Chapter 8.

The Evolution of Pine Plantation Silviculture in the Southern United States

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Abstract—*In the 1950s, vast acreages of cutover forest land and degraded agricultural land existed in the South. Less than 2 million acres of southern pine plantations existed at that time. By the end of the 20th century, there were 32 million acres of southern pine plantations in the Southern United States, and this region is now the woodbasket of the world. The success story that is southern pine forestry was facilitated by the application of research results generated through cooperative work of the U.S. Department of Agriculture Forest Service, southern forestry schools, State forestry agencies, and forest industry. This chapter reviews the contributions of applied silvicultural research in land classification, tree improvement, nursery management, site preparation, weed control, and fertilization to plantation forestry in the South. These practices significantly increased productivity of southern pine plantations. Plantations established in the 1950s and 1960s that produced < 90 cubic feet per acre per year have been replaced by plantations established in the 1990s that are producing > 400 cubic feet per acre per year. Southern pine plantations are currently among the most intensively managed forests in the world. Growth of plantations managed using modern, integrated, site-specific silvicultural regimes rivals that of plantations of fast-growing nonnative species in the Southern Hemisphere. Additional gains in productivity are likely as clonal forestry is implemented in the South. Advances in forest biotechnology will significantly increase growth and quality of future plantations. It appears likely that the South will remain one of the major wood-producing regions of the world.*

INTRODUCTION

Pine (*Pinus* spp.) plantation silviculture in the Southern United States is one of the major success stories for forestry in the world. In 1952, there were only 1.8 million acres of pine plantations in the South (fig. 8.1), containing 658 million cubic feet of timber (U.S. Department of Agriculture, Forest Service 1988). At the turn of the 21st century, there are 32 million acres of pine plantations in the South that contain 23.9 billion cubic feet of timber (Wear and Greis 2002). Perhaps more remarkable is the significant increase in productivity that occurred during this period (fig. 8.2). Mean annual increment of pine plantations has more than doubled, and rotation lengths have been cut by > 50 percent. The success of pine plantation silviculture has turned the South into the woodbasket of the United States (Schultz 1997).

These remarkable changes in the last 60 years were the result of a variety of factors that came together at the end of World War II. Economic factors, including a declining agricultural economy coupled with a rapidly expanding pulp and paper industry based on southern pine, combined to provide the impetus for the large increase in southern pine plantations. The success of this effort was due in large part to the cooperative research and technology transfer efforts of many organizations, including the U.S. Department of Agriculture Forest Service (Forest Service), State forestry agencies, forestry programs at southern universities, and forest industry.

The objectives of this chapter are to describe the evolution of southern pine plantation silviculture over the last 50 years and to outline our view of the current state of the art of pine plantation silviculture in the South. Rather than present an exhaustive review of the literature,

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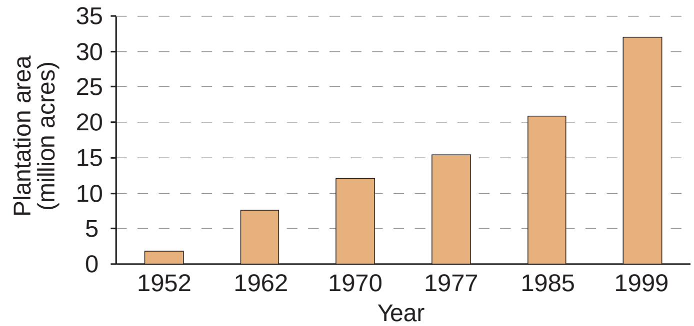


Figure 8.1—Number of acres of pine plantations in the Southern United States from 1952 to 1999 (data from U.S. Department of Agriculture 1988, Wear and Greis 2002).

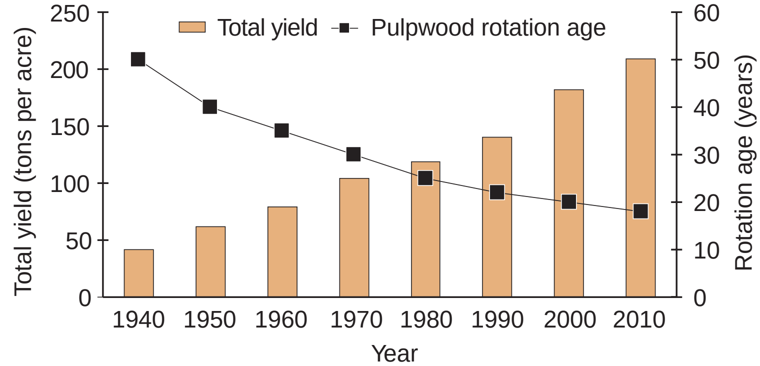


Figure 8.2—Estimated total yield and pulpwood rotation age in pine plantations in the Southern United States from 1940 through 2010.

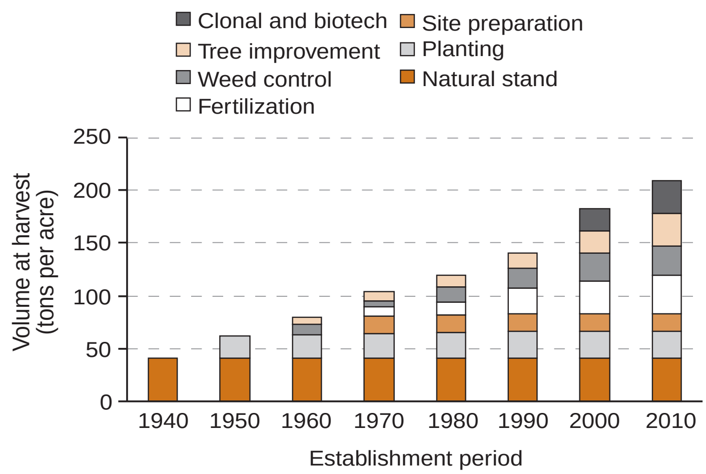


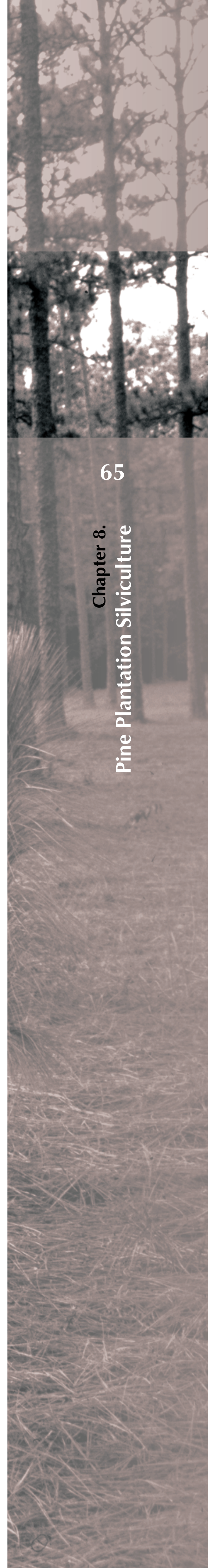
Figure 8.3—Estimated contributions of intensive management practices to productivity in pine plantations in the Southern United States from 1940 through 2010.

we will highlight what we believe are the major advances during the last 50 years and illustrate their contribution to the productivity gains that have been observed during this time (fig. 8.3). As part of this, we hope to demonstrate the significant contributions that applied coop-erative research has made to this success story.

SETTING THE STAGE FOR PLANTATION FORESTRY IN THE SOUTH

Clearing of forests for crop production occurred throughout the Coastal Plain and Piedmont from the colonial period until the beginning of the Civil War (Williams 1989). In Virginia > 25 million acres, or 47 percent of the total land area in the State, had been cleared by 1860. Soil erosion was a serious problem associated with production of cotton and tobacco, which were the most important agricultural crops throughout the South (Bennett 1939). Declining soil productivity due to erosion, accompanied by low prices for cash crops and pest problems such as the boll weevil (*Anthonomus grandis grandis*), caused large amounts of agricultural land to be abandoned throughout the South between the end of the Civil War and World War II.

The South has been an important source of timber and forest products since colonial times (Williams 1989). Other than timber for local use, the first major products from southern forests were naval stores from longleaf pine (*P. palustris* Mill.) and ship timbers from live oak (*Quercus virginiana* Miller) (Butler 1998, Williams 1989).



The production of lumber in the South increased gradually following the Civil War and more dramatically beginning in the 1880s and 1890s, when available timber in the Lake States was depleted. Between 1890 and 1920, the South was the major lumber-producing region in the country. Production peaked at approximately 140 billion board feet in 1909, when the South produced 46 percent of all timber cut in the United States (Williams 1989). After 1909, lumber production declined gradually until the start of the Great Depression in 1929, when production fell sharply.

The discovery by Charles Herty that acceptable pulp and paper could be made from southern pine had a dramatic impact on southern forestry beginning in the 1930s (Reed 1995). A rapid increase in the pulp production in the South followed this discovery (Josephson and Hair 1956). Numerous pulp and paper mills were constructed throughout the South during the 1930s, increasing the demand for smaller diameter southern pine timber. Pulp and paper companies purchased large tracts of timberland during this period to provide pulpwood for these new facilities (Williams 1989).

At the start of the 20th century, almost no effort was devoted to reforestation following timber harvest (Williams 1989). Destructive fires often followed logging, killing much of the natural regeneration that might otherwise have become established on many cutover tracts. During the 1920s, the Forest Service recognized the need for large-scale tree planting in the South and began a research program to address reforestation issues. The first large-scale planting of southern pine occurred between 1920 and 1925 when the Great Southern Lumber Company planted approximately 7,000 acres near Bogalusa, LA (Wakeley 1954). During the 1920s, the Forest Service also began its reforestation program in the South with the planting of 10,000 acres in the Sumter National Forest in South Carolina. During the 1930s, the Civilian Conservation Corps planted > 1.5 million acres across the South. The success of these early efforts demonstrated the feasibility of establishing pine plantations.

THE ADVENT OF PLANTATION FORESTRY

At the end of World War II, the legacy of abusive agricultural practices that had degraded soil productivity to the point where crop production was no longer profitable, coupled with exploitative timber harvesting without provision for regeneration, left the South with a substantial acreage of land requiring reforestation. Commenting on the situation in the 1950s, Wahlenberg (1960) stated, "Much land suitable for loblolly pine that has been made unproductive through heavy cutting, wildfire, natural catastrophe, or abandonment of agriculture is in need of planting." Wakeley (1954) estimated that there were 13 million acres of land requiring planting in the South in 1950.

Tree planting in the South, which had nearly ceased during World War II, rapidly increased in the years immediately following the war (U.S. Department of Agriculture, Forest Service 1988). A large percentage of this planting occurred on farmland associated with the Soil Bank Program of the 1950s. The successful reforestation of abandoned and degraded agricultural land illustrated the conservation value of trees and their role in reducing soil erosion and improving water quality (Bennett 1939). The rapid expansion of the pulp and paper industry in the South during the 1930s increased the demand for pine pulpwood and stimulated planting on forest industry land. By this time, the superior growth and yield of pine plantations relative to naturally regenerated stands had become evident. For example, the original plantations established by Great Southern Lumber Company clearly showed the potential value of fully stocked plantations compared to the poorly stocked naturally regenerated stands that were the norm at the time (Wakeley 1954).

NURSERY PRACTICES AND SEEDLING HANDLING

Artificially regenerating the large acreages found in the South required an abundant supply of high-quality seedlings. A concerted research effort of the Forest Service on reforestation in the South began in the 1920s and culminated with the publication of Agricultural Monograph 18 "Planting the Southern Pine" (Wakeley 1954). This classic publication provided foresters detailed information on seed collection and processing, seedling production, and planting practices needed to successfully establish southern pine plantations. With its publication, the stage was set for the rapid expansion of southern pine seedling production. In 1950, the Forest Service, the Soil Conservation Service, the Tennessee Valley Authority, and all States in the South operated forest nurseries to produce pine seedlings for reforestation activities on public and private land (U.S. Department of Agriculture, Forest Service 1949). Many industrial organizations also began to establish or expand nurseries to meet their seedling needs at this time.

Wakeley (1954) developed a widely used grading system for southern pine seedlings based on seedling height, root-collar diameter, and stem and needle characteristics that were correlated with seedling survival. However, seedling survival was a continuing problem throughout the South during the 1950s, 1960s, and 1970s (Dierauf 1982). Although many of the factors affecting seedling survival, such as weather, insects, and disease, were thought to be difficult to control, the problem received considerable attention because of the relative scarcity and high cost of genetically improved seed. The formation of the Auburn Southern Forest Nursery Management Cooperative in 1970 highlights the importance placed on improving nursery practices and seedling quality. Root characteristics of seedlings, including root:shoot ratio and the number of first-order lateral roots, were demonstrated to be important factors affecting seedling performance (Carlson 1986). Improved nursery practices, such as sowing seed by size class and single family groups, reducing nursery bed density, top pruning, root pruning, increasing nitrogen (N) fertilization, and mycorrhizal inoculation, were incorporated into standard operating procedures at most pine seedling nurseries, substantially improving the size and quality of the seedlings produced (Mexal and South 1991). Although seedling survival is still probably best correlated with root-collar diameter (South 2000), physiological criteria such as root growth potential were also developed to better evaluate seedling quality (Johnson and Cline 1991). Proper care and handling of seedlings during lifting and transport to the planting site were found to be the critical factors ensuring initial survival and growth of seedlings (Dierauf 1982, U.S. Department of Agriculture 1989). The use of refrigerated vans for seedling storage and transport, now widespread throughout the South, was probably the single most important factor in making certain that seedlings arrive at the planting site in good condition. Improved survival and growth also occurred when larger seedlings were planted deeper and earlier in the season; i.e., prior to December (South 2000). Today, improved nursery practices, together with proper care and handling of seedlings during transport, storage, and planting, have increased survival rates for planted seedlings to levels commonly > 90 percent.

Tree Improvement and Genetic Gain

A major limitation on seedling production in the 1950s was the absence of reliable supplies of high-quality seed from desirable sources (Squillace 1989). Geographic variation in seed sources was known to affect growth of southern pine, with local sources outgrowing more distant sources (Wakeley 1944). Therefore, use of local seed, collected within 100 miles of the planting site, was recommended for reforestation (McCall 1939). At that time, most seed was obtained from cones collected from trees felled during logging of natural stands (Wakeley 1954). In order to provide a more consistent supply of cones, seed production areas were often established in natural stands containing good phenotypes (Goddard 1958).

The seed orchard concept was proposed as early as the late 1920s as means of producing genetically improved seed (Bates 1928). The high cost of establishing and managing seed orchards was initially a major obstacle to their widespread use (Perry and Wang 1958), because it was not widely accepted that genetic improvement through selection and breeding would lead to significant gains in the growth of southern pine (Wakeley 1954). This view began to change in the 1950s as evidence supporting the value of genetic improvement in forest trees started to emerge (Lindquist 1948, Schreiner 1950). The value of genetically improved seed was finally recognized when it was demonstrated that the costs associated with seed orchards could be economically justified (Perry and Wang 1958). Bruce Zobel, on behalf of the Texas Forest Service and in cooperation with 14 forest products companies, formed the first tree improvement program in the South (Zobel and Talbert 1984). The formation of this industry-university-Government applied research cooperative was a major event in southern pine plantation forestry. The future success of southern pine plantation forestry was in large part a direct result of the applied research conducted through cooperative programs at universities throughout the South. Additional tree improvement research cooperatives were soon founded at the University of Florida in 1953 and North Carolina State University in 1956 (Southern Industrial Forest Research Council 1999).

The seed orchard concept quickly gained favor and became the preferred method of producing southern pine seed (Zobel and others 1958). The first southern pine seed orchard was established by the Texas Forest Service in 1952 to produce drought-hardy loblolly pine (*P. taeda* L.) (Zobel 1953). Industrial members of the University of Florida Cooperative Forest Genetics Research Program began establishing slash pine (*P. elliottii* Engelm. var. *elliottii*) seed orchards in 1953 (Wang and Perry 1957). By 1987, > 9,700 acres of seed orchards had been established in the South, and > 85 percent of the trees planted in the South originated from improved seed produced in seed orchards (Squillace 1989).

Tree improvement programs in the South focused primarily on improving volume growth, tree form, disease resistance, and wood quality (Dorman 1976, Zobel and Talbert 1984). Because of the length of time required for tree breeding and testing, the gains in wood production due to tree improvement were not fully realized for several decades (Todd and others 1995, Zobel and Talbert 1984). Seed from first-generation seed orchards became available in large quantities in the 1960s and early 1970s. When these plantations matured in the 1980s, they produced 8 to 12 percent more volume per acre at harvest than trees grown from wild seed (Squillace 1989). The increased financial value of plantations established with first-generation improved seed probably exceeded 20 percent when gains from other traits such as stem straightness, disease resistance, and wood density were included (fig. 8.4) (Todd and others 1995). Continued breeding and testing led to the development of second-generation orchards in 1980s. Second-generation seed orchards currently produce more than 50 percent of the seed in the South. It is estimated that volume growth in current plantations will be 14 to 23 percent greater than in plantations established using first-generation material (fig. 8.4) (Li and others 1997).

MECHANICAL SITE PREPARATION

Before the 1950s, planting was generally limited to old fields and grassy savannas that originated on cutover sites following frequent wildfires. Most cutover pine sites in the South were regenerated after harvest by leaving six to eight seed trees per acre (Duzan 1980). Unfortunately many of these stands failed to regenerate pine adequately due to competition from hardwoods. The inconsistent results obtained with natural regeneration led to trials with clearcutting and planting. Foresters faced considerable obstacles in their attempt to convert these natural stands of mixed pine and hardwoods to plantations after harvest. Lack of markets for low-grade hardwoods often led to poor utilization that left large numbers of nonmerchantable stems and heavy logging slash on the site. This inhibited planting and, coupled with the rapid regrowth of hardwoods, led to poor survival and growth of seedlings planted in the rough.

Initially, little site preparation was done because of the cost (Shoulders 1957). However, the need for site preparation was highlighted by the failure of many plantations established on cutover sites, which was in stark contrast to the success of plantations established on old agricultural fields and grassy savannas. The old-field effect on improved survival and growth was attributed to various factors, including low levels of competing hardwood vegetation, improved soil physical properties, and improved soil fertility due to residual fertilizer and lime. Therefore, the aim of site preparation was to re-create these old-field conditions on cutover sites using various mechanical means such as anchor chaining, chopping, burning, root raking, shearing, and disking. Mechanical site preparation practices often evolved more rapidly through trial and error by field foresters and equipment manufacturers than through formal research and development efforts.

The most consistent thread in the development of site preparation practices on upland cutover sites in the South was the need to control competing hardwood vegetation (Haines and others 1975). Roller-drum choppers were introduced as a site preparation tool in the middle 1950s and quickly gained popularity. Chopping, especially when followed by prescribed fire, reduced logging slash and residual nonmerchantable stems and, thus, improved access to the site for planting (Balmer and Little 1978). However, chopping did not effectively control competing hardwood vegetation. Disk harrows were first employed in the late 1950s to provide soil tillage similar to that found in old fields and to control hardwood sprouting. However, the level of hardwood control achieved following harrowing was often

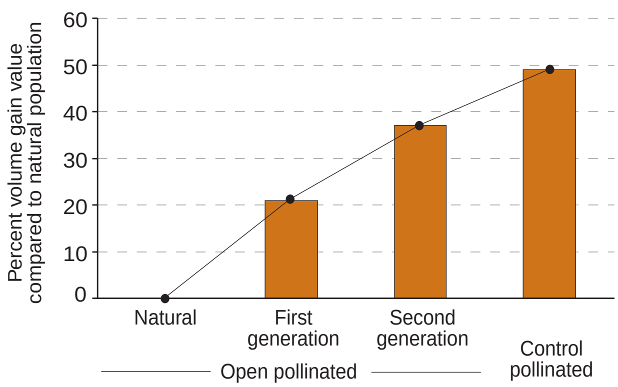


Figure 8.4—Growth increases in southern pine plantations due to tree improvement practices in the Southern United States (adapted from Li and others 1997, Todd and others 1995).

disappointing (Duzan 1980). The intensity of mechanical site preparation continued to increase during the 1960s and 1970s in pursuit of the desired old-field conditions, culminating in the widespread use of shearing, windrowing, and broadcast disking as the standard practice throughout much of the Piedmont and upper Coastal Plain (Haines and others 1975, Wells and Crutchfield 1974). Large bulldozers were used in this three-pass system. Residual stems and stumps were first sheared near the groundline using a KG blade. The slash and logging debris were raked into piles and windrows. Unless great care was taken, the forest floor and topsoil were often raked into the piles and windrows along with the slash. The area was then broadcast disked with a large harrow. In many cases, the windrows and piles were then burned after the debris dried. The improved survival and early growth of seedlings planted on these intensively prepared sites, coupled with the greatly reduced hardwood sprouting, suggested that foresters had finally achieved the holy grail of site preparation—turning cutover sites into old fields.

Foresters in the lower Coastal Plain faced a different set of problems than their counterparts in the Piedmont. In addition to the concerns with the control of competing vegetation, the presence of poorly drained soils with high seasonal water tables greatly affected survival and growth of planted seedlings. The widespread conversion of swamps into productive agricultural lands through intensive drainage clearly demonstrated the value of removing excess water from wet sites for crop production (Wooten and Jones 1955). The first large-scale drainage project for forestry in the South occurred in the Hofmann Forest in eastern North Carolina in the late 1930s. By the 1950s the improved growth of loblolly and slash pine planted adjacent to drainage canals was clearly evident (Maki 1960, Miller and Maki 1957, Schlaudt 1955). The phenomenal growth response of planted pines following drainage reported in a number of studies, ranging from 80 percent to almost 1,300 percent (Terry and Hughes 1975), led to the widespread drainage of forested wetlands in the Atlantic and Gulf Coastal Plain in the late 1960s and early 1970s. Large draglines were used to construct sophisticated drainage systems including primary, secondary, and third-stage ditches that removed excess water and, thus, improved access, reduced soil disturbance during harvesting, and improved survival and growth of planted seedlings (Terry and Hughes 1978).

As on upland sites, reducing logging debris and controlling competing hardwood vegetation were major objectives of site preparation on wet soils in the Coastal Plain. Chopping, burning, KG shearing, windrowing, and root-raking practices evolved much as they had on upland sites. However, seasonally high water tables and flooding limited the survival and growth of planted seedlings on poorly drained soils, even when harrowing was combined with intensive debris clearing (Cain 1978). Even on drained sites, reduced evapotranspiration rates in young plantations led to extended periods when the soils were saturated during the winter, which decreased seedling survival and growth (Burton 1971). The improved growth of seedlings on elevated microtopography with improved soil aeration (McKee and Shoulders 1970) led to the development of bedding in the Coastal Plain. The first bedding was done with fire plows modified to produce a raised planting site for seedlings (Bethume 1963, Smith 1966). Specialized bedding plows were introduced in the 1960s, and bedding soon became the standard site preparation practice on poorly drained soils, based on the superior growth observed on bedded compared to flat-planted sites (McKee and Shoulders 1974, Terry and Hughes 1975, Wells and Crutchfield 1974). Because slash interferes with bedding and decreases the quality and height of the beds, intensive land clearing, often involving KG shearing and windrowing, was usually conducted on sites requiring bedding to ensure that quality beds were formed (Duzan 1980). Effective bedding treatments improved surface soil tillage and soil aeration, and reduced shrub competition. In some cases double bedding, using two passes of the bedding plow, was required to achieve the conditions needed to ensure superior survival and growth of planted seedlings.

CONCERN OVER SUSTAINABILITY AND ENVIRONMENTAL IMPACTS OF INTENSIVELY MANAGED PLANTATIONS

The intensity of site preparation conducted in both the Piedmont and the Coastal Plain to simulate old-field conditions soon generated concern about long-term site productivity. A report by Keeves (1966) on second-rotation productivity declines in radiata pine (*P. radiata* D. Don) on intensively prepared sites in Australia, apparently caused by heavy windrowing, stimulated great interest in the South. Subsequent work with radiata pine in New Zealand confirmed that windrowing on sandy soils induced severe nutrient deficiencies that would degrade site quality (Ballard 1978). Foresters throughout the South observed the wavy height growth pattern in windrowed plantations where trees adjacent to the windrows were considerably taller than trees between the windrows. A large windrow effect on growth of loblolly pine was documented in the North Carolina Piedmont (Fox and others 1989, Glass 1976). Windrowing decreased site index by 11 feet in this loblolly pine plantation. As in New Zealand and Australia, it was demonstrated that declines in growth observed on windrowed sites were caused by nutrient deficiencies due to displacement of the forest floor and topsoil from the interior of the stand to the windrows (Morris and others 1983, Vitousek and Matson 1985). These observations led to the search for alternative, less intensive site preparation treatments that would maintain site quality (Burger and Kluender 1982, Tippin 1978).

Nutrient losses associated with intensive whole-tree harvesting also generated much concern during this period. Nutrient budget calculations seemed to suggest that whole-tree harvesting would deplete soil nutrient reserves, particularly such elements as calcium, and consequently degrade site quality (Ballard and Gessel 1983, Mann and others 1988). Numerous studies comparing conventional bole-only harvests with whole-tree harvests were installed in response to this concern. Long-term analysis of these studies eventually revealed that whole-tree harvesting had no detrimental effects on soil nutrient levels or site productivity on most sites if the slash and logging debris were left on site (Johnson and Todd 1998). Where excessive soil disturbance during harvest and site preparation did have negative effects, ameliorative treatments such as soil tillage and fertilization restored productivity in nearly all cases (Fox 2000, Nambiar 1996).

Because long-term site productivity was closely tied with organic matter and N availability, harvesting and site preparation treatments were modified during the 1980s to leave as much organic matter on site as possible. The goal was to obtain the amount of soil tillage required to achieve acceptable seedling survival while leaving most of the logging slash and forest floor on site (Morris and Lowery 1988). The link between improved harvest utilization and site preparation led to more integrated harvesting and site preparation regimes (Burger and Kluender 1982). In the Piedmont, the desire to minimize soil disturbance during site preparation, concerns over nutrient losses and long-term site productivity, and the availability of newly developed herbicides that effectively controlled hardwood sprouts combined to shift most of the site preparation from mechanical to chemical treatments. In the Coastal Plain, mechanical treatments were modified so that sites could still be bedded with larger amounts of slash and logging debris left on site. V-blades were developed that pushed aside logging debris and cleared a path for bedding plows without removing organic matter and nutrients from the site. Also, larger bedding plows were developed that cut through thick root mats and residual slash while still creating well-formed beds that elevate seedlings above high water tables, thus reducing the need for windrowing on poorly drained sites.

The impacts of intensive forest management on water quality have long been an important issue in the South. The large amount of bare soil exposed following harvest and site preparation often led to increased erosion on steeply sloping land in the Piedmont (Nutter and Douglass 1978). The work of Coile and Schumaker (1964) demonstrated the correlation between topsoil depth and site quality in the Piedmont. Given the degraded site quality in most of the Piedmont caused by the past agricultural practices, additional losses of topsoil by erosion following harvest and site preparation were a concern. There were also concerns about the offsite environmental impacts of intensive harvesting and site preparation. Increased erosion and movement of sediment that increased turbidity in streams became a major issue with the amendment of the Federal Water Pollution Control Act in 1972, which for the first time regulated forestry activities as nonpoint sources of pollution. Best Management Practices (BMP) were developed in all the Southern States in response to this legislation to minimize soil erosion and offsite movement of sediment from forestry activities (Cubbage and others 1990). These BMPs have proven to be very effective at reducing nonpoint sources of pollution from forestry activities when properly implemented (Aust and others 1996). Although voluntary in most States, compliance with BMPs is uniformly high today in forestry operations across the South (Ellefson and others 2001).

CONTROLLING COMPETING VEGETATION

The detrimental effects of hardwood competition on growth and yield of southern pines were recognized from the earliest days of plantation forestry (Cain and Mann 1980, Clason 1978, Duzan 1980). One of the main objectives of site preparation was to create old-field conditions where hardwood competition was absent. However, chemical site preparation was not widely used during this period, generally because the poor utilization during harvest required mechanical methods to provide acceptable access to the site (Lowery and Gjerstad 1991). Unfortunately on most cutover sites, mechanical site preparation alone did not effectively control hardwood sprouting. In the absence of follow-up release treatments, many plantations turned into low-quality hardwood stands with scattered, poorly growing pines (Duzan 1980). During the 1960s and 1970s, 2,4,5-T was widely used to release young pine plantations from competing hardwoods, because it was inexpensive to apply and effective on many species of hardwoods, and pines were resistant to the herbicide (Lowry and Gjerstad 1991).

The registration of 2,4,5-T for forestry uses was cancelled in 1979. At that time, both hardwood release treatments and chemical site preparation essentially ceased for a number of years in the South. However, concerns about sustainability of the long-term productivity of sites that were intensively prepared mechanically, and concerns about hardwood sprouting on less intensively prepared sites, fostered the search for herbicides that could replace 2,4,5-T (Fitzgerald 1982). The Auburn University Silvicultural Herbicide Cooperative was formed in 1980 to identify and test herbicides suitable for use in forestry. Numerous trials were established to evaluate herbicide efficacy and document the growth response of pines following herbicide application.

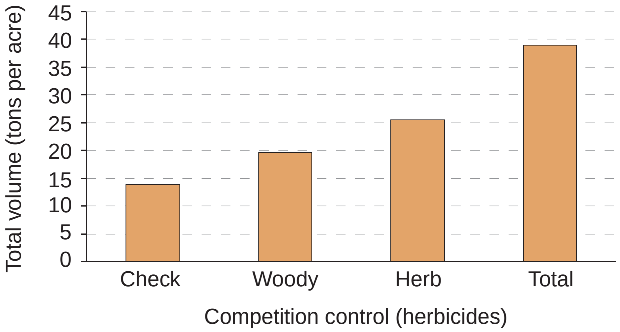


Figure 8.5—Effect of competition control on growth of loblolly pine at age 8 (adapted from Miller and others 1995).

Several alternative herbicides such as glyphosate (Roundup®, Accord®), hexazinone (Velpar®), imazapyr (Arsenal®), sulfometuron methyl (Oust®), and triclopyr (Garlon®) were soon registered for forestry uses. The newer compounds were more environmentally benign, with low mammalian and fish toxicity, rapid degradation, and minimal offsite movement (Neary and others 1993). Hardwood control in pine plantations using these newer herbicides was generally more successful than previous treatments with herbicides such as 2,4,5-T (Minogue and others 1991).

The use of herbicides for site preparation began to increase as results from studies of the newer herbicides revealed that these compounds effectively controlled hardwood sprouting (Fitzgerald 1982, Miller and others 1995) and, thus, increased pine growth (fig. 8.5). Chemical site preparation expanded rapidly when it was discovered that similar or better growth occurred at a lower cost on chemically prepared sites compared to mechanically prepared sites (Knowe and others 1992). By the 1990s, chemical site preparation had replaced mechanical site preparation on most upland sites (Lowery and Gjerstad 1991) and is currently the dominant form of site preparation in the Piedmont and upper Coastal Plain.

Although the effect of hardwood competition on pine growth was well documented (Cain and Mann 1980, Clason 1978), the effect of herbaceous vegetation in young pine stands was not well known in the 1960s, because herbicides that effectively controlled grasses and other herbaceous vegetation without damaging pine seedlings were not available. However, mechanical weeding experiments in young pine plantations showed that height growth of seedlings increased significantly following control of grass and herbaceous vegetation (Terry and Hughes 1975). With the advent of newer herbicides such as hexazinone in the 1970s that effectively controlled herbaceous weeds without damaging young pine seedlings, large and consistent growth responses following herbicide applications were widely observed (Fitzgerald 1976, Holt and others 1973, Nelson and others 1981). By the late 1980s, it was clear that herbaceous weed control had a long-term impact on pine growth (fig. 8.5) (Glover and others 1989, Smethurst and Nambiar 1989). Control of herbaceous weeds during the first growing season was soon a widespread practice in pine plantations throughout the South (Minogue and others 1991).

ACCELERATING GROWTH BY FERTILIZATION

Even though a considerable body of research on forest soil fertility, tree nutrition, and response to fertilizers existed showing that growth increases following fertilization were possible (Walker 1960), forest fertilization did not develop as an operational silvicultural practice until the 1960s. Operational deployment was hampered by an inability to accurately identify sites and stands that consistently responded to fertilization. A major breakthrough occurred with the discovery of spectacular growth responses in slash pine following phosphorus (P) additions on poorly drained clay soils, locally called gumbo clay, in the flatwoods of Florida (Laird 1972, Pritchett and others 1961). Volume gains of up to 5 tons per acre per year over 15 to 20 years were observed on similar soils throughout the Coastal Plain (Jokela and others 1991a). The long-term growth response following P fertilization on these gumbo clays translated into 5- to 15-foot increases in site index. When foresters learned to identify these P-deficient sites and prescribe appropriate fertilizer applications, fertilization emerged as an operational treatment (Beers and Johnstono 1974, Terry and Hughes 1975). Typically, optimal growth responses were achieved on these sites when approximately 50 pounds per acre of elemental P was added at the time of planting (Jokela and others 1991a).

Results from fertilizer trials on other soil types in the Coastal Plain and Piedmont were encouraging, but they remained somewhat inconsistent (Pritchett and Smith 1975). This inconsistency limited further expansion of forest fertilization programs. The Cooperative Research in Forest Fertilization (CRIFF) Program at the University of Florida and the North Carolina State Forest Fertilization Cooperative were formed in 1967 and 1970, respectively, to address this problem. Researchers in these two programs and the Forest Service worked to identify reliable diagnostic techniques to identify sites and stands that responded to fertilization. Diagnostic techniques including soil classification, soil and foliage testing, visual symptoms, and greenhouse and field trials were developed to help foresters decide whether or not to fertilize (Comerford and Fisher 1984; Wells and others 1973, 1986). The soil classification system developed by the CRIFF Program proved to be an effective tool for determining the likelihood of obtaining an economic growth response following fertilization and was adopted widely (Fisher and Garbett 1980). Critical foliar concentrations for N and P were identified for slash and loblolly pine that were well correlated with growth response following fertilization (Comerford and Fisher 1984, Wells and others 1973).

Field trials conducted by both the North Carolina State Forest Fertilization Cooperative and the CRIFF Program, initiated in the 1970s and 1980s, revealed that growth of most of the slash and loblolly pine plantations in the South were limited by the availability of both N and P (Allen 1987, Fisher and Garbett 1980, Gent and others 1986, Jokela and Stearns-Smith 1993, North Carolina State Forest Nutrition Cooperative 1997). This work confirmed that a large and consistent growth response following midrotation fertilization with N (150 to 200 pounds per acre) and P (25 to 50 pounds per acre) occurred on the majority of soil types (fig. 8.6). Growth response following N plus P fertilization averaged 75 cubic feet per acre per year on poorly drained soils and 69 cubic feet per acre per year on well-drained soils, which represents a growth increase of approximately 25 percent (North Carolina State Forest Nutrition Cooperative 1997). These responses have typically lasted for at least 6 to 10 years, depending on soil type, fertilizer rates, and stand conditions. Based on these results, the number of acres of southern pine plantations receiving midrotation fertilization with N and P increased from 15,000 acres annually in 1988 to approximately 975,000 acres in 2000 (North Carolina State Forest Nutrition Cooperative 2001). By the end of 2000, > 11.1 million acres of southern pine plantations had been fertilized in the United States since 1969.

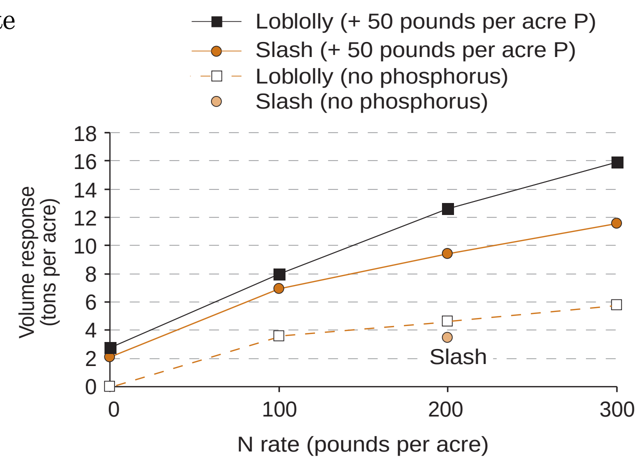


Figure 8.6—Growth response of loblolly and slash pine on a variety of soil types following midrotation application of nitrogen (N) and phosphorus (P) fertilizer (adapted from North Carolina State Forest Nutrition Cooperative 1997).

DEVELOPMENT OF FOREST SITE CLASSIFICATION

Site quality is perhaps the single most important factor affecting growth and yield of plantations. Merchantable yield tends to increase in an exponential fashion as site quality increases. This relationship became more important in the early 1950s as management shifted from natural stands to plantations because the financial returns from the investment in plantation forestry were insufficient on poor-quality sites. Unfortunately in the early years of plantation forestry in the South, it was often difficult to assess the quality of many sites scheduled for planting because they were cutover and poorly stocked (Coile 1960). This led to a large effort in the 1950s and 1960s to correlate soil properties, understory vegetation characteristics, geology, and landform with forest site quality (Carmean 1975). Soil properties such as drainage class, depth to the subsoil, and texture of the topsoil and subsoil were correlated with loblolly and slash pine site index (Barnes and Ralston 1955, Coile and Schumaker 1964). The Coile system of land classification was widely used by industrial landowners throughout the South to identify and prioritize sites suitable for planting (Coile 1960, Thornton 1960).

The need for detailed soil information increases as management practices become more intensive (Stone 1975). Growth responses to silvicultural treatments such as drainage, site preparation, fertilization, thinning, and weed control were found to be strongly affected by soil properties (Fox 1991). For example, growth response to P fertilization was large and sustained on poorly drained Ultisols in the lower Coastal Plain, but was small and inconsistent on sandy Spodosols in the same landscape (Comerford and others 1983). Soil properties were also found to strongly influence the efficacy and offsite movement of herbicides, such as hexazinone, and had to be taken into account to develop appropriate prescriptions (Lowery and Gjerstad 1991). Equipment limitations and the potential for erosion, compaction, and puddling during harvest and site preparation were also affected by soil type (Morris and Campbell 1991).

Specialized soil classification programs were developed to provide managers with the information needed to make silvicultural decisions in intensively managed plantations. The CRIFF system was created to identify soils most likely to be nutrient deficient based on soil morphological properties (Fisher and Garbett 1980). Many organizations initiated detailed soil mapping programs to provide foresters with site-specific information on soil properties considered important for intensive forest management (Campbell 1978, Thornton 1960). These soil surveys were developed specifically for forestry purposes and have generally proven more useful than the multipurpose soil maps produced by the Natural Resources Conservation Service (Morris and Campbell 1991).

The development of sophisticated Geographic Information Systems during the 1990s provided a powerful tool to assist with the implementation of intensive silvicultural regimes. Spatial analysis of the growth responses to silvicultural practices on different soil types enables foresters to make detailed silvicultural recommendations on a site-specific basis. Use of Global Positioning Systems allowed foresters to very accurately determine their exact location. Armed with these tools, foresters are now able to make detailed silvicultural prescriptions on a site-by-site basis. These site-specific prescriptions are a great improvement over the general recommendations previously used.

REALIZING THE GROWTH POTENTIAL OF SOUTHERN PINE

When planted in the Southern Hemisphere, slash and loblolly pine were found to grow significantly faster than in their natural range (Sedjo and Botkin 1997). Foresters in the South were puzzled by this phenomenon, and over the years numerous explanations were put forward to explain the observed differences in growth potential between the two regions. For example, climatic differences, especially lower nighttime temperatures leading to lower respiration rates, were often proposed as explanations for the differences (Harms and others 1994). In addition, diseases endemic to the Southern United States, such as fusiform rust [*Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme* (Hedge. & N. Hunt) Burdsall & G. Snow] and those caused by root pathogens, were not found in the Southern Hemisphere.

It was also noted that plantation management practices in the Southern Hemisphere were usually more intensive than those in the Southern United States (Evans 1992). Complete removal of weeds, especially during the first few years of the rotation, was a standard practice. Fertilizers were used to correct nutrient deficiencies throughout the rotation. This was in contrast to the operational silvicultural practices used in the Southern United States through the 1980s that focused on reducing costs per acre. Early herbicide applications, whether for chemical site preparation, herbaceous weed control, or hardwood release, usually did not completely control competing vegetation. Even though growth response was found to be proportional to the amount of competing vegetation controlled (Burkhart and Sprinz 1984, Liu and Burkhart 1994), operational herbicide treatments were usually based on application rates that achieved a threshold level of control at the lowest cost. Similarly, fertilization treatments were generally limited to a single application during the rotation to minimize costs (Allen 1987). Perhaps more importantly, silvicultural treatments were generally applied as individual, isolated treatments rather than as part of an integrated system. Notable in this respect for many organizations was the debate over the relative value of genetic improvement and silvicultural treatments for increasing stand productivity. In the Southern Hemisphere, it was recognized early on that to achieve high levels of productivity in southern pine plantations, genetics and silvicultural factors must be considered as equal components of an integrated management system.

Several forward-looking research projects established during the 1980s provided direct evidence of the growth potential of intensively managed southern pine within its native range. Most notable among these were studies established by the Plantation Management Research Cooperative at the University of Georgia and the Intensive Management Practices Assessment Center at the University of Florida.

Table 8.1—Growth rates of pines throughout the World[a]

Location	Species	Age	MAI
		years	*ft³/ac/yr*
Costa Rica	*Pinus caribaea*	8	449
New Zealand	*P. radiata*	25	457
Brazil	*P. taeda*	15	429
South Africa	*P. taeda*	22	412
Australia	*P. taeda*	20	302
United States			
Florida	*P. elliottii*	20	207
Georgia	*P. taeda*	14	374

MAI = mean annual increment.
[a] Data from Arnold (1995), Evans (1992), Borders and Bailey (2001), Yin and others (1998).

Empirical results from these studies demonstrated spectacular growth responses of both slash and loblolly pine following complete and sustained weed control in combination with repeated fertilization (Borders and Bailey 2001, Colbert and others 1990, Neary and others 1990, Pienaar and Shiver 1993). These results demonstrated that the growth potential of southern pines was not being achieved in most operational plantations in the South, and that growth rates rivaling those in the Southern Hemisphere could be achieved in the South through intensive management (table 8.1).

PREDICTING GROWTH AND YIELD IN SOUTHERN PINE PLANTATIONS

Throughout the 1950s and early 1960s, forest managers were forced to rely on yield predictions developed for natural stands. Miscellaneous Publication 50 (U.S. Department of Agriculture, Forest Service 1929) was the most widely used source of southern pine volume predictions at that time. However, it was soon apparent that stand growth and yield in plantations differed fundamentally from that in natural stands. Growth-and-yield models for southern pine plantations began to appear in the 1960s in response to the need for improved growth-and-yield information (Bennett 1970, Bennett and others 1959, Burkhart 1971, Clutter 1963, Coile and Schumaker 1964). Initially, plantation growth-and-yield models were whole-stand models that simply predicted current stand yield (Bennett 1970, Bennett and others 1959). However, more sophisticated models were soon developed that were able to predict total yield as well as the diameter distribution of the stand (Bennett and Clutter 1968, Burkhart and Strub 1974, Smalley and Bailey 1974). These diameter distribution models, although more complicated and data intensive, proved to be substantially more useful tools for forest managers, because volume of specific products could be estimated which provided a more accurate estimate of stand value. In the 1970s, distance-dependent individual-tree growth models were developed that incorporated the effects of neighboring competing trees on growth (Daniels and Burkhart 1975). Distance-dependent tree growth models should provide better estimates of the impact of silvicultural practices such as thinning. However, it has generally been found that diameter distribution models give results very similar to those of individual-tree growth models in most cases with less effort and lower cost (Clutter and others 1983).

Growth-and-yield research in the South was enhanced tremendously by the work of the Plantation Management Research Cooperative that formed at the University of Georgia in 1976 and the Virginia Polytechnic Institute and State University Growth and Yield Cooperative that formed in 1979. These two programs have produced sophisticated and very accurate models of growth and yield in southern pine plantations. Models have been developed that accurately predict the impact of silvicultural practices such as site preparation (Bailey and others 1982, Clutter and others 1984), thinning (Amateis and others 1989, Cao and others 1982), fertilization (Amateis and others 2000, Bailey and others 1989), and the impact of hardwood competition on stand structure and yield (Burkhart and Sprinz 1984, Liu and Burkhart 1994). Modern growth-and-yield models, whether individual tree growth models or diameter distribution models, can accurately predict stand-level timber production in intensively managed pine plantations with a remarkable degree of precision (Pienaar and Rheney 1995).

As plantations replaced natural stands, foresters strove to create a fully regulated forest that optimized financial returns from the overall land base under management (Davis 1966). The introduction of linear programming as a forest planning tool in the 1960s was a major advance in this effort (Chappelle 1966, Curtis 1962, Leak 1964). Improvements in computers in the 1960s made it possible to use linear programming techniques to solve realistically sized forest harvest scheduling problems for the first time (Clutter and others 1983). The development of the MAX-MILLION linear programming-based harvest scheduling program (Clutter 1968) fundamentally changed pine plantation management throughout the South. For the first time organizations were able to use this technique to manage timberland in an organized and quantitative manner that optimized the present value of future cash flows. Forest managers were also able to use these harvest planning tools to predict the financial returns from alternative silvicultural regimes that improved plantation growth. It was soon widely recognized that increased survival and growth of plantations resulting from improved genetics, site preparation, weed control, fertilization, and density management could significantly increase the financial returns from forest management. This realization was the driving factor in the widespread implementation of intensive silviculture that occurred in the 1980s and 1990s. The descendants of these original harvest scheduling models have been revised and improved to the point where they are now able to solve the extremely complex harvest scheduling problems presented by the adjacency and harvest block size restrictions now imposed on industrial plantations in the South (Van Deusen 1999).

CURRENT STATE-OF-THE-ART: INTEGRATED, SITE-SPECIFIC SILVICULTURE

Management of southern pine plantations in the United States is being transformed from a relatively extensive system of planting coupled with isolated individual treatments to a much more intensive system in which genetic and site resources are manipulated in concert to optimize stand productivity. Heretofore, site quality was viewed as a static property, and individual treatments were applied in isolation with little understanding of their interactions and synergies. Today, management is moving toward a more fully integrated approach in which improved genotypes are matched to specific soil types, and silvicultural treatments, including site preparation, weed control, and fertilization, are integrated to maintain optimal water and nutrient availability throughout the rotation (Allen and others 1990, Neary and others 1990). With this approach, site quality is no longer fixed, but can be improved greatly by proper management.

In the past, most silvicultural decisions were based primarily on the results of empirical field trials. An important feature of current state-of-the-art silvicultural regimes is that they are now based on both empirical results and an understanding of the physiological processes controlling forest productivity. It is now widely recognized, not only by research scientists but also by operational foresters, that forest productivity is determined by the ability of the forest to capture incoming solar radiation and convert it to stemwood biomass (Cannell 1989). Productivity of southern pine plantations is related to stand leaf area (fig. 8.7), which is controlled by the genetic potential of the trees and the availability of light, water, and nutrients (McCrady and Jokela 1998, Vose and Allen 1991, Vose and others 1994). Recent research has shown that nutrient availability, rather than availability of light or water, most strongly affects leaf area development and, consequently, controls productivity on most sites in the South (Albaugh and others 1998, Colbert and others 1990, Dalla-Tea and Jokela 1991).

In intensively managed plantations, interactions among silvicultural treatments and genetics are now recognized. There are also large differences in growth efficiency among families of both loblolly and slash pine, and these differences can now be exploited to improve stand productivity (Li and others 1991, McCrady and Jokela 1998, Samuelson 2000). The combined effect on growth potential that results from the use of improved genotypes and intensive silviculture appears to be at least additive (McKeand and others 1997). Recent results from progeny tests demonstrated that the growth of some better families increased more than the growth of poorer families as site quality or silvicultural inputs, or both, increased (fig. 8.8). Foresters are now using this information to deploy better genotypes to higher quality sites that will be managed more intensively.

Foresters now modify silvicultural practices to take advantage of interactions among treatments based on a better understanding of their impacts on site resource availability (Allen and others 1999). As an example, both chemical site preparation and disking treatments are used to control competing hardwoods. Although disking also improves soil physical properties, it is likely that the combined growth response following disking coupled with herbicide treatment would be less than additive. Therefore, chemical treatments are now substituted for mechanical treatments on sites where hardwood competition is a severe problem. In contrast, the growth response following fertilization coupled with herbicide control of competing hardwoods might be more than additive since hardwoods responding to fertilizer compete more vigorously with the pine crop tree for light and water (Borders and Bailey 2001, Swindel and others 1988). Weed control plus fertilization is the most widespread treatment used to accelerate growth in pine plantations in the South (Albaugh and others 1998, Colbert and others 1990, Jokela and others 2000). Fertilization regimes have been developed that enable foresters to match nutrient supply with the demand of the stand. Depending on the soil type, various types and amounts of fertilizer may be added four or more times during a 20-year rotation to augment native soil fertility and maintain high nutrient availability. These fertilizer applications are coordinated with site preparation treatments and weed control as needed during the rotation to ameliorate soil physical limitations and eliminate competition for soil water and nutrients, thus insuring optimal growing conditions for the designated crop trees throughout the rotation.

Current growth rates in intensively managed plantations in the South may exceed 350 cubic feet per acre per year (Borders and Bailey 2001), which puts them on par with fast-growing plantations in other parts of the World (table 8.1). These intensively managed plantations offer landowners attractive financial returns (Yin and Sedjo 2001, Yin and others 1998). Although the costs associated with intensive management are higher, financial returns from such plantations are higher because the growth rates are much greater and the rotation lengths shorter. General realization of this fact is causing a paradigm shift in the philosophy of forest landowners in the South. Current management of pine plantations is moving away from the traditional focus on minimizing cost per acre to a new emphasis on decreasing cost per ton of wood produced. Because wood costs are usually the single largest cost in pulp, lumber, and engineered wood production, minimizing wood cost through intensive management may be the best way for forest industry in the South to remain competitive in global markets.

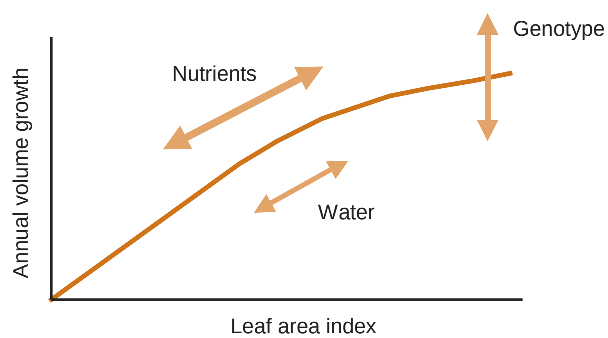


Figure 8.7—Relationship between leaf area index and growth rate in southern pine plantations.

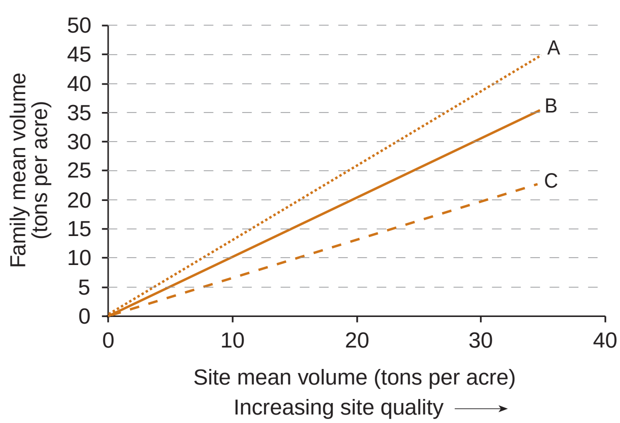


Figure 8.8—Performance of loblolly pine families [identifications are (A) 07–56, (B) 08–59, and (C) 01–64] as site quality increases (adapted from McKeand and others 1997).

THE FUTURE: CLONAL FORESTRY AND THE PROMISE OF BIOTECHNOLOGY

Because of the continued increase in the world's populations, demand for forest products is increasing, while large amounts of forest land are being lost to other land uses such as urbanization (Wear and Greis 2002) or degraded (Food and Agriculture Organization of the United Nations 1997). In addition, timber harvesting in native forests in many parts of the world is being restricted. The use of intensively managed plantations for timber production will have to increase in the future to meet the increasing demand for wood and fiber and still reserve large areas of native forests for conservation and preservation uses (Sedjo and Botkin 1997).

Implementing integrated site-specific silvicultural management regimes that optimize water and nutrient availability throughout the rotation will remain the paradigm of plantation forestry in the future. However, at some point the growth response to some silvicultural treatments will probably level off. Once a site is weed-free, no additional growth gains are likely from additional herbicide application until the weeds grow back. Current management regimes are approaching this level of competition control in some plantations (Yin and others 1998). However, the future of fertilization may be somewhat different. As growth rates of forest stands increase, the demand for nutrients will also increase. The nutrient supply in most forest soils is not high enough to meet these increased demands. Current fertilization regimes focus on maintaining N and P supply. It is likely that as growth rates and nutrient demand increase, deficiencies of nutrients other than N and P will develop in the South as they have in other parts of the World (Evans 1992, Gonçalves and Benedetti 2000, Jokela and others 1991b, Will 1985). Fertilization regimes in the South will have to be modified to supply both macronutrients and micronutrients in a manner that matches nutrient demand of the stand throughout the rotation. Mechanistic models of soil nutrient supply, tree demand, and uptake are being developed for southern pines so that fertilizer regimes can be optimized for specific soil types across the region. Significant growth increases in the future are likely to occur from this more sophisticated management of nutrient availability.

The potential gains in future plantations through genetic manipulation of southern pine are large. At the turn of the 21st century, most plantations were still planted with open-pollinated, half-sib families. Many organizations are moving toward the use of seed produced by controlled pollination of elite parents, because this can increase growth significantly (fig. 8.4). One drawback of controlled pollination is the additional expense and time required to produce this seed. Consequently, the quantity of control-pollinated seed now available is not sufficient to meet large-scale reforestation needs. To overcome this obstacle, rooted cuttings are being used to multiply the limited number of seedlings available from controlled pollination (Foster and others 2000). This technology is widely used in other parts of the world with species such as radiata pine and eucalyptus (*Eucalyptus* spp.) and will soon be operational with southern pine in the United States.

Clonal forestry holds the greatest promise for increasing the productivity of southern pine plantations in the near term. Clonal forestry relies on vegetative propagation procedures to mass produce identical copies of selected individual trees that possess excellent genetic potential (Gleed and others 1995). Clonal eucalyptus plantations are widely planted in the Southern Hemisphere and have dramatically improved productivity (Arnold 1995). Growth rates exceeding 600 cubic feet per acre per year have been documented in clonal eucalyptus plantations in Brazil (Evans 1992). In addition, clones with specific wood properties have been developed to optimize pulp production. The technology to mass produce clones of southern pine is still under development and includes the use of rooted cuttings and somatic embryogenesis. In the near term, it is likely that some combination of somatic embryogenesis and rooted cuttings will prove to be the most economical and efficient way to produce adequate numbers of southern pine clones (fig. 8.9). Based on results from clonal

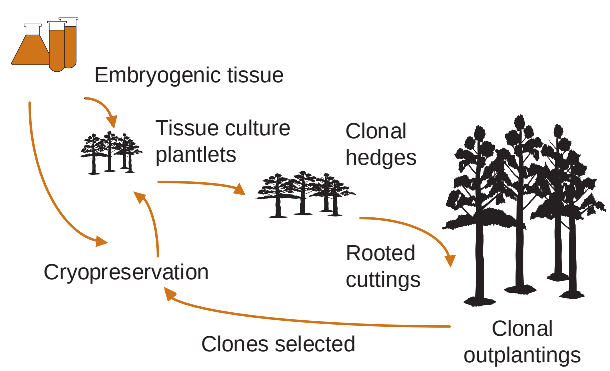


Figure 8.9—Integration of rooted cuttings and somatic embryogenesis into a clonal forestry program for southern pines in the United States.

plantations in other parts of the world, it will likely be possible to increase productivity of southern pine plantations by at least 50 percent by deploying appropriate clones to specific soil types and then implementing integrated, intensive silvicultural regimes. Mean annual increments > 500 cubic feet per acre per year may soon be within our reach on selected sites in the South.

In the longer term, prospects for new developments in forest biotechnology are bright. Research is revealing the genetic basis of disease resistance, wood formation, and growth in southern pine. Molecular markers are being developed that will substantially increase the efficiency of conventional tree breeding programs because they will no longer have to rely on phenotypic expression of desired traits in long-term field trials (Williams and Byram 2001). The use of molecular markers is particularly valuable with complex traits that have low heritability, which is usually the case in southern pine.

Genetic engineering accomplished by directly introducing foreign DNA into trees has been reported in a number of species, including radiata pine and hybrid poplar (Bauer 1997). The potential for this technology to dramatically improve wood properties, disease resistance, and growth rates of forest trees has been reported widely in both the technical and popular press. Unfortunately, although the first successful transgenic trees were produced in the 1980s (Fillatti and others 1987), it remains difficult to produce transgenic trees, especially the southern pines. Numerous hurdles remain to be overcome before the promise of genetic engineering in trees is fulfilled (Sederoff 1999). Even with the concerted research efforts currently underway in this area, it seems likely that several decades will elapse before transgenic trees are a feature of operational southern pine plantations.

CONCLUSIONS

Management practices in southern pine plantations have undergone a dramatic evolution over the last 50 years. By applying research results to operational plantations, foresters have more than doubled the productivity of operational southern pine plantations over this period (fig. 8.3). For example, older management practices that produced plantations with growth rates of < 90 cubic feet per acre per year have been replaced by new practices that create stands that are currently producing 400 cubic feet per acre per year on some sites. Pine plantations in the South are among the most intensively managed forests in the world (Schultz 1997). Site-specific, integrated management regimes that incorporate the genetic gains available from tree improvement along with silvicultural practices that optimize resource availability throughout the rotation are now the norm. Growth rates in many pine plantations in the South are now approaching those in the Southern Hemisphere. Additional gains in productivity are likely as management regimes are refined further. In the near term, implementation of clonal forestry holds the greatest promise to dramatically increase productivity in southern pine plantations. As a result, the South is likely to remain the woodbasket of the United States for the foreseeable future.

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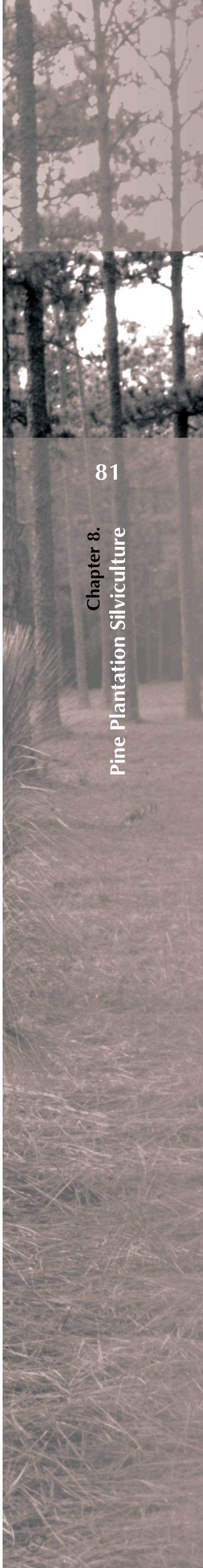

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