The Development of Pine Plantation Silviculture in the Southern United States

Thomas R. Fox, Eric J. Jokela, and H. Lee Allen

ABSTRACT

In the 1950s there were vast acreages of cutover forestland and degraded agricultural land across the South. Less than 2 million ac of southern pine plantations existed at that time. By the end of the 20th century, there were 32 million ac of southern pine plantations in the US South and this region is the wood basket 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 US Forest Service, southern forestry schools, state forestry agencies, and forest industry. This article reviews the contributions of applied silvicultural research in 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established in the 1950s and 1960s, which produced less than 90 $\text{ft}^3\ \text{ac}^{-1}\ \text{yr}^{-1}$, have been replaced by plantations established in the 2000s, which may produce in excess of 400 $\text{ft}^3\ \text{ac}^{-1}\ \text{yr}^{-1}$. Currently, southern pine plantations are among the most intensively managed forests in the world. Growth of plantations managed using modern, integrated, site-specific silvicultural regimes now can rival that of plantations of fast-growing exotic species in the Southern Hemisphere.

Keywords: loblolly pine, site preparation, tree improvement, fertilization

Pine plantation silviculture in the southern United States is one of the major success stories in the world for forestry. In 1952, there were only 1.8 million ac of pine plantations in the South (Figure 1) containing 658 million ft^3 of timber (USDA 1988). At the turn of the 21st century, there were 32 million ac of pine plantations in the South that contain 23.9 billion ft^3 of timber (Wear and Greis 2002). Perhaps more remarkable is the significant increase in productivity that occurred during this period. Mean annual increment of pine plantations has more than doubled and rotation lengths have been cut by more than 50% (Figure 2). The success of pine plantation silviculture has turned the South into the wood basket 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 WWII. The success of this effort was due in large part to the cooperative research and technology transfer efforts of many organizations, including the US Forest Service, state forestry agencies, forestry programs at southern universities, and forest industry.

The objective of this article was to describe the evolution of southern pine plantation silviculture over the last 60 years. As part of this, we hope to show the significant contributions that applied cooperative research has made to this success story.

Setting the Stage for Plantation Forestry in the South

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 (*Pinus palustris* L.) and ship timbers from live oak (*Quercus virginiana* P.

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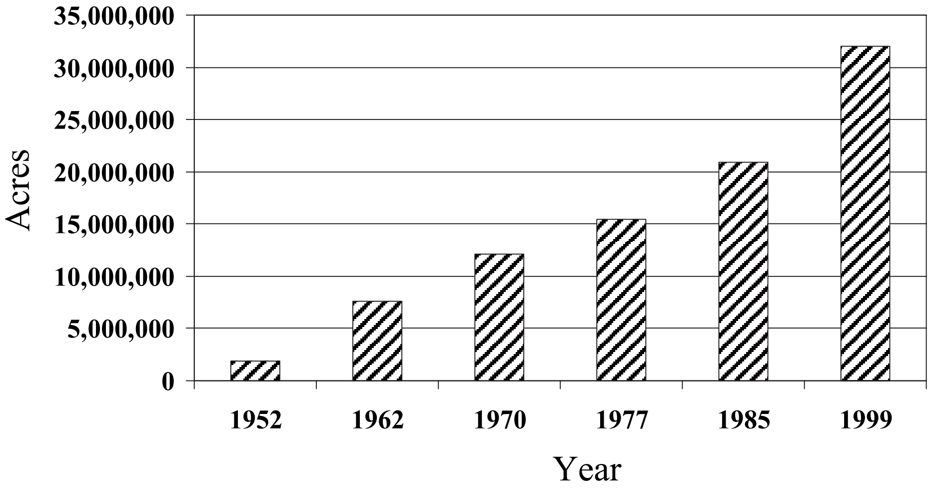

Figure 1. Number of acres of pine plantations in the southern United States from 1952 to 1999.

Mill.; Butler [1998], Williams [1989]). 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 over 25 million ac, or 47%, 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, caused large amounts of agricultural land to be abandoned throughout the South between the end of the Civil War and WWII.

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

The Advent of Plantation Forestry

At the start of the 20th century, almost no effort was devoted to reforestation after 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. At the end of WWII, 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, Wakeley (1954) stated "The area in the South still in need of planting is 13 million acres. . . . Every state from Virginia to Texas has substantial areas where the land should be planted for timber production or erosion control. Much is on farms and much is industrially owned. A very sizable portion is in the hands of small investors and some is in public hands." Wahlenberg (1960) estimated that in the late 1950s there were still 29 million ac in need of planting throughout the South.

During the 1920s, the US 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 ac near Bogalusa, Louisiana (Wakeley 1954). During the 1920s, the US Forest Service also began its reforestation program in the South with the planting of 10,000 ac in the Sumter National Forest in South Carolina. During the 1930s, the Civilian Conservation Corps planted over 1.5 million ac across the South. The success of these early efforts indicated the feasibility of establishing pine plantations.

Tree planting in the South, which had nearly ceased during WWII, rapidly increased in the years immediately after the war (USDA 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 provided additional impetus for the large increase in southern pine plantation forestry (Reed 1995).

Seedling Production

Artificially regenerating the large acreages in the South required an abundant supply of high-quality seedlings. A concerted research effort of the US 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 establish successfully southern pine plantations. With its publication, the stage was set for the rapid expansion of southern pine seedling production. In 1950, the US 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 (USDA 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, stem, and needle characteristics that was 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 Southern Forest Nursery Management Cooperative at Auburn University in 1970 highlights the importance placed on improving nursery practices and seedling quality (Southern Industrial Forest Research Council [SIFRC] 2000). Their research led to improved nursery practices such as sowing seed by size class and single family groups, reducing nursery bed density, top pruning, root pruning, increasing nitrogen fertilization, and mycorrhizal inoculation. These practices were incorporated into standard operating procedures at most pine seedling nurseries, substantially improving the quality of the seedlings produced (Mexal and South 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, USDA 1989). The use of refrigerated vans for seedling storage and transport, now widespread throughout the South, probably was the single most important factor in making certain that seedlings arrive at the planting site in good condition. With improved nursery practices, together with proper care and handling of seedlings during transport, storage, and planting, survival rates for planted seedlings commonly exceeds 90%.

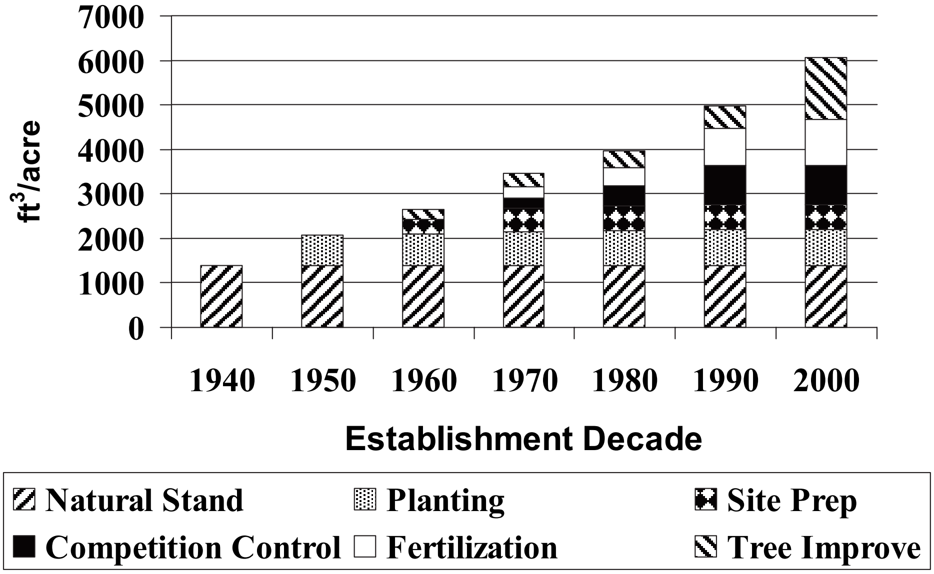

Figure 2. Estimated total yield and contributions of individual silvicultural practices to productivity of pine plantations in the southern United States from 1940 to 2000.

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 mi 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). To provide a more consistent supply of cones, seed production areas often were established in natural stands containing good phenotypes (Goddard 1958).

The seed orchard concept was proposed as early as the late 1920s as a 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 shown 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 watershed 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 soon were founded at the University of Florida in 1953 and North Carolina State University in 1956 (SIFRC 2000).

The seed orchard concept quickly gained favor and became the preferred method of producing southern pine seed (Zobel et al. 1958). The first southern pine seed orchard was established by the Texas Forest Service in 1952 to produce drought-hardy loblolly pine (*Pinus taeda* L.; Zobel [1953]). Industrial members of the University of Florida Cooperative Forest Genetics Research Program began establishing slash pine (*Pinus elliottii* Engelm.) seed orchards in 1953 (Wang and Perry 1957). By 1987, over 9,700 ac of seed orchards had been established in the South and nearly all the southern pine seedlings 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 caused by tree improvement were not fully realized for several decades (Zobel and Talbert 1984, Todd et al. 1995). 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 8–12% 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% when gains from other traits such as stem straightness, disease resistance, and wood density were included (Todd et al. 1995). Continued breeding and testing led to the development of second-generation orchards in the 1980s. Second-generation seed orchards currently produce more than 50% of the seed in the South. It is estimated that volume growth in current plantations will be 14–23% greater than in plantations established using first-generation material (Li et al. 1997).

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. However, many organizations are moving toward the use of seed produced through the control pollination of elite parents, because of the potential growth improvements made possible with this technique. Mass control pollination is now used by several organizations in the South to produce large quantities of control pollinated seed (Steve McKeand, NC State University, pers. comm., 2007).

Clonal forestry holds the greatest promise to increase 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 et al. 1995). In addition, clones with specific wood properties have been developed to optimize pulp production. Clonal eucalyptus plantations are widely planted in the Southern Hemisphere and have dramatically improved productivity (Arnold 1995). Growth rates exceeding 600 ft^3 ac^{-1} yr^{-1} have been documented in clonal eucalyptus plantations in Brazil (Evans 1992). The technology to mass produce clones of southern pine, such as somatic embryogenesis, still is under development. However, based on results from clonal plantations in other parts of the world, it likely will be possible to increase productivity of southern pine plantations by at least 50% by deploying appropriate clones to specific soil types and then implementing integrated, intensive silvicultural regimes. Mean annual increments exceeding 500 ft^3 ac^{-1} yr^{-1} may be within our reach on selected sites in the South.

In the longer-term, the promise of biotechnology looms 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 usually is the case in southern pine.

Genetic engineering accomplished by directly introducing foreign DNA into trees has been reported in a number of woody plants, including hybrid poplar (Bauer 1997). The potential for this technology to improve dramatically wood properties, disease resistance, and growth rates of forest trees has been reported widely in both the technical and the popular press. Although the first successful transgenic trees were produced in the 1980s (Fillatti et al. 1987), it remains difficult to produce transgenic trees, especially with the southern pine. Numerous hurdles must be overcome before the promise of genetic engineering in trees is widely implemented (Sederoff 1999). Even with the concerted research effort underway in this area, it seems likely that at least a decade or two will elapse before transgenic trees are a feature of operational southern pine plantations.

Site Preparation

Before the 1950s, planting generally was limited to old fields and grassy savannahs that originated on cutover sites after frequent wildfires. Most cutover pine sites in the South were regenerated after harvest by leaving six to eight seed trees per acre (Duzan 1980). Many of these stands failed to regenerate pine adequately because of 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, 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 savannahs. The improved survival and growth on old fields was attributed to various factors including low levels of competing hardwood vegetation, improved soil physical properties, and improved soil fertility caused by residual fertilizer and lime. Therefore, the aim of site preparation was to recreate these old-field conditions on cutover sites using various mechanical means such as anchor chaining, chopping, burning, root raking, shearing, and disking (Balmer and Little 1978). Mechanical site preparation practices often evolved more rapidly through trial and error by field foresters and equipment manufacturers than through formal R&D 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 et al. 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 used 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 after harrowing often was 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 (Wells and Crutchfield 1974, Haines et al. 1975). 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. Then, the area was broadcast disked with a large harrow. In many cases, the windrows and piles were then burned after the debris dried. Mechanical treatments that include disking increased growth of southern pine seedlings by 15–90% compared with sites that were not disked (Haines et al. 1975; Lantagne and Burger 1983, 1987).

Subsoiling gained popularity on upland sites in the South with the advent of combination plows in the 1980s that disked the surface soil and ripped the subsoil in a single pass (Lowery and Gjerstad 1991). The deeper ripping was thought to improve root penetration into the heavy clay subsoil that frequently occurs in the Upper Coastal Plain and Piedmont. However, the documented growth responses after subsoiling have been variable. Early work found that volume growth increased by up to 20% in young stands that were less than 5 years old (Berry

1979, Lantagne and Burger 1983, Wittwer et al. 1986). However, the growth response after tillage caused by changes in soil physical properties often was confounded with the growth impact of improved weed control that occurred after tillage. A number of studies of subsoiling have been conducted recently on sites where competing vegetation was effectively controlled using herbicides, which eliminates the confounding effects of differing levels of competing vegetation (Wheeler et al. 2002, Carlson et al. 2006). In both of these studies, subsoiling had little impact on survival or growth of planted seedlings when compared with disking only.

Intensive site preparation treatments used to create old-field conditions soon generated concern about long-term site productivity. Unless great care was taken, the forest floor and topsoil often were raked into the piles and windrows along with the slash during site preparation. This displaced large quantities of nutrients from the site (Morris et al. 1983). A report by Keeves (1966) on second rotation productivity declines in radiata pine (*Pinus radiate* D. Don.) on intensively prepared sites in Australia, caused by 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 et al. 1989). Windrowing decreased site index by 11 ft in this loblolly pine plantation. As in New Zealand and Australia, it was shown that the growth declines observed on windrowed sites was caused by nutrient deficiencies due to displacement of the forest floor and topsoil from the interior of the stand to the windrows (Morris et al. 1983, Vitousek and Matson 1985). These observations lead to the search for alternative, less-intensive site preparation treatments that would maintain site quality (Tippin 1978, Burger and Kluender 1982). Chemical site preparation treatments began to gain favor because they effectively controlled competing hardwood vegetation with minimal site disturbance (Lowery and Gjerstad 1991).

One of the main objectives of site preparation was to create conditions where hardwood competition was absent. However, 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). The use of herbicides for site preparation began to increase in the 1970s after development of herbicides that effectively controlled hardwood sprouting (Fitzgerald 1982, Miller et al. 1995) and thus increased pine growth. Chemical site preparation expanded rapidly when it was discovered that similar or better growth occurred at a lower cost on chemically prepared sites compared with mechanically prepared sites (Knowe et al. 1992). By the 1990s, chemical site preparation had replaced mechanical site preparation on most upland sites (Lowery and Gjerstad 1991) and remains the most common form of site preparation in the Piedmont and Upper Coastal Plain.

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 establishes 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 on 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 (Schlaudt 1955, Miller and Maki 1957, Maki 1960). The large growth response of planted pines after drainage reported in a number of studies, ranging from 80% to almost 1,300% (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). However, use of drainage as a silvicultural tool essentially stopped in the South by the early 1990s because of concerns over conversion of jurisdictional wetlands to uplands by following drainage (Gaddis and Cubbage 1998).

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 seedlings planted 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. Bedding soon became the standard site preparation practices on poorly drained soils where it improved surface soil tillage and soil aeration and reduced shrub competition. Many studies observed large short-term growth responses after bedding on poorly drained soils (McKee and Shoulders 1974; Wells and Crutchfield 1974; Terry and Hughes 1975, 1978, Gent et al. 1986). For example, on a poorly drained site in the Coastal Plain of Virginia, total volume at age 21 years in a bedded treatment was 1,844 $ft^3\ ac^{-1}$, which was significantly greater than total volume in the chop treatment, which was only 1,214 $ft^3\ ac^{-1}$ (Kyle et al. 2005). The growth response of bedding tends to decline when rotations longer than 30 years are used (Wilhite and Jones 1981, Kyle et al. 2005).

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 (Clason 1978, Cain and Mann 1980, Duzan 1980). During the 1960s and 1970s, the herbicide 2,4,5-T was widely used to release young pine plantations from competing hardwoods because it was inexpensive to apply, 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, hardwood release treatments essentially ceased for a number of years in the South. However, continued concerns about hardwood competition across the South 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 (SIFRC 2000). Numerous trials were established to evaluate herbicide efficacy and document the growth response of pines after herbicide application. Several alternative herbicides were soon registered for forestry uses including glyphosate, hexazinone, imazapyr, metsulfuron methyl, and trychlopyr. The newer compounds were more environmentally benign, with low mammalian and fish toxicity, rapid degradation, and minimal off-site movement (Neary et al. 1993). Hardwood control in pine plantations using these newer herbicides generally was more successful than previous treatments with herbicides such as 2, 4, 5-T (Minogue et al. 1991). Growth of southern pines can be increased by more than 100% after effective control of competing hardwoods (Burkhart and Sprinz 1984, Minogue et al. 1991, Borders and Bailey 2001, Amishev and Fox 2006). The control of natural regeneration of pine in new pine plantations is a major concern today, particularly when more expensive, elite genotypes are planted. There are no herbicides currently available that can be used to control competing pines without damaging the desired pine crop trees.

Although the effects of hardwood competition on pine growth was well documented (Clason 1978, Cain and Mann 1980), the effect of herbaceous vegetation on growth 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 after control of grass and herbaceous vegetation (Terry and Hughes 1975). With the advent of herbicides such as hexazinone, imazapyr, and sulfometuron methyl, which effectively controlled herbaceous weeds without damaging young pine seedlings, large and consistent growth responses were widely observed (Holt et al. 1973, Fitzgerald 1976, Nelson et al. 1981). By the late 1980s, it was clear that herbaceous weed control had a long-term impact on pine growth (Glover et al. 1989). Control of herbaceous weeds during the first growing season was soon a widespread practice in pine plantations throughout the South (Minogue et al. 1991).

Accelerating Growth by Fertilization

Early research on forest soil fertility, tree nutrition, and response to fertilizers indicated that growth increases after fertilization of southern pine were possible (Walker 1960). However, 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 large growth responses in slash pine after phosphorus additions on poorly drained clay soils in the flatwoods of Florida (Pritchett et al. 1961, Laird 1972). Volume gains over 150 ft^3 ac^{-1} yr^{-1} over 15 to 20 years were observed on similar soils throughout the Coastal Plain (Jokela et al. 1991). The long-term growth response after phosphorus fertilization on these wet clays translated into 5- to 15-ft increases in site index. When foresters learned to identify these phosphorus-deficient sites and prescribe appropriate fertilizer applications, fertilization emerged as an operational treatment (Beers and Johnston 1974, Terry and Hughes 1975). Typically, optimal growth responses were achieved on these sites when approximately 50 lb^{-1} ac^{-1} of elemental phosphorus was added at the time of planting (Jokela et al. 1991).

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 1969, respectively, to address this problem (SIFRC 2000). Researchers in these two programs and the US 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 (Wells et al. 1973, 1986; Comerford and Fisher 1984). 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 after fertilization and was adopted widely (Fisher and Garbett 1980). Critical foliar concentrations for nitrogen and phosphorus were identified for slash and loblolly pine that were well correlated with growth response after fertilization (Wells et al. 1973, Comerford and Fisher 1984).

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 nitrogen and phosphorus (Fisher and Garbett 1980, Comerford et al. 1983, Gent et al. 1986, Allen 1987, Jokela and Stearns-Smith 1993, Hynynen et al. 1998, Amateis et al. 2000). This work confirmed that a large and consistent growth response after midrotation fertilization with nitrogen (150–200 lb^{-1} ac^{-1} of N) and phosphorus (25–50 lb^{-1} ac^{-1} of P) occurred on the majority of soil types. Growth response after N plus P fertilization in loblolly pine stands averaged 50–60 ft^3 ac^{-1} yr^{-1}, which represents a growth increase of approximately 25% (Fox et al. 2007). These responses have typically lasted for at least 6–10 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 ac annually in 1988 to about 1.2–1.4 million ac/year since 2000 (Fox et al. 2007). By the end of 2004, over 16 million ac of southern pine plantations had been fertilized in the United States (Albaugh et al. 2007). Recent work has shown that deficiencies of other nutrients such as potassium, calcium, copper, and boron occur on certain soil types in the South and significant growth increases occur after application of these nutrients (Kyle et al. 2005, Fox et al. 2007).

Predicting Growth and Yield in Southern Pine Plantations

Throughout the 1950s and early 1960s, forest managers relied on yield predictions developed for natural stands. Miscellaneous Publication 50 (USDA 1929) was the most widespread source of southern pine volume predictions in use at that time. However, it was soon apparent that stand growth and yield in plantations was fundamentally different than 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 et al. 1959, Clutter 1963, Coile and Schumacker 1964, Bennett 1970, Burkhart 1971). Initially, plantation growth and yield models were whole stand models that simply predicted current stand yield (Bennett et al. 1959, Bennett 1970). 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, distant-dependent individual-tree growth models were developed that incorporated the effects of neighboring competing trees on growth (Daniels and Burkhart 1975). Distant-dependent tree growth models should provide better estimates of the impact of silvicutural practices such as thinning. However, generally, it is has been found that diameter distribution models give very similar results as individual-tree growth models, in most cases, with less effort and lower cost (Clutter et al. 1983).

Growth and yield research in the South was enhanced tremendously by the work of the Plantation Management Research Cooperative (PMRC) that formed at the University of Georgia in 1976 and the Virginia Tech Growth and Yield Cooperative that formed in 1979 (SIFRC 2000). These two programs have produced sophisticated and very accurate models of growth and yield in southern pine plantations. Models have been developed and modified to predict the impact of silvicultural practices such as site preparation (Bailey et al. 1982, Clutter et al. 1984), thinning (Cao et al. 1982, Amateis et al. 1989), fertilization (Bailey et al. 1989, Amateis et al. 2000), and the impact of hardwood competition (Burkhart and Sprinz 1984, Liu and Burkhart 1994) on stand structure and yield. Additional improvements in growth and yield models will be needed to model intensively managed plantations where growth rates will exceed those heretofore seen in the South. It will be particularly important to develop improved mortality functions and basal area growth functions for intensively managed stands where mortality rates appear to be less and basal area growth rates are much greater. Changes in growth and yield models are also needed to account for the increased uniformity that is likely to occur in clonal plantations.

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 et al. 1994). In addition, diseases endemic to the southern United States, such as fusiform rust 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 and 1990s 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 PMRC at the University of Georgia, the Intensive Management Practices Assessment Center at the University of Florida, and the Southeast Tree Research and Education Study established by the US Forest Service and North Carolina State University in North Carolina (SIFRC 2000). Empirical results from these studies showed large growth responses of both slash and loblolly pine after complete and sustained weed control in combination with repeated fertilization (Colbert et al. 1990, Neary et al. 1990, Pienaar and Shiver 1993, Borders and Bailey 2001, Albaugh et al. 2004). These results indicated 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. On many sites where prior management practices produced plantations with growth rates of less than 90 $ft^3\ ac^{-1}\ yr^{-1}$, modern, state-of-the-art integrated management regimes create stands that are currently producing more than 350 $ft^3\ ac^{-1}\ yr^{-1}$ (Figure 2).

Conclusions

Management practices in southern pine plantations have undergone a dramatic evolution over the last 50 years. Many pine plantations in the South are now among the most intensively managed forests in the world (Schultz 1997). Current growth rates in intensively managed plantations in the South may exceed 400 ft^3 ac^{-1} yr^{-1} (Borders and Bailey 2001), which puts them on par with fast-growing plantations in other parts of the world (Evans 1992). These intensively managed plantations offer landowners attractive financial returns (Yin et al. 1998, Yin and Sedjo 2001). 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 are shorter (Allen et al. 2005). The improved productivity of intensively managed plantations makes it possible to maintain and even increase the amount of timber produced in the South, even as urban expansion reduces the land dedicated to long-term timber production (Wear and Greis 2002).

Implementing 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 is the key to enhancing productivity of southern pine plantations. The knowledge required to develop these sophisticated management regimes was developed in large part through collaborative research conducted by universities, forest industry, and government agencies such as the US Forest Service. By applying research results to operational plantations, foresters have more than doubled the productivity of southern pine plantations over the last 50 years. Although much of this research was initially supported and first implemented by forest industry, most of the knowledge quickly became available to nonindustrial private landowners in the region via industry-sponsored landowner assistance programs and university cooperative extension and outreach efforts.

There has been a substantial transformation in timberland ownership in the South in the last 10 years. Most of the large integrated forest products companies that dominated southern pine plantation forestry through the 1980s divested their timberland holdings over the last 10 years (Clutter et al. 2005). A new class of forest landowners has emerged during this period including Timberland Investment and Management Organizations (TIMO) and Real Estate Investment Trusts. Because the investments in timberland by TIMOs are relatively short term, usually between 10 and 15 years, many of the TIMOs are less inclined to invest in silvicultural practices, particularly those made early in the rotation (Clutter et al. 2005). However, these new forest landowners still can take advantage of many of the advances from silvicultural research to improve the productivity, profitability, and sustainability of their southern pine plantations (Allen et al. 2005).

A major concern associated with the transition in forestland ownership in the South has been the decrease in support of forestry research. Both internal proprietary research and external cooperative research programs have declined substantially or has been entirely eliminated by the new landowners who acquired the timberland assets from the integrated forest products companies (Clutter et al. 2005). Consequently, several of the university/industry research cooperatives in the South were terminated in the last 10 years and the support for some of the remaining programs has declined to the point where their long-term survival is questionable (SIFRC 2000, Clutter et al. 2005). During this time, there also has been a significant decline in the research focused on forest productivity at southern universities and the US Forest Service (SIFRC 2000). This is an alarming trend because the increases in productivity that make plantation forestry an attractive investment in the South would not have occurred without the accumulated knowledge generated by research over the last 50 years. We believe that additional support for research focused on forest productivity will be needed in the coming decades if we hope to continue to make the advances in plantation productivity similar to those that have occurred in the past. A renewed commitment to forestry research will help to insure that the South remains the wood basket of the United States.

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