment cutting should be the least desirable in the stand, and should include trees of undesirable species as well as trees of desirable species that are of poor vigor, form or quality. As a result, the trees retained after the establishment cutting will not only be of the species desired to provide seed for the establishment of advance reproduction, but will also be of sufficient vigor and quality to experience increased growth and value in response to the increased growing space afforded by the establishment cutting.

In most hardwood species, any type of partial cutting may lead to the production of epicormic branches along the boles of residual trees. Although epicormic branching may be a potential problem associated with the shelterwood method in hardwoods, retention of predominantly high-vigor trees following the establishment cutting should minimize the detrimental effects of epicorrnic branching on stand quality, particularly if those residual trees are removed in the final harvest within a few years. Final removal of the overwood will release the established advance reproduction and allow it to develop into the next stand.

Several variations and modifications of the classical shelterwood method have been attempted in southern bottomland hardwood stands, with mixed success. One necessary modification is to supplement partial overstory removal with control of the midstory and understory prior to final harvest (Hodges and Janzen, 1987; Janzen and Hodges, 1987). Most southern bottomland hardwood stands have such dense, well-developed midstories and understories of shade-tolerant species that cutting in the overstory alone is insufficient to provide enough sunlight to the forest floor to promote the development of an adequate crop of oak advance reproduction prior to final harvest. Consequently, control of undesirable species in the midstory and understory, usually by chemical means, is essential for successful application of the shelterwood method to regenerate red oaks in southern bottomland hardwood forests.

3. Uneven-aged silvicultural systems

3.1. Single-tree selection

In the single-tree selection method of regeneration, single mature trees are removed from throughout the stand at regular, periodic intervals to create or maintain uneven-aged stands. Depending upon the size of the individual tree removed, openings created through single-tree selection in southern bottomland hardwood stands could range in size from 0.02 to 0.08 ha. Because these openings are small and do not allow much sunlight to the forest floor, the single-tree selection method of regeneration favors the development of shade-tolerant species. However, there are few commercially valuable, shade-tolerant species in southern bottomland hardwood forests (see Tables 1 and 2). In fact, when single-tree selection is applied repeatedly in stands containing commercially valuable shade-intolerant species, such as most bottomland oaks, composition will gradually shift to less-valuable, more-tolerant species, such as sugarberry, boxelder, elms, maples and hickories (Johnson and Krinard, 1989).

The small openings created by the removal of single trees in red oak-sweetgum stands may provide sufficient light to allow the establishment of new oak seedlings, but, because most bottomland red oaks are at least moderately intolerant to shade, the light is not sufficient to allow the oak seedling to eventually develop into an overstory tree. Rather, the small opening will eventually be filled by a tree of a more tolerant species. In general, red oaks need at least 2-3 h/day of direct overhead sunlight to survive and grow, but more than that to grow well enough to develop into overstory trees (Johnson and Krinard, 1989). Consequently, the single-tree selection method of regeneration is not recommended for bottomland oaks (McKnight, 1966; Toliver and Jackson, 1989; Clatterbuck and Meadows, 1993).

3.2. Group selection

In the group selection method of regeneration, small groups of mature trees are removed from throughout the stand at regular, periodic intervals to create or maintain uneven-aged stands. As a general rule, the diameter of group selection openings is limited to a distance no greater than the equivalent of twice the height of the mature trees in the stand. In most mature southern bottomland hardwood forests, the maximum opening size allowed for group selection cuts would then be limited to a diameter of approximately 70-75 m. Depending upon its shape, the largest group selection opening would occupy an area of approximately 0.40–0.55 ha. In this strict application of the group selection method, the small openings created usually fail to allow sufficient light to reach the forest floor for satisfactory establishment and development of shade-intolerant species, such as most bottomland oaks (Clatterbuck and Meadows, 1993). In openings of this size, light conditions on the forest floor in the center of the opening would likely satisfy the ecological requirements for successful establishment of all but the most shade-intolerant species. However, the suitability of light conditions for intolerant species declines with increasing distance from the center of the opening, such that occupancy of the opening by intolerant species is limited to a small area at or near the center. Consequently, in southern bottomland hardwood forests, the group selection method, as described, generally results in stands dominated by low-value, shade-tolerant species.

Patch cutting, a combination of uneven-aged (group selection) and even-aged (clearcutting) silviculture, designed to create larger openings of up to 1-2 ha, has been successfully used by many forest managers to produce an uneven-aged stand that consists of many small, irregularly shaped, even-aged groups (Marquis, 1989). Expressed another way, patch cutting allows for the even-aged development of small groups within an uneven-aged forest matrix. It combines the biological advantages of clearcutting, by creating larger openings, with the aesthetic, wildlife and market advantages of group selection, by always retaining a substantial number of large trees in the stand. Consequently, patch cutting, though difficult to implement, is becoming increasingly common in bottomland hardwood forests across the South.

The key to the successful use of patch cutting is to match the size of the opening to the reproductive requirements of the desired species to be regenerated, and then to cut all stems within the selected opening. More specifically, the opening should be large enough to allow adequate sunlight to the forest floor to nurture the development of desired seedlings. The opening must also be large enough to provide sufficient sunlight to promote the eventual development of those seedlings into overstory trees. To successfully regenerate Nuttall oak through the patch cutting technique, Johnson and Krinard (1989) recommended openings of at least 90 m in diameter. Openings smaller than that would not provide enough sunlight to Nuttall oak seedlings to allow them to develop into overstory trees, and would eventually become dominated by more shade-tolerant species. Although patch cutting is a complicated and intensive approach to forest management, it can, if applied properly, produce the biological conditions necessary for the successful establishment and development of bottomland oak reproduction (Clatterbuck and Meadows, 1993).

4. Intermediate operations

Silvicultural systems should include a planned program of intermediate operations, such as improvement cutting, thinning and other partial cuttings, designed to enhance the growth and development of those species favored during the regeneration process. A secondary, but equally important, objective of many intermediate silvicultural operations, particularly those conducted late in the rotation, should be to create environmental conditions favorable for the establishment and development of advance reproduction of desirable species.

Most intermediate cutting operations allow additional light to reach the forest floor, which will promote the establishment of advance reproduction of various species. If adequate seed sources are available, the amount of sunlight reaching the forest floor determines the species composition of the advance reproduction, i.e. the relative proportions of shade-tolerant and shade-intolerant species. However, if a dense understory is present, as commonly occurs in southern bottomland hardwood forests, cutting in the main canopy alone may be insufficient to provide adequate sunlight to the forest floor to promote the establishment and development of advance reproduction of shade-intolerant species, such as most bottomland oaks. Minor modifications may be necessary to fulfil the secondary objective of the intermediate cutting operation. For example, to provide light conditions on the forest floor favorable for oak advance reproduction, it may be necessary, in conjunction with partial cutting in the main canopy, to control understory stems that may interfere with oak establishment and growth. Once advance reproduction of desired species is established, partial cuttings should be conducted frequently enough to maintain the growth of that reproduction. In this way, partial cuttings, along with any necessary modifications, can be used to adequately prepare the existing stand for future regeneration to desired species.

Improvement cuttings are generally applied to previously unmanaged bottomland hardwood stands to remove low-value, overmature, damaged, or cull trees and trees of undesirable species. The objective is to improve both species composition and quality of individual trees in the residual stand. Improvement cuttings in bottomland hardwoods typically involve both harvesting of merchantable material and the use of herbicides to deaden unmerchantable trees, and may or may not result in immediate financial gain. Putnam et al. (1960) recommended improvement cutting as the first step in bringing a previously unmanaged bottomland hardwood stand into active management.

Commercial thinning is an increasingly common tool in the management of southern bottomland hardwood forests, particularly since the development of a strong hardwood pulpwood market in many areas of the South. Johnson (1981) presented some general guidelines for thinning in bottomland hardwood stands: (1) begin thinning early in the life of the stand; (2) favor the largest trees with well-developed crowns; (3) thin from below whenever possible to remove trees with inferior crowns; (4) use frequent, light thinnings instead of infrequent, heavy thinnings and (5) avoid excessive logging damage to residual trees. Marking should favor the best trees and discriminate against the worst, generally resulting in a low thinning. Most of the material removed will be pulpwood, especially during the first thinning. During subsequent thinnings, low-to-medium quality sawtimber will constitute an increasingly greater proportion of the material removed.

Other partial cuttings employed today in bottomland hardwood forests typically involve some form of crop-tree release, in which individual crop trees are selected early in the life of the stand and are periodically released from competition to promote maximum growth and quality development in those trees. Crop-tree release has been used to successfully manage stands of northern hardwoods (Smith and Lamson, 1983; Stringer et al., 1988; Lamson et al., 1990; Voorhis, 1990), but has only recently received serious attention in southern hardwood forests.

Two serious drawbacks associated with any partial cutting, especially in hardwood stands, are the possible production of epicormic branches on the boles of residual stems and excessive logging damage to boles and/or roots of residual trees. Because of their effects on bole quality, both of these events may lead to a significant loss in value of the residual stand.

Epicormic branches are frequent contributors to log grade reduction in partially cut hardwood stands. In the past, many foresters believed that epicormic branches developed on residual trees following partial cutting primarily in response to increased sunlight on the bole. But, much evidence has shown that tree vigor plays a major role in determining the propensity of an individual to produce epicormic branches (Wahlenberg, 1950; Skilling, 1957; Erdmann et al., 1985; Meadows, 1993b). Individual-tree vigor apparently acts as the primary controlling mechanism for the production of epicormic branches, while sudden exposure to sunlight, or some other type of disturbance, serves as the primary triggering mechanism for the release of those suppressed buds that eventually develop into epicormic branches (Brown and Kormanik, 1970). The interaction of these two factors, individual-tree vigor and sudden exposure to sunlight, control and trigger the phenomenon of epicormic branching. To minimize the production of epicormic branches on residual trees, any partial cutting in hardwood stands should be designed to favor only trees of medium-to-high vigor, and to remove trees of low vigor. Crown size and shape, as well as foliar density within the crown, are excellent indicators of tree vigor. High-vigor hardwood trees generally have wide, deep, well-shaped crowns with dense foliage and little evidence of crown deterioration or dieback. Bark characteristics may also be used to indicate tree vigor, but these vary by species and are more indicative of past health rather than current condition. Frequent, light thinnings, as opposed to infrequent, heavy thinnings, will also minimize the production of epicormic branches on residual trees.

Partial cutting may also result in several types of logging damage to residual trees. Logging wounds that expose living sapwood may lead to eventual decay and/or discoloration of the wood in the tree. These types of damage not only result in loss of both log grade and log volume, they may also eventually lead to death of the tree. Meadows (1993b) surveyed logging damage following partial cutting (low thinning) in a green ash-sugarberry stand in the Mississippi Delta. The thinning removed about 40% of the trees and 25% of the basal area, for a residual density of 232 trees ha-' with 26 m^2 ha-' of basal area. The thinning also increased the relative proportion of green ash and decreased the relative proportions of sugarberry and other less-valuable species. The logging operation caused widespread damage to the residual stand, with about 62% of the residual trees being damaged at least to some extent. Damage to the lower bole and to exposed lateral roots, both of which occurred primarily during the skidding operation, were the two most common types of injury. Meadows (1993b) emphasized, however, that the damage observed in this stand was more widespread than necessary or expected, and concluded that logging damage to residual trees can be minimized if the logging operation is carefully and properly planned, implemented, and controlled.

5. Recommended silvicultural systems for important species groups

In choosing an appropriate silvicultural system, one of the greatest challenges is simultaneously managing for apparently incompatible objectives. For example, many area-sensitive neotropical migratory birds seem to require the maintenance of a continuous forest canopy for their survival. However, successful regeneration of commercially valuable timber species, such as red oaks, requires harvest openings of a size that may be detrimental to the continued survival of these birds. More research is needed to evaluate various silvicultural alternatives that may allow successful cooperative management for these two seemingly incompatible objectives.

Recommended silvicultural systems for the eight most important species groups found in southern bottomland hardwood forests are presented in Table 3.

5.1. Cottonwood

Eastern cottonwood is a very shade-intolerant pioneer species that occurs on “new land” along rivers and streams. Putnam et al. (1960) defined “new land” as an area of newly created land along a river, formed by gradual accretion of sediments from further upstream. Because of its extreme intolerance to shade, cottonwood does not succeed itself naturally. Sunlight that filters through a cottonwood canopy to the forest floor permits invasion of the site by other species, principally sycamore, sweet pecan, green ash, boxelder, sugarberry and sweetgum (Johnson, 1981). Single-tree selection in these stands will favor the more tolerant sugarberry and boxelder. Even-aged regeneration methods that provide ample sunlight to the forest floor will favor sycamore, pecan, ash and boxelder. The only way to regenerate cottonwood naturally is to use mechanical scarification to expose bare mineral soil, in conjunction with either a seed-tree cut or a clearcut (Johnson, 1965).

5.2. Black willow

Black willow is very similar to cottonwood, in that it is a very intolerant pioneer species, but it is

Table 3
Expected regeneration under different silvicultural systems for eight important southern bottomland hardwood species associations

Species association	Silvicultural system	Species usually favored
Cottonwood	Seed tree with site preparation	Cottonwood
	Clearcut	Sycamore, sweet pecan, green ash, boxelder
Black willow	Seed tree with site preparation	Black willow
	Clearcut	Sugarberry, green ash, baldcypress, American elm, overcup oak, bitter pecan, Nuttall oak
Cypress-water tupelo	Group selection	Baldcypress, water tupelo, and sometimes green ash, overcup oak. bitter pecan
	Clearcut	Baldcypress, water tupelo, and sometimes green ash, overcup oak, bitter pecan, or elm and maple
Elm-sycamore-pecan-sugarberry	Group selection	Sweetgum, red oaks, sycamore, sweet pecan, sugarberry, green ash
	Clearcut	Same as above
Elm-ash-sugarbeny	Clearcut	Elm, green ash, sugarberry, Nuttall oak, willow oak
	Group selection	Same as above
Sweetgum-red oak	Group selection	Sweetgum, red oaks, green ash
	Clearcut	Heavy to sweetgum, but also red oaks, green ash
	Shelterwood	Red oaks, sweetgum, green ash
Red oak-white oak-mixed species	Shelterwood	Red oaks, white oaks, hickory, green ash, sweetgum, American hornbeam
	Group selection	Same as above
Overcup oak-bitter pecan	Group selection	Overcup oak, bitter pecan
	Shelterwood	Overcup oak, bitter pecan, Nuttall oak, green ash

Source: Johnson (1981) and Kennedy and Johnson (1984).

usually limited to the fine-textured soils on "new land." Black willow also does not succeed itself naturally. Because willow occurs on wetter and more fine-textured sites than does cottonwood, the mixture of species found beneath a willow canopy is somewhat different from that found under cottonwood. The understory beneath black willow typically consists of sugarberry and green ash, but possibly with some baldcypress, American elm, overcup oak, bitter pecan and Nuttall oak. Any even-aged silvicultural system in black willow stands will tend to favor the development of these species. Although less is known about regeneration of black willow, Johnson (1981) speculated that mechanical soil scarification in conjunction with either a seed-tree cut or a clearcut would probably successfully regenerate the stand to black willow.

5.3. Cypress-water tupelo

Baldcypress and water tupelo normally occur together in true swamps, areas that are more or less permanently inundated. Because other species cannot tolerate the semi-permanently flooded conditions, any regeneration method usually results in the perpetuation of the cypress-tupelo association (Johnson, 1981). The biggest problem is the possibility of no reproduction of commercial species at all following a harvest operation. Because cypress-tupelo stands are extremely dense with little or no sunlight reaching the forest floor, advance reproduction is usually sparse. This problem is further complicated because new seedlings cannot become established in standing water. Sprouting from stumps of both baldcypress and water tupelo is erratic and unreliable (Kennedy, 1982). Because of the difficulty in establishing new seedlings on these flooded sites, it appears that a dry cycle of several years is required for widespread establishment and development of adequate advance reproduction of commercial species (Johnson, 198 1). If the stand is very dense, a light thinning to reduce basal area to about 30-35 m^2 ha-' may be necessary during a dry cycle to allow sufficient sunlight to the forest floor to encourage establishment and development of advance reproduction. Once established seedlings attain a height greater than the depth of normal flooding, a regeneration harvest operation should be scheduled to take full advantage of the advance reproduction.

5.4. Elm-sycamore-pecan-sugarberry

The elm-sycamore-pecan-sugarberry species association typically occurs on river-front sites-fronts and high ridges within the bottomland (Hodges, 1997). These relatively drier sites are very productive and usually support a wide diversity of species. In general, these mixed-species stands will regenerate to the same species found in the overstory, regardless of the regeneration method used (Johnson and Shropshire, 1983). The proportions of each species will vary with the amount of sunlight provided to the forest floor. Consequently, single-tree selection and small group selection cuts will tend to increase the proportion of more shade-tolerant species in the new stand, such as elm and sugarberry, whereas seed-tree cuts and clearcuts will tend to increase the proportion of shade-intolerant species, such as red oaks and pecan, if adequate advance reproduction of these species is present. In most cases, however, differences in the relative proportions of individual species will be slight.

5.5. Elm-ash-sugarberry

The elm-ash-sugarberry species association commonly occurs on wide flats within a bottomland. As such, it is one of the most common and widespread species associations in southern bottomland hardwood forests. Species diversity is not as great as in the elm-sycamore-pecan-sugarberry association because the sites are generally wetter, less productive, and, therefore, support a narrower range of species. However, regeneration guidelines are similar. Any of the regeneration methods will produce a new stand composed of essentially the same species found in the overstory of the previous stand; only the relative proportions of individual species will change depending upon the amount of sunlight provided to the forest floor (Johnson and Shropshire, 1983).

5.6. Sweetgum-red oak

The sweetgum-red oak species association occurs on ridge sites within major river bottoms and on the higher sites within minor streambottoms. These commercially important sites are very productive and yield much of the high-quality oak sawtimber grown in southern bottomland hardwood forests. Successful regeneration of these stands to red oak is difficult and not always predictable. Because most bottomland red oaks are at least moderately intolerant to shade, the single-tree selection method of regeneration is not recommended. Strict application of the group selection method, with openings generally less than 0.40-0.55 ha, is also not recommended to regenerate these stands to red oak. Perpetuation of the sweetgum-red oak type can be achieved, however, through the clearcutting and shelterwood methods, as well as through the patch cutting modification of the group selection method, in which openings are generally up to about l-2 ha. As discussed previously, however, the shelterwood method is difficult to implement successfully and yields erratic results in bottomland oak stands. Successful implementation of the shelterwood method in southern bottomland oak stands probably requires effective control of midstory and understory plants.

Clatterbuck and Meadows (1993) offered four guidelines to maintain an acceptable component of red oak when regenerating sweetgum-red oak stands.

1. Secure adequate oak advance reproduction prior to final harvest: The key to securing adequate oak advance reproduction is to create, prior to final harvest, light conditions on the forest floor favorable for the establishment and development of

new oak seedlings. To regulate the amount of light reaching the forest floor, it may be necessary to manipulate the overstory and/or the midstory and understory. The adequacy of oak advance reproduction must be assessed in terms of both size and number of stems. Johnson and Deen (1993) developed a field technique to evaluate oak regeneration potential in southern bottomland hardwood forests. The technique is based on the number and size of oak advance reproduction and on stump and seedling sprout potential, and is currently being tested under operational conditions.

2. Create an opening large enough to maintain light conditions on the forest floor that are favorable for the continued development of oak reproduction: Regeneration openings should provide enough light to the forest floor to sustain oak reproduction in a free-to-grow position. Johnson and Krinard (1989) suggested openings of at least 90 m in diameter to successfully regenerate Nuttall oak. Smaller openings favor the development of more shade-tolerant species rather than the oaks. More research is needed to determine minimum opening sizes necessary to successfully regenerate the various bottomland red oak species.
3. Control shade-tolerant competition in the midstory and understory prior to final harvest: A dense midstory or understory beneath a maturing sweetgum-red oak stand may interfere with or prevent satisfactory establishment and development of oak advance reproduction. To provide favorable light conditions to the forest floor and, thus, to promote the development of adequate oak advance reproduction, it may be necessary to control this dense competition in the midstory and understory. Undesirable stems in these lower strata may be controlled through the use of herbicides or, possibly, through the use of prescribed fire. Frequent fires apparently played an historical role in allowing oak reproduction to develop in the understory of mature stands at the expense of shade-tolerant, fire-intolerant species (Van Lear and Watt, 1993). Prescribed fire may be an effective silvicultural alternative for the control of dense, shade-tolerant competition in the midstory and understory of sweetgum-red oak stands, and may, therefore, contribute significantly to the establishment and development of adequate oak advance reproduction prior to final harvest.
4. Sever all stems within the regeneration area during the final harvest operation: To promote satisfactory growth of both oak advance reproduction and stump sprouts from severed oak stems, it is important to sever all stems larger than seedlings within the regeneration area during the final harvest operation. Unmerchantable stems not removed at the time of final harvest will interfere with the future development of oak regeneration, which may lead to a reduction in the oak component of the new stand.

5.7. Red oak-white oak-mixed species

The red oak-white oak-mixed species association occurs on ridges within older, infrequently flooded bottomlands. This association represents a later sere within the succession of southern bottomland hardwood forests. Hickories, rather than sweetgum, represent the largest non-oak component in these stands. Red oak species generally include cherrybark, Shumard, water, willow and Nuttall oaks. White oak species are white and swamp chestnut oaks. Many of the recommendations given for maintenance of an adequate oak component when regenerating sweetgum-red oak stands also apply for regeneration of red oak-white oak-mixed species stands (Johnson and Shropshire, 1983; Clatterbuck and Meadows, 1993).

5.8. Overcup oak-bitter pecan

The overcup oak-bitter pecan species association generally occurs only on low flats or in sloughs within southern bottomlands. These wet sites are not very productive and support only a few species that can tolerate the harsh conditions. Because species diversity is low, any of the regeneration methods will likely perpetuate the overcup oak-bitter pecan association. During dry cycles, green ash, sugarberry and Nuttall oak will likely invade the site, but will not persist or grow well unless drainage of the area is improved. Clearcutting, shelterwood and patch cutting are the recommended methods to maintain a high component of overcup oak (Johnson, 1981). Because overcup oak is moderately intolerant of shade, it cannot be regenerated successfully through single-tree selection.

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