STAND DEVELOPMENT PATTERNS IN SOUTHERN BOTTOMLAND HARDWOODS: MANAGEMENT CONSIDERATIONS AND RESEARCH NEEDS

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Abstract: Stand development involves changes in stand structure over time. Knowledge of stand development patterns is crucial for effective forest management, especially of southern bottomland hardwood forests. These forests contain more than 70 tree species, many of which have commercial timber and wildlife habitat value. In this paper, current techniques in stand development research are reviewed. Emphasis is placed on stand development studies in bottomland red oaks (*Quercus* spp.), especially cherrybark oak (*Q. pagoda*), although examples from other oak forest types are included. These studies were divided into 3 broad categories: pure, single-cohort stands; mixed, single-cohort stands; and mixed, multi-cohort stands. Management implications based on these development patterns are discussed, including the importance of many of the non- or less-commercial species during stand development. Areas for future research also are suggested to increase the knowledge base on bottomland hardwood stand development.

Key Words: bottomland hardwoods, cherrybark oak, chronosequence, reconstruction, stand development.

Stand development involves changes in stand structure over time (Oliver and Larson 1996). These changes occur in a horizontal sense, or distribution of trees by species and diameter, and in a vertical sense, or distribution of tree heights, within a stand (Kittredge 1986). An understanding of how bottomland hardwood stands develop is essential for long-term management of these forests for their various functions (including wildlife habitat and nutrient retention) and values (including water quality maintenance, recreational opportunities, and wood production capabilities). The objectives of this paper are to: (1) provide an overview of basic stand development research techniques, (2) provide a synopsis of bottomland hardwood stand development research and applicable upland hardwood stand development research, (3) relate these stand development patterns to possible silvicultural practices for both quality sawlog production and wildlife habitat, and (4) develop a list of research priorities for increasing our knowledge of bottomland hardwood stand development and summarize the current status of ongoing stand development research.

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STAND DEVELOPMENT RESEARCH TECHNIQUES

An understanding of stand development patterns, management implications, and possible research opportunities requires a knowledge of basic stand development research techniques. Oliver (1982) listed 5 techniques used in stand development research: chronosequence, reconstruction, permanent plots, observation of tree physiological characteristics, and observation of existing stand physiognomy. Three of these techniques are pertinent to this paper to understand results from the stand development studies presented in the next section.

Chronosequence

A chronosequence consists of a series of stands of different ages, but on similar sites, that are assumed to have been similar in species composition and structure at a given age (Clatterbuck and Hodges 1988). Such stands can be used to represent different ages of the same stand development pattern (Oliver 1982). Advantages of using a chronosequence include the ability to move forward and backward along a time/stand development gradient. This technique also allows the study of stand development patterns over a relatively short period of time. However, it is difficult to locate stands growing on similar sites with similar disturbance histories, species compositions, and spatial distribution and age distribution patterns (Oliver 1982). The need for homogeneous sites is especially important for stands growing on floodplains of meandering streams and rivers given the heterogenous nature of the landscape (Putnam et al. 1960, Hodges and Switzer 1979).

Reconstruction

Stand reconstruction, or stem analysis, involves tracing the growth of individual trees backward in time. This is usually accomplished by aging and measuring growth of increment cores and/or stem cross-sections cut at intervals from felled trees. Advantages of this method include the ability to study stands which are currently in a desirable form (Oliver 1982). Reconstruction, though labor intensive, also requires only a small sample size to effectively determine development patterns. A drawback of this method though is the inability to detect the presence of species and individual trees that have disappeared during stand development up to the time of sampling. Reconstruction also requires destructive sampling; therefore, development of individual trees cannot be followed into the future. Safety considerations in operating a chainsaw and felling trees also must be considered.

Permanent Plots

The permanent plot technique consists of establishing plots for the purpose of re-measuring desired tree and stand characteristics over time. Permanent plots are the most accurate technique available for studying stand development patterns. This accuracy is due to having baseline data containing reliable trends of developmental patterns. Advantages include: (1) direct measurement of changes in tree and stand development, rather than inferring changes that could be attributed to differences in site, disturbance, or species composition; (2) precise documentation of mortality; and (3) easy recording of tree growth without the need for destructive sampling (Oliver 1982). Disadvantages include the length of time (usually several decades) and expense required before useful information on stand development patterns can be obtained. Furthermore, such a long-term project will be subject to administration and measurement by different people, thus possibly introducing biases, especially in height measurements.

In summary, the chronosequence, reconstruction, and permanent plot techniques each provide valuable information in trying to decipher stand development patterns. Because each of these techniques has its own advantages and disadvantages, stand development studies usually involve various combinations and refinements of these techniques along with stand-history information to gain more insight into changes in stand structure.

STUDIES OF BOTTOMLAND HARDWOOD STAND DEVELOPMENT

Few studies have been conducted on bottomland hardwood stand development, focusing primarily on red oak species. Research into bottomland hardwood stand development patterns can be divided into 3 categories: (1) pure, single-cohort stands, (2) mixed, single-cohort stands, and (3) mixed, multi-cohort stands.

Pure, Single-Cohort Stands

Pure, single-cohort stands (even-aged stands composed of 1 species) are relatively rare in bottomland hardwood forests. Specific examples include cottonwood (*Populus deltoides*) or black willow (*Salix nigra*) stands on newly formed land near major river systems (Hodges and Switzer 1979), baldcypress (*Taxodium distichum*) or water tupelo (*Nyssa aquatica*) growing in sloughs and swamps (Hodges and Switzer 1979), and relatively pure red oak stands (pure in the sense of a single genus) that grow on poor-quality flats or follow specific disturbances including fire, grazing, and/or mowing (Aust et al. 1985).

Johnson and Burkhardt (1976) used the chronosequence technique to observe that natural cottonwood stands initially establish in large numbers, e.g., thousands of stems per acre. At such densities, stagnation of the stand would seem likely. But Johnson and Burkhardt (1976) indicated that individual cottonwood trees express dominance by age 3 or even earlier. Dominant cottonwoods quickly overtop neighboring cottonwood trees resulting in a stratified stand rather than a stagnated stand. Stratification through early intra-specific competition (competition within a species) was due to the large genetic diversity among cottonwood trees (Johnson and Burkhardt 1976). This development pattern resulted in more desirable trees for quality sawlog production than that associated with pure cottonwood plantations.

The occurrence of single-genus, single-cohort stands of bottomland red oak is believed to be the result of fortuitous events early in the life of the stand, such as fire, grazing, and/or mowing that eliminated competing species (Aust et al. 1985). While pure stands of water oak (*Q. nigra*) and willow oak (*Q. phellos*) can be found on poorly-drained flats (often called pin-oak flats), pure stands of cherrybark oak occur much less frequently. Studies of how such stands develop provide useful insight into how bottomland red oaks interact when confronted with intra-specific (or intra-genus) competition throughout their life. At present, only 1 study has been conducted on stand development in natural single genus stands of bottomland red oaks.

Aust (1985) used the chronosequence technique to identify factors important in determining stand structure in relatively pure red oak stands. Stratification in these pure stands differed from that of mixed-genus, single-cohort stands. In single-genus, natural red oak stands, increased intra-specific (or intra-genus) competition among oaks may result in individual trees growing taller with lower live-crown percentages as compared to oaks from mixed stands. Such a development pattern is common in cottonwood (Johnson and Burkhardt 1976) and loblolly pine (*Pinus taeda*) (Guldin and Fitzpatrick 1991) stands. These conditions could lead to increased lengths of branch-free boles through continual natural pruning by neighboring oak stems as with pure cottonwood stands. Kittredge (1986) found that the height to the base of the main fork in individual red oaks was positively related to the amount of northern red oak present in pre-stratified, mixed stands, which suggests that intra-specific competition early in a stand's development produced longer merchantable bole lengths. But similar results were not found by Aust (1985) in pure bottomland red oak stands under either narrow or wide spacing between oak stems. Furthermore, early intra-specific competition between bottomland red oaks may increase stress within individual oaks, possibly increasing the probability of epicormic branching and lowering of bole quality (Meadows 1995). Early intra-specific competition may also reduce crown area with a possible decrease in mast production.

Mixed, Single-Cohort Stands

Mixed, single-cohort stands (even-aged stands composed of 2 or more tree species or genera) are common in bottomland hardwood forests. Development of such stands typically results in stratified mixtures with each crown stratum being occupied by a different species or genus usually of different shade tolerances (Oliver and Larson 1996).

Clatterbuck and Hodges (1988) used a combination of the chronosequence and reconstruction techniques in mixed cherrybark oak-sweetgum (*Liquidambar styraciflua*) stands growing on old-field bottomland sites. Their results identified 3 patterns of cherrybark oak development depending upon the average spacing between a cherrybark oak and adjacent sweetgum during the pole stage of development. The patterns were "restricted," "unrestricted," and "overtopped."

In the restricted pattern of development, spacing between a cherrybark oak and neighboring sweetgum was approximately 6-18 feet (2-5.4 m). This spacing resulted in cherrybark oak being initially shorter than sweetgum. Then, 20-23 years after stand initiation, cherrybark oak overtopped sweetgum and emerged into the canopy overstory. Cherrybark oak emergence was the result of a decrease in the rate of sweetgum height growth along with an increase in the rate of cherrybark oak height growth. Clatterbuck (1985) suggested several reasons for this:

(1) Crown architecture. Sweetgum exhibits a narrow, excurrent crown form while cherrybark oak exhibits a semi-excurrent crown form when competing with sweetgum but changes to a decurrent, spreading, form after emergence into the overstory. The narrow crowns of sweetgum allow direct sunlight to reach cherrybark oak trees that may be 3-6 feet (1-2 m) shorter in height. This gives cherrybark oak trees the opportunity to reach the overstory with the sweetgum.

(2) Crown abrasion. Sweetgum twigs are thinner and more brittle at a given age as compared to cherrybark oak twigs; thus, during wind events (especially squall lines associated with frontal storms), terminal buds and twigs of sweetgum tend to break when scraped against twigs of neighboring cherrybark oak stems.

(3) High initial sweetgum density. A high initial sweetgum density may delay intra-specific (within species) crown differentiation, thus leading to stagnation of the sweetgum (Johnson 1968).

(4) Phenology. Bud break in cherrybark oak, though occurring several days later than in adjacent sweetgum, occurs basipetally from the top of the crown while bud break in sweetgum occurs acropetally beginning at the base of the crown (Young 1980). Early growth of cherrybark oak twigs at the top of the crown may give cherrybark oak a competitive advantage when competing with sweetgum, especially during events leading to crown abrasion.

In the unrestricted pattern of development, spacing between a cherrybark oak and neighboring sweetgum was greater than 18 feet (5.4 m) or the cherrybark oak was several years older than the sweetgum. Cherrybark oak, growing in these conditions, was essentially free-to-grow and thus experienced little crown competition from sweetgum following stand initiation. This condition is depicted in the height growth patterns in which cherrybark oak is always taller than adjacent sweetgum.

In the overtopped pattern of development, spacing between a central cherrybark oak and neighboring sweetgum was less than 6 feet (2 m). Under these conditions cherrybark oak stems were subordinate to adjacent sweetgum and stood little chance for survival (Clatterbuck 1985).

We speculate that a comparison of the restricted and unrestricted patterns would show that the distance of neighboring sweetgum, i.e., the amount of inter-specific (between species) competition, affects the carbon allocation patterns of cherrybark oak. With relatively small distances to neighboring sweetgum, more photosynthates would be allocated to height growth as the oak tree competed for dominance; a survival mechanism. After emergence, or stratification, cherrybark oak height growth rate would slow but crown and basal area, or diameter, growth would increase. This change reflects the spreading habit of emergent oak crowns which increases leaf area, thus leading to greater photosynthate production.

The spreading habit of oak crowns following stratification has been noted by Kittredge (1988). This study, involving mixed stands of northern red oak, black birch (*Betula lenta*), and red maple (*Acer rubrum*), combined the reconstruction and chronosequence techniques. Stands chosen were approximately 40-60 years of age, a time in which northern red oak had recently stratified above birch and maple. Stands differed primarily in the density of oak present in the overstory. Because cherrybark oak and northern red oak may have similar patterns of development (Hodges and Janzen 1987), this study may shed light on bottomland red oak development as well.

Kittredge (1988) found that the number of trees, primarily black birch, red maple, and red oaks, within a 32.8-foot (10 m) radius of a northern red oak tree did not have a negative impact on 5-year basal area growth. On the other hand, the amount of oak basal area and number of oak trees within the same 32.8-foot (10 m) radius had a significantly negative effect on the northern red oak tree basal area growth. Total basal area also had a negative effect on central oak basal area growth but to a lesser extent than neighboring oak basal area. The major reason for this growth reduction involved intra-specific competition between oak crowns in the upper canopy following stratification. Crown expansion and subsequent basal area growth of individual oaks was greater in the presence of few oak competitors rather than many, a result of decreased intra-specific competition for growing space in the upper canopy. Kittredge (1986) suggested that this effect was due to: (1) wider crowns (lower oak density) have a greater surface area and are thus exposed to a higher quantity and quality of sunlight; (2) increased crown surface area in full sunlight produced a higher sun: shade foliage ratio and thus increased photosynthate production, and; (3) smaller crowns (higher oak density) have an increased incidence of crown abrasion with stout twigs of neighboring oaks and possibly within individual crowns itself. Therefore, an individual oak will allocate more photosynthate defensively to branch thickening at the expense of bole thickening.

Clatterbuck and Hodges (1988), Kittredge (1988), and Oliver (1976) demonstrated the phenomenon of oak stratification in mixed stands through the chronosequence and reconstruction techniques. But only 1 study has given unequivocal evidence to bottomland red oak stratification through use of the permanent plot technique.

Johnson and Krinard (1988) found that 28 years after stand initiation, bottomland red oak species (cherrybark, water, and willow oaks) began to emerge above sweetgum. They stated this situation was hardly predictable after 9 years when the overstory was composed primarily of sweetgum, river birch (*Betula nigra*), and American hornbeam (*Carpinus caroliniana*). During normal stand development, the river birch began to die due to increasing competition while the American hornbeam was relegated to an understory position. The authors postulated that red oak would exceed sweetgum in height within 30-35 years after stand initiation. The difference in time of stratification between this study and Clatterbuck and Hodges' (1988) study was probably due to the cutover sites utilized by Johnson and Krinard (1976, 1983, 1988) compared to the old-field sites utilized by Clatterbuck and Hodges. Similar results were reported by Bowling and Kellison (1983) in mixed stands of water oak, sweetgum, blackgum (*Nyssa sylvatica* var. *biflora*) and American hornbeam.

In summary, these studies suggest that cherrybark oak, and possibly water oak and willow oak, can reach a dominant or codominant position in mixed, single-cohort bottomland hardwood stands. If given some direct overhead sunlight during the early years of stand development, bottomland red oaks will eventually surpass species such as river birch, American hornbeam, and sweetgum through inter-specific competition. Once in the overstory, intra-specific (or intra-genus) competition among oaks plays a major role in regulating growth and development of individual oak trees. But recent studies in other mixed-genus stands have shown that cherrybark oak (and probably other bottomland red oaks) will not stratify above species such as sycamore (*Platanus occidentalis*; Clatterbuck et al. 1987), loblolly pine (Clatterbuck 1989), and yellow-poplar (*Liriodendron tulipifera*; O'Hara 1986) in stream and river floodplains.

The major differences between pure and mixed, single-cohort stands, in terms of growth and development of an individual red oak stem, are: (1) the timing and intensity of intra-specific and intra-genus competition among oaks and; (2) the lack of inter-specific competition in single-genus stands. Aust (1985) concluded that pure red oak stands had no major advantages or disadvantages over mixed-genus oak stands in terms of growth and yield. On the contrary, individual stems in mixed-genus stands will probably have larger crown and bole diameters. On a per-acre basis, fewer red oak stems of higher quality may produce more mast and be worth more economically than red oak stems grown in relatively pure stands. At present, this is speculative.

Mixed, Multi-Cohort Stands

Most research and management practices for bottomland hardwood stands have assumed that stands are even-aged (Hodges 1987). Development of uneven-aged stands has largely been neglected. This is due to several factors such as the relative scarcity of uneven-aged stands relative to even-aged ones, their more complicated stand structure, and even the sense that uneven-aged silviculture, in the strictest sense, in bottomland hardwoods is not viable (DeBell et al. 1968, Hodges 1987).

However, Guldin and Parks (1989) conducted a stem analysis study in an uneven-aged cherrybark oak stand. The study consisted of 0.2-acre plots, each of which contained 3 distinct age classes of cherrybark oak. Their data suggested that cherrybark oak stratification occurred within canopy gaps created by removal of large overstory trees. Two types of stratification were depicted. The first occurred within an age class, particularly the oldest age class, in which a single cherrybark oak seemed to dominate. The second type of stratification occurred between age classes. This was expected given that younger stems start below older stems. These stratification patterns do not take into account the effects of older, residual trees surrounding these gaps which should affect development within gaps.

Based on these results, Guldin and Parks (1989) stated that development of cherrybark oak in gaps might be similar to even-aged developmental dynamics as outlined by Clatterbuck and Hodges (1988). They also suggested that the absence of cherrybark oak in gaps created by single-tree and group selection cuts might be due to lack of sufficient advance oak regeneration at the time of harvest, rather than to the inability of existing advance growth to develop.

MANAGEMENT IMPLICATIONS

Management of bottomland hardwoods stands, especially red oak stands, is less complicated once stand development patterns have been recognized. Important considerations include species composition and ability of the forest resource manager to elucidate development patterns early in the stand development game, i.e., small-pole stage of development (4-6 inches dbh). If possible, desired trees should be identified at this stage. The following suggestions for bottomland hardwood management are based on neighboring species composition. These suggestions assume intermediate stand conditions; therefore, no consideration for regeneration is given. Also, biological maturity is assumed instead of economic maturity for rotation length due to an inherent bias for high-quality sawlogs and benefits of large trees for wildlife habitat.

Pure, Single-Cohort Stands

Development patterns in cottonwood result in an early stratification of dominants and codominants from the remaining trees. Thereafter, development of the dominant cottonwoods seems relatively unaffected by those that fall behind in height. Johnson and Burkhardt (1976) stated that "thinning does not increase gross volume production nor does it significantly improve the growth of individual dominant and codominant trees." So why thin? The benefits from thinning cottonwood stands revolve around capturing potential mortality and gaining economic benefits during the stand development process (Smith et al. 1997). Thinning also will increase forage production for wildlife. Plantation cottonwood apparently lacks the genetic diversity needed for stand stratification processes, resulting in potential stagnation of such stands. Therefore, thinning cottonwood plantations is more critical to development of desired individual trees than in natural stands.

Stratification in pure, single-cohort bottomland red oak stands differs from that in cottonwood stands. Red oaks apparently do not stratify as readily as pure stands of cottonwood, due possibly to less genetic diversity, differences in inherent growth patterns, crown shape, etc. The lack of inter-specific (or inter-genus) competition forces forest resource managers to rely on intra-genus competition to act as trainers of crop trees. This results in smaller crowns and bole diameters, maybe even lower bole quality, in crop trees. Therefore, several thinning operations may be needed to promote good growth of selected red oak crop trees. Such operations increase the risk of damage to both crowns and boles of crop trees. Thinning may also increase the incidence of epicormic branching, further lowering bole quality (Stubbs 1986, Meadows 1995).

Development of relatively pure bottomland red oak stands occurs in 1 of 2 situations. Poorly-drained flats usually contain species mixtures dominated by water oak and willow oak. These lower-quality sites cannot support high species diversity; therefore, development will progress as relatively pure red oak stands. Pure red oak stands on medium to high-quality sites are usually the result of disturbance early in the life of the stand (Aust et al. 1985), which should be avoided. Conventional wisdom suggests that it is better to have too much oak than none at all. But attempts should probably be made to control disturbances that promote establishment and development of relatively pure red oak stands, in favor of retaining mixed-species stands if large mast crops and high-quality sawlogs are the desired product. Cleaning or early thinning operations can especially be utilized to promote development of large crowns for wildlife habitat.

Mixed, Single-Cohort Stands

The key to managing red oak in mixed, single-cohort bottomland hardwood stands is the composition and spacing between neighbors and the crop tree, beginning with the small-pole stage of development. If neighboring trees are species such as American hornbeam, dogwood *(Cornus florida)*, sugarberry (*Celtis laevigata*), elm (*Ulmus* spp.), river birch or sweetgum, then bottomland red oaks (especially cherrybark oak) should stratify above these species. A common feature of these species is their inherent rapid early height growth that tapers off as individual species age. It is possible that stratification among these species and bottomland red oaks will occur in 2 stages. First, bottomland red oaks would stratify above those species whose height growth patterns decline early, such as American hornbeam and dogwood, which are then regulated to a subordinate canopy position or perish. Following a period of time, maybe as long as 20-30 years, bottomland red oaks would then emerge above species which slow in height growth at this time, such as river birch and sweetgum and possibly sugarberry and elms, and comprise the main canopy. Once the oaks have stratified above these species, crown expansion would begin leading to increased diameter growth. The limiting factor on diameter growth would then depend on the onset of intra-specific and intra-genus competition between oak crowns in the upper canopy.

Under this development scenario, deadening or thinning the competing species before the oaks gain dominance (a cleaning operation) would not be necessary, because the oaks will gain dominance regardless of these other species unless directly overtopped at an early age (Kittredge 1986). Results from understory vegetation control in a mixed-species hardwood stand in central Massachusetts, growing on a good site with adequate growing season soil moisture, showed no overstory oak growth response 13 years after treatment (Kelty et al. 1987). Thinning these "trainer" species may lower merchantable height and bole quality of the oaks thereby reducing their ultimate value. These trainer species also may act as a buffer for crop trees during future harvesting operations (Meadows 1996). Furthermore, these species increase the vertical structure of the stand, an important habitat feature for various bird species. An assumption of this management option of basically do nothing is that individual bottomland red oak stems attain some direct overhead sunlight throughout most of the early stages of their development. If wildlife habitat objectives revolving around large red oak crowns are of primary importance, then a cleaning operation combined with thinning among red oak stems would be needed to maximize red oak crown expansion.

If neighboring trees have inherent rapid height growth rates that continue to be high throughout much of the life of the tree compared to bottomland red oaks, such as yellow-poplar, sycamore, loblolly pine, and possibly green ash (*Fraxinus pennslyvanica*), it is less likely that bottomland red oaks can stratify above these species. Therefore, these species are the key competitors of bottomland red oaks. In the early stages of stand development it would be of benefit to the oaks if these key competitors were removed from the stand by deadening or harvesting. Because ash crown dynamics seem to be similar to that of oaks (Kittredge 1986), and given the current stumpage value for premium ash, stems of this species also may be considered as crop trees.

If neighboring trees are other oak species then spacing is especially critical. While the effects of other oak species competing with each other are not yet clear, it is reasonable to assume that intra-specific or intra-genus competition is more intense than inter-genus competition. If neighboring oak trees are relatively close to crop trees, but not close enough to compete before stratification above other species, then intra-specific competition will begin soon after stratification. This competition for space in the upper canopy will decrease growth of the crown, and thus the bole. Therefore, 2 options exist to either avoid or alleviate early intra-specific competition following stratification. One option is to deaden or pre-commercially thin some of the future oak competitors early in the life of the stand. This option is heavily dependent upon the forest resources manager's ability to pick crop trees at a young age. A second option is to conduct a crown thin following emergence of oak into the overstory. The purpose of this thinning operation is to reduce the number of emerging red oaks. Such an operation is risky given the destructive nature of harvest operations on residual crop trees, especially in relatively young, dense stands (Meadows 1993). If neighboring oaks are so close as to cause intra-specific competition early in the life of the stand, then development will be similar to that of a pure oak stand.

An optimum range of spacings between bottomland red oaks and its various neighboring species has yet to be determined except for cherrybark oak-sweetgum mixtures. Therefore, crop trees should be selected early in development of a mixed stand and neighboring composition identified. Species such as yellow-poplar, sycamore, and loblolly pine should be girdled or deadened if they will compete directly with the oaks in the future. Subsequent sprouts of the girdled hardwood species may not be able to compete starting underneath a small pole-sized stand. Many of the remaining species, i.e., those with slower rates of height growth compared to bottomland red oaks, should be left. These species will enhance development of the oaks by acting as "trainer" species while maintaining vertical canopy diversity.

Mixed, Multi-Cohort Stands

Management of bottomland red oak in uneven-aged stands is hampered by the scarcity of information about development of such stands. At present, it may be best to view red oak development in the gaps of uneven-aged stands as development of small, even-aged mixtures. Guldin and Parks (1989) noted that the trees developing within an individual gap were of relatively the same age. Because plots were selected for cherrybark oak, data also depicted intense intra-specific competition within a gap. Furthermore, these oaks probably competed with trees of older age classes with larger crowns surrounding the canopy gap. Therefore, red oak crop trees have 2 conditions of intra-specific competition, within a gap and from around the gap. While intra-specific competition within a gap may produce crop trees with smaller crowns, the periodic removal of trees around the gap may allow crop trees to spread their crowns. Therefore, such trees may have more desirable characteristics, such as large crowns, as compared to those grown in pure, single-cohort stands. Obviously, more information is needed on bottomland hardwood development in uneven-aged stands before more definite silvicultural prescriptions can be made.

FUTURE RESEARCH

There are many areas worthy of future research in stand development of southern bottomland hardwoods. What follows is a list briefly describing several of these areas.

Stand Development

Future stand development studies should use combinations of the chronosequence and reconstruction techniques to better understand development patterns. Variations of these techniques could include point-chronosequence using stands of similar ages but with varying amounts of oak density (similar to Kittredge 1988). Another variation could include using gaps of different ages as a chronosequence within a stand for studying development in uneven-aged stands. These studies should include the following situations: (1) different sites within floodplains, such as ridges and fronts on small river bottoms, and within the loessial hills; (2) different species compositions such as green ash, hickory (*Carya* spp.), etc., and; (3) varying densities of bottomland red oak species. In addition to using chronosequence and reconstruction techniques, efforts should be made to include permanent plots in the situations listed above.

Mixed-Species Plantations

At present, much effort is being expended on reforestation activities to convert former agricultural land to forest (Allen and Kennedy 1989). These activities involve establishing relatively pure bottomland oak stands or mixing several oak species. Based on reviews of previous stand development studies, such plantations may suffer in the long-run as oak trees of smaller crown dimensions and lower bole quality may be produced (unless such stands are judiciously thinned). Therefore, mixed-species stand development patterns need testing using artificial regeneration techniques, such as planting and direct seeding. Such plantations could potentially produce more biomass compared to single-species plantations as different species occupy different canopy layers (Kelty 1992). Greater vertical structure also will increase the number of niches available for various wildlife species. Results from a 17-year-old mixed cherrybark oak-sweetgum planting indicated that stand stratification processes can occur in hardwood plantations (Lockhart et al. 2000). Seven years following planting, sweetgum trees were taller and had greater diameters than associated cherrybark oak trees. By 17 years, no differences existed in height or diameter between the 2 species; essentially the cherrybark oak had caught up to the sweetgum. Another research effort studying mixed-species plantations and effects of intra-specific and inter-specific competition is underway using mixtures of Nuttall oak (*Q. nuttallii*), water oak, and green ash in an elaborate experimental design (Goelz 1995). Additional studies need to include other less-desirable species (from a timber standpoint) such as sweetgum, American hornbeam, sugarberry, hickories, and elms to determine if such species can contribute significantly to increased bole quality in addition to the added benefit of increased species diversity.

Crown Architecture

More study on the role of crown architecture in determining stand development patterns is warranted. Based on the previously discussed studies, the ability of a crop tree to compete successfully in the upper canopy depends on how well it can occupy physical growing space in the canopy. Future studies should include tests of relative twig and branch strength among species and how these relationships interact during wind events. Studies could also be conducted on crown expansion rates, foliage type (sun versus shade), and foliage distribution within a canopy.

Whole Tree Physiology

How well a crop tree competes ultimately depends on its ability to increase carbon allocation when more growing space becomes available. Therefore, information is needed on whole-tree leaf area and gas-exchange, i.e., net photosynthesis and transpiration. This information would not only increase knowledge on how bottomland red oaks grow but also provide insight into how they respond to competition from different species. Such a study has recently been completed with northern red oak, red maple, and black birch mixtures (Moser 1994).

Permanent Plots

While establishing more permanent plots to specifically study stand development would be desirable, the costs of such projects are probably prohibitive. Therefore, efforts should be made to expand data collection in existing bottomland hardwood growth and yield plots to encompass testing hypotheses about stand development. Furthermore, efforts should be made to retain permanent plot data, both growth and yield and continuous forest inventories, when long-term studies or inventories are terminated. Such data may contain as yet unrealized benefits regarding stand development patterns.

CONCLUSIONS

An understanding of how bottomland hardwood species develop is essential to making effective silvicultural recommendations for forest resource managers and landowners of bottomland hardwood forests. The fact that oaks can exist for decades beneath other species and yet can ultimately dominate the stand reflects the dynamic and robust nature of the genus. Recommendations for intermediate silvicultural treatments must reflect these unique developmental dynamics.

The fact that oak developmental dynamics are so different from those of the southern pines is part of the challenge for forest resources managers and landowners in the South. For example, if pines lag behind other species, they generally cannot recover. Forest managers who are accustomed to thinning and releasing pines from competing species at young ages might be tempted to apply similar tactics in young mixed-species bottomland hardwood stands -- and they might be making poor silvicultural decisions if they did.

The studies cited here epitomize how silvicultural recommendations must reflect the best scientific information available for the species being managed. Although forest resource management ultimately depends on the objectives of the landowner, it is up to the forest resources manager to advise on how to best meet these objectives. Finally, knowledge of stand development patterns is rewarding in itself, in simply knowing how a stand grows and in being able to predict how it will look in the future.

ACKNOWLEDGMENTS

The authors thank Sean Blackburn, E. C. Burkhardt, Wayne Clatterbuck, Jim Guldin, Jamie Kellum, Kimberly Sykes, Philip Tappe, Rodney Wishard, French Wynne, and 2 anonymous reviewers for constructive comments on earlier versions of this paper. This paper is publication number 99046 of the Arkansas Agricultural Experiment Station.

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Ecology and Management of Bottomland Hardwood Systems:

The State of Our Understanding

A SYMPOSIUM

March 11-13, 1999

The Peabody Hotel
Memphis, TN

Ecology and Management of Bottomland Hardwood Systems:
The State of Our Understanding

Publishers: University of Missouri-Columbia, Gaylord Memorial Laboratory Special Publication No. 10
Mississippi State University, Forest and Wildlife Research Center, Publication WF-212

Acknowledgements: Redactory and copy editing by Sandy Clark

Illustrations and photos courtesy of: Forest History Society, Durham, NC, Wylie C. Barrow, Jr. for cover photo and use of photos by James T. Tanner, Frank Nelson, Karen Kyle, U. S. Fish & Wildlife Service

Editors: L. H. Fredrickson, S. L. King, and R. M. Kaminski

Production/design: Karen Kyle

Citation:
2005. Ecology and Management of Bottomland Hardwood Systems: The State of Our Understanding. L. H. Fredrickson, S. L. King and R. M. Kaminski, editors. University of Missouri-Columbia. Gaylord Memorial Laboratory Special Publication No. 10. Puxico.

Gaylord Memorial Laboratory Special Publication No. 10
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