




Southern Forest Science:
Past, Present, and Future

H. Michael Rauscher and Kurt Johnsen, Editors

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FRONT COVER PHOTOS (left to right):

The Macon Fire Laboratory in Georgia has a long history of providing solutions on wildfire control, prescribed burning, and smoke management—solutions that will come into play again as more and more southerners leave cities and suburbs and move into the wildland urban interface. (SRS photo)

Since the 1930s, survey crews have been collecting information about forest conditions on thousands of permanent plots established on public and private land—their results form the basis of economic forecasts of timber markets, public land management policies, and incentives for afforestation on private lands. (Photo by M. Ward)

In early global change research at the Duke Forest in Durham, NC, chambers were constructed to measure the effects of acid rain and ozone on loblolly pines. (Photo by M. Schoeneberger)

As they did in reforestation efforts a century ago, disease resistant seedlings continue to play an important role in the sustainability of southern forests. (SRS photo)

The Bent Creek Experimental Forest, known for its work on oak regeneration, also conducts research on bears and other species in mountain landscapes. (SRS photo)

Divers estimate abundance of trout in a study of fish habitat in the Southern Appalachians. (Photo by P. Flebbe)

BACK COVER PHOTOS (left to right):

Researchers who are located on university campuses often serve in adjunct faculty positions and as advisors for graduate students. (Photo by D. Dwinell)

Since the 1930s, the weirs at the Coweeta Hydrologic Laboratory have provided long-term data on the effects of natural events and human activities, with early studies on clearcutting, mountain farming, grazing, and road building giving way to later research on air pollution, insect infestations, and prescribed burning. (SRS photo)

When introduced insect pests threaten forests, researchers often find solutions by combining new study results with techniques learned from old enemies like the southern pine beetles. (Photo by B. Lea)

Mycorrhiza is a beneficial fungus that has been found to promote root formation and tree growth on sites disturbed by mining and other commercial activities. (SRS photo)

After Hurricane Hugo scored a direct hit on the wetlands and flatlands of South Carolina in 1989, artificial cavities served as temporary shelters for critically low populations of red-cockaded woodpeckers. (SRS photo)

Declining frog and toad populations sometimes are cited as "early warning signs" of adverse changes in the environment. Whether such changes result from local disturbance or from global climate change, the unique vocalizations of amphibians may hold the ecological key. Here, a field scientist calibrates a frog-logger (an automated recording device to detect changes in the amphibian populations of a southern wetland. (Photo by Z. Hoyle)






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Foreword

Forest science, like any science, is a continuous process. Research scientists collaborate in a largely informal, world-wide network to produce new knowledge—most frequently in the form of peer-reviewed articles—published in the scientific literature. It is difficult, even for those working in some area of forest science, to be aware of and understand the impact of this steady accumulation of theoretical and practical knowledge. For nonscientists, keeping up with forest science knowledge is indeed a daunting task.

It is equally difficult to appreciate the career-long contributions to forest science knowledge of the many, many dedicated researchers in the South we must thank for painstakingly building the level of understanding of ecosystems and their management that we have attained today. Research scientists are usually rewarded individually for their particular contributions. However, the collective effort of that broad and deep community of scientists who have worked at universities, at State research centers, in private industry, and at Federal agencies for nearly a century is seldom formally recognized. It is the aggregate effort of these men and women in all fields of southern forest science that we have to thank for the huge improvement in our understanding and management skill.

This book was produced as a way to recognize and celebrate that contribution. It was produced to highlight the summits of knowledge that we have attained. It was produced to point out the marvelous results generated by the scientific method applied over a long period of time by dedicated, and often brilliant, forest scientists. Finally, it was produced in recognition that access to knowledge and the ability to use it wisely have always been the hallmarks of successful individuals, organizations, and nations.

As we celebrate the first centennial of Forest Service stewardship, we gratefully dedicate this work to all who have toiled to advance the frontier of knowledge about southern forests and their management.

Pete

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Looking Back

Chapter 1.

A History
of Southern Forest Science, Management, and Sustainability Issues

H. Michael Rauscher[1]

The 13 Southern States from Virginia to Texas have a combined area of approximately 500 million acres. Our understanding of the complex cultural and ecological history of this large region is still evolving. It may be fair to say that until recently, our view of the native peoples of the South and the landscape in which they lived derived chiefly from reports provided by the few European explorers who traveled through this region between A.D. 1500 and A.D. 1700. Their factual descriptions were accurate, but their understanding of the native cultures and ecology was limited and this led to erroneous conclusions (Owen 2002).

Native Americans have lived in the South for about 10,000 years. Early estimates of pre-European population density, which were based on early English accounts, are now thought to be much too low (Carroll and others 2002). It is now believed that there were 1.5 to 2 million members of the Mississippian cultures living in the region in the year 1500. Diseases introduced by the Spanish explorers in the next 100 years greatly reduced the size of this population and resulted in the collapse of the Mississippian culture by 1600 (Carroll and others 2002). It is now thought that approximately two-thirds of the Native American population in the South was eliminated (Owen 2002). As a result, the large areas that had been used for farming and fire-managed forest lands throughout the South changed between 1600 and 1700 from "a mosaic of open pine and hardwood woodlands, prairies, meadows, and oak or pine savannas in a variety of successional stages" (Carroll and others 2002) to a forest that was much denser in both its overstory and understory (Owen 2002). It was this rapidly revegetating, dense forest with a large proportion of remnant old growth that the Europeans interpreted as pristine wilderness largely untouched by human hands. This limited understanding of the ecological dynamics of the pre-European South found its way into our history books and has resulted in a distorted popular vision of what the natural southern forest ecosystem was and should be today.

The second chapter "Southern Forests: Yesterday, Today, and Tomorrow" by R. Neil Sampson focuses on the events that most strongly affected the land, forests, and people of the South between 1900 and the present. Until about 1880, European settlement and forest exploitation tended to be concentrated on flat lands adjacent to rivers. Thus we learn that a map of forest conditions in the South at that time clearly indicates the patterns of rivers, which show up as areas where all of the merchantable pine had been cut. The coming of the railroad opened up the interior South to economical forest harvesting, mining, and agriculture. The railroad was the key to getting products to market profitably. Between 1860 and 1920, 90 million acres of mature longleaf pine (*Pinus palustris* Mill.) stands were harvested (Barnett 2004). Land was cheap and plentiful, and this led to large-scale land speculation, timber exploitation, and finally resale of the denuded land to farmers. Large areas of marginal land, thus, came into cultivation or were used for grazing and then slowly abandoned as the soil was eroded and its fertility depleted. Copper and iron smelters sprung up in many areas of the South, and their acid fumes and fuel needs denuded thousands of acres of land. These deplorable conditions brought about the rise of the conservation movement around 1900; purchasing of unwanted land by the public to create the first national forests in the East; creation of the U.S. Department of Agriculture Forest Service and State forestry agencies; and the beginning of scientifically based forest management.

The third chapter "Southern Forest Resource Conditions and Management Practices from 1900–1950: Benefits of Research" by James P. Barnett tells the story of forest science

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during the first half of the 20th century. The most urgent needs between 1900 and 1930 were the reforestation of the millions of acres of cutover forest land and the control of wildfire on that land. In 1900 we had little scientific knowledge about reforestation. By 1933 when the Civilian Conservation Corps (CCC) was established to provide employment to some 3 million men, our reforestation knowledge and technology had advanced far enough so that we could use this manpower effectively in the first major effort to tackle our Nation's huge forest and soil conservation needs. "With only a handful of professional foresters and despite little technical support and primitive working conditions, forestry in the South has made tremendous gains" (Barnett 2004). This first half century of achievement in forest science provided the basic knowledge that forest managers have used to make the South's Coastal Plain the most productive timber growing region in the world and to restore the mountain South's deciduous hardwood forests, which have great ecological importance.

The story of forest science in the South continues in the fourth chapter, "Southern Forest Resource Conditions and Management Practices from 1950–2000: Benefits of Research," by Jacek P. Siry. The basic knowledge of forest management developed earlier was refined and, most importantly, implemented on a very large scale between 1950 and 2000. This chapter tells the story of the South's distinctive system of intensive planted pine management. Hardwood forests occupy more than half of the region's forest land, and management of hardwoods has received substantial research effort. However, there has been less research and investment in hardwood management than in pine management because hardwood management has been less profitable than pine management (Siry 2004).

In the 1950s, southern pines were managed primarily in natural stands and with low intensity. Even after the large CCC reforestation campaign, only 2 million acres had been planted in pine forests while 7 million acres were still classified as nonstocked and in need of reforestation (Siry 2004). By 1997, however, there were 30 million acres of pine plantations in the South. Pine management was intensifying rapidly and productivity was increasing continuously. By 2040, the area in planted pine is expected to expand to 54 million acres, mostly as a result of reforestation of abandoned agricultural land (Wear and Greis 2004). The South's planted and natural pine forests represent < 3 percent of global conifer forest cover, and yet the region supplies nearly 19 percent of global industrial softwood harvests (Siry 2004). No other region or country in the world supplies more softwood timber than the U.S. South. This impressive success story is not widely known or appreciated by the people in the United States. It should be pointed out that the 30 million acres of pine plantations is still much less than the 90 million acres of longleaf pine forest in the South in 1900.

In the last quarter century, timber harvesting and development of land for urban uses has increased substantially in the South, leading to questions about the health, productivity, and sustainability of the South's forests (Wear and Greis 2004). The Southern Forest Resource Assessment was initiated in 1999 to address these concerns (Wear and Greis 2002). The final chapter entitled "The Southern Forest Resource Assessment: What We Learned" by David N. Wear and John G. Greis is a summary of the findings of this assessment.

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Chapter 2.

Southern Forests:

Yesterday, Today, and Tomorrow

R. Neil Sampson[1]

Abstract—*In the 20th century, southern forests changed dramatically. Those changes pale, however, when compared to what happened to the people of the region. In addition to growing over fourfold in numbers, the South's population has urbanized, globalized, and intellectualized in 100 years. Rural and isolated in the 19th century, they are today urban and cosmopolitan. One result has been a complete change in the approach to forestry. No longer an industrial process harvesting what nature has grown, it is now a scientifically based management process that produces a wide variety of goods and services. Thus what is happening in today's southern forest is unlike anything that would have been imagined 100 years ago. A large part of that is due to the advances in forest science and its wholesale adoption by industrial corporations, nonindustrial forest owners, and public agencies.*

As the human population has grown and urbanized, however, a new threat to forest management has arisen. Urban pressures not only convert land from forest to other uses, they also pressure forest managers to eliminate practices that offend the sensibilities of urban people. This "proximity pressure" threatens to take far more forest out of sustainable management than actual land use conversion will take. In some southern areas, it may eliminate forest management entirely in the coming century.

Forest science is, thus, challenged to find new ways to manage forests and communicate the values of that management in ways acceptable to urban neighbors. If they do not, they will face the reality that knowing how to manage a forest well is of little value unless there are forests where management can occur.

INTRODUCTION

The story of the southern forests is a rich one, told in many ways by many people. This brief review will touch on three aspects of that story—land, forests, and people. It will feature two snapshots in time—1900 and 2000—spanning a century of great change to illustrate insights that could be of some value as we enter this 21st century. The main events that shaped the land, forests, and people of the South in the last century are well known. They include:

- The decline of agriculture and mining in the region, and the legacies these activities left behind on the land
- The movement of the timber industry to the region
- The development of professional forestry and land management
- The creation and growth of the U.S. Department of Agriculture Forest Service (Forest Service), the National Forest System, and the State forestry agencies
- The rise of the conservation movement with its new agencies and programs
- Two World Wars and the accompanying surges of demand for natural resources
- Population growth and associated urbanization

As this history unfolds, it reveals changes of such magnitude that, had they been foretold by scholars in 1900, those good people would have no doubt been made a laughingstock. As we enter the 21st century, we ask ourselves whether it is possible that changes of similar magnitude lie in store for the region. If so, we can only speculate as to what those new situations may be and how people and organizations may need to respond to them.

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THE PAST—LAND, FORESTS, AND PEOPLE IN 1900

The South consists of 13 Southern States running in a broad band from Virginia to Texas, with a total area of just over half a billion acres. That size has not changed markedly in the last century, and is perhaps the only common statistic between then and now. Everything else is different.

According to U.S. census figures, there were around 21 million people living in the region in 1900. That same source shows that somewhere around 60 percent of all Americans were living in rural areas at the time and it is clear that the South was overwhelmingly rural (U.S. Census Bureau 1990).

And the region's inhabitants were clearly "southern," often insulated from more than local influence by the limits of the communication and transportation systems of the day. For example, as late as 1936, one author describes the people in the Tennessee Valley in this way:

> The people . . . are hospitable, proud, salty, independent, illiterate by modern standards, and desperately poor. They are poor because many of their ancient crafts have lapsed or because in the highly specialized economy of today the exchange value of these crafts is low (Chase 1936).

Land and forest statistics were few in 1900, and estimates of the forest resource, for example, were little more than educated guesses. In 1896, Chief Fernow of the U.S. Department of Agriculture (USDA), Division of Forestry had this to say: "There are no forestry statistics in existence. Even the census figures referring to the lumber industry are avowedly imperfect and based on partial returns. The data given, therefore, are only approximations and must be taken with that reserve" (Fernow 1896). For the South, Fernow suggested that somewhere around 50 percent of the region still retained its forest cover. If he was correct, that would mean somewhere in the range of 250 million acres of forest at that time. He estimated the annual national timber harvest at somewhere around 40 billion board feet, with the South contributing about 25 percent. By 1900, however, it was estimated that the South was producing more lumber than any other region, and by 1919 it was said to be producing around 37 percent of the national total (Williams 1989).

Longleaf (*Pinus palustris* Mill.) and shortleaf (*P. echinata* Mill.) pine were the most important commercial species of the day, and Fernow had this to say about loblolly (*P. taeda* L.): "It is the 'old field' pine of the Southern States. Thus far it has been of much less importance as a source of lumber than the other Southern pines." He also noted that, among the oaks, white oak (*Quercus alba* L.) had been the type most harvested, being used "almost exclusively for construction and cooperage." "Black walnut," he wrote, "once common in the rich bench lands of the Mississippi Basin has been so largely cut as almost to have disappeared from market quotations" (Fernow 1896).

The pattern of forest harvest was telling. In an 1880 map of forest conditions of the South, the pattern of rivers and streams was clearly defined, shown as regions from which all of the merchantable pine had been cut (Williams 1989). The high value of the waterways for floating heavy logs to market made those areas the first to be cut over. In the swamps where the highly valued cypress (*Taxodium* spp.) was found, the trees were girdled and killed so that they would lose enough sap to float, then harvested from boats or by men wading in the water, to be skidded to a rafting point by "pull boats" that plied along channels that were blasted into the swamp to give a central access route to which the logs could be cable-skidded. With these methods, two things happened: cypress harvest rose to around 1 billion board feet per year by 1905, and the species was virtually cut out by 1913 (Williams 1989).

Forest conservation and management were virtually nonexistent. In many areas, trees were free for the asking, and public land could be taken for free or nearly free, as well. Private speculators were buying land for $1.25 an acre, estimating that it would yield from 6 to 12 thousand board feet per acre (Williams 1989). For the most part, the valuable pine trees were utilized only to the lowest branch, with the remainder left to rot or burn.

Other major southern forest products were the rosin and turpentine that were produced almost entirely by distilling the gum of southern pines. At the turn of the century, these were produced by tapping trees and collecting the resulting sap. By 1920, much of it was coming from the steam distillation of the old stumps left behind by early logging. Today, these products come as a byproduct of the process of pulping to turn pine trees into paper products (U.S. Department of Agriculture, Forest Service 1988).

For farmers in 1900, getting rid of trees so they could plow the land was the important concern, and valleys filled with smoke testified to the

widespread use of fire as a primary land clearing tool (Plair and Spillers 1960). Any lumber company that employed a technical forester for his knowledge of forest management would have been laughed out of the woods. You didn't need a college degree to swing an axe or wrestle floating logs out of a swamp.

Technology was coming into the woods rapidly, cutting costs, increasing output, and expanding the logger's reach across the landscape. Oxen skidding was slow and expensive, so wherever possible, it was being supplemented or replaced by splash dams, dynamited channels, pull boats, and other forms of water transport. Where the land was dry, railroads expanded rapidly to access valuable pine timber. Much of that technology was highly damaging to the environment, but those concerns were many decades from being effectively voiced. It was a time of "cut out and get out" to maximize the profits from land speculation.

For the lumber companies, the last profits from the land often came from selling it to would-be farmers, and many set up real estate offices to promote the virtues of farming on the cutover lands. But the soils were often sandy or swampy, and while a few farmers succeeded on the better lands, many simply played out their money and abandoned the place (Williams 1989). By 1920, it was estimated that 30 million acres of cutover forest showed little prospect of restocking or helping the region recover its resource strength (Williams 1989).

Thus the forest legacy in the early parts of the 20th century was one of cutover pine lands, a depleted cypress resource, and high-graded hardwood forests. As timber harvesting and agricultural land clearing continued, the region's forest acreage declined, reaching a low some time around 1920 (U.S. Department of Agriculture, Forest Service 1988). Adding to the region's forest woes was the chestnut blight {*Cryphonectria parasitica* (Murrill) Barr [formerly *Endothia parasitica* (Murrill) Anderson & Anderson]}. The killer fungus reached Virginia in 1912 and by 1920 had largely eliminated one of the most valuable species in the southern hardwood forests (Yarnell 1998).

Equally significant to the region's landscapes, agriculture was undergoing major change. King cotton was under siege by the boll weevil (*Anthonomus grandis grandis*), and crops were rapidly vanishing from hillside soils where cultivation had exposed susceptible soils to rapid erosion. A 1911 soil survey of Fairfield County, SC, for example, determined that 90,000 acres of formerly cultivated land should be classified as rough gullied land as a result of erosion (Bennett 1939). Those gullies, common across the region's sloping lands, were beginning to be a major topic of concern. Hugh Hammond Bennett, who would become the national leader in a new soil conservation movement, wrote the following about the soil erosion situation in the South:

> A much lighter rain than formerly now turns the Tennessee River red with wash from the red lands of its drainage basin. Added to the severe impoverishment of a tremendous area of land throughout this great valley, and its extensions southward into Georgia and Alabama and northward into Virginia, are the gullied areas, which are severely impaired or completely ruined by erosion ravines that finger out through the numerous hill slopes and even many undulating valley areas. Field after field has been abandoned to brush, and the destruction continues (Bennett and Chapline 1928).

In other places, the environmental effects of industry were plainly evident. In eastern Tennessee and northern Georgia, the acid fumes from copper and iron smelting killed thousands of acres of forest (Yarnell 1998). Stuart Chase (1936) describes one such scene in Tennessee:

> The road curved around the crest and Ducktown rose before us – a little village and a huge smelter perched on a hill. In a great circle about the smelter, measuring perhaps ten miles in diameter, every living thing had been destroyed by the sulphur fumes. These were bad lands without the balance and natural composure of a desert.

The picture that emerges from this long look back is pretty grim. Across the southern landscape, the evidence of land misuse would have been appalling to today's eyes. But the beginnings of the conservation movement were taking root, and the warnings were beginning to be heard across the land. In some respects, those warnings sound overly alarmist today, but then they were a wake-up call. There was much talk of a "timber famine," for example. How wrong was Pinchot (1910) when he wrote:

> The figures cited are, however, sufficiently reliable to make it certain that the United States has already crossed the verge of a timber famine so severe that its blighting effects will be felt in every household in the land.

Or what about Bennett, who testified in Congress (1935) that the soil erosion surveys conducted by the Department of Agriculture

> . . . revealed 51,465,097 acres of land essentially destroyed by wind or water erosion insofar as having further use for crop production, except for occasional patches. Most of this had been cultivated, and once was good soil.[2]

The timber famine, of course, never materialized, nor did millions of acres of American land turn into sterile desert. Does this indicate that the warnings were false, or does it indicate that an awakened citizenry could address land management problems and effectively correct destructive trends before they continued to disaster? There is ample evidence, I think, to support the latter view. Pioneers like Pinchot and Bennett, along with dozens of others in public service and private business, created the climate of public concern needed to support new public policies, agencies, programs, and expenditures. The increase in scientific knowledge through research and practice provided new tools to combat land waste. Private citizens, seeing that the future of their life's investments, whether in a family farm or an industrial corporation, required a more sustainable approach to land management, often led the way in experimentation.

LAND MANAGEMENT COMES TO THE SOUTH

As the 20th century dawned, a major national conservation movement was beginning to emerge. Slowly in many places and with many faces, it began to address the serious resource problems of America. Nowhere was this more evident, or more needed, than in the South.

From the time of his work on the Biltmore Estate in the 1890s, and also after he became Chief of USDA's Division of Forestry in 1898, Gifford Pinchot was intent on changing the manner in which private lumber companies were managing the Nation's forests. Within weeks after taking over the USDA job, he issued Circular 21, which launched an ambitious program of technical assistance to the companies. Secretary of Agriculture Wilson noted that, under this new approach, Federal technicians would provide advice and "the private owners will pay the expenses of Department agents who give instructions." Many companies accepted the offer, sending cash and offering free transportation and board to Federal agents who would come and help them (Steen 1976).

One example was the Kirby Lumber Company, which owned 1.2 million acres that contained about 80 percent of all the longleaf pine forest in Texas. A 50-man team from the Bureau of Forestry worked to gather data for a plan that contained recommendations on minimum tree size for logging, which trees to leave as a seed source, a timber marking plan, and a fire protection plan. This focus on assisting private landowners continued for only a decade or so, displaced not so much by failures in the program as by the enormous workload placed on the newly named Forest Service when the National Forest System was created under its management in 1905 (Steen 1976).

The administration of the forest reserves was transferred to the Forest Service, and the 1911 Weeks Act opened the way for the purchase of the lands that became the national forests of the South. These actions were largely the result of political action by citizens' organizations. Chief among these actors was the American Forestry Association (AFA), which had been founded in 1875 and counted virtually all of the top national forestry officials in its leadership. Also critical in the political wars were organizations like the American Civic Association and the General Federation of Women's Clubs. There was powerful opposition to the use of Federal funds for the purchase of forest reserves, and only the persistent and growing power of citizen's groups could overcome it (Clepper 1975). Land purchases under the Weeks Act started immediately after the law was enacted. In 1912, 287.7 thousand acres were approved for purchase at an average price of $5.65 per acre (Clepper 1975). The purchases continued across the region into the late 1930s, leading to the current system of national forests, comprising some 12.3 million acres in the region (U.S. Department of Agriculture, Forest Service 2000).

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[2] Bennett, H.H. 1935. Statement presented before Subcommittee of House Committee on Public Lands, March 20, 1935.

The Weeks Act and later the Clarke-McNary Act spurred great growth in the cooperation between the Forest Service and the State forestry agencies. By the 1920s, thousands of landowners were receiving technical forestry advice from State service foresters, supported by a combination of Federal and State cooperative funds.

During this same period (1903 to 1928), Hugh Bennett was conducting soil surveys throughout the Southern States, and his warnings about the extent and danger of soil erosion were attracting increasing attention. Finally in 1929, Congress appropriated $160,000 for soil erosion studies and Bennett was placed in charge of the work (Sampson 1981).

THE NEW DEAL'S CONSERVATION DECADE

The 1930s brought enormous change to the forestry and land conservation programs of the United States. It was a time of great environmental and social stress. Thousands of displaced people, jobless and destitute, fled damaged farm and forest lands to seek work in cities, where there were few opportunities following the stock market crash of 1929. For President Franklin D. Roosevelt, the challenge seemed twofold—economic recovery and environmental repair. His proposal, in 1933, for a Civilian Conservation Corps (CCC) to provide needed employment and tackle the forest and soil conservation needs of the Nation, was passed into law by Congress after only 10 days (Sampson and DeCoster 1997). Young men were put to work for $30 a month in salary, half of which was to be sent home to their families. In addition, they were provided room, board, uniforms, and medical care.

In its 9 years of existence, some 3 million CCC men were provided with work and training, for a total cost of some $2.5 billion (Zimmerman 1976). Some of their impressive forestry accomplishments included the construction of more than 1,300 fire lookout towers, almost 40,000 miles of telephone lines, over 50,000 miles of roads and trails, 1.25 billion trees planted, and over 2 million man-days of fire fighting. Many of the campground facilities, lodges, and recreational sites developed by the CCC remain in use today.

In 1934, as the first national soil erosion surveys were being completed, dust from the drought-stricken Great Plains darkened skies in Washington, DC, and a new national soil conservation program was born (Sampson 1981). Although spared much of the Dust Bowl damage (except in Oklahoma and Texas), the South was the focal point of much of the new activity because of the widespread damage caused by gullying. As the new Soil Conservation Service was moved into USDA in 1935, it was given supervision of over 450 CCC camps that provided the manpower needed to address soil and water conservation problems. The CCC boys attacked gullies with little more than shovels and axes and, in the process, demonstrated that this serious erosion could be halted (Sampson 1985).

To help facilitate the local work of soil and water conservation, a new form of local special Government was created—the soil conservation district. As with many other innovations, it saw its first implementation in the South as Brown Creek District in North Carolina became the first to be formed (Sampson 1985).

Another influential venture of the period was started in 1927 when the AFA set out to raise money for an educational campaign on forest fire prevention and control aimed at the rural people of the South. Known officially as the Southern Forestry Educational Project, it was launched in Florida, Georgia, and Mississippi with the purchase and outfitting of five trucks. Each truck had an electric generator to power a motion picture projector and carried two men—a lecturer and a projector operator. Movies produced by the USDA and the AFA were shown in thousands of rural towns and were often the first motion pictures seen by many of the residents. At the end of the first year of operation, it was estimated that the trucks had traveled 78,000 miles into 94 counties and reached 700,000 people (Clepper 1975). By the time it was closed down in 1931, it was estimated that the "Dixie Crusaders," as the teams had begun to be called, had reached some 3 million people in the 3 Southern States and South Carolina, which had been added to the program (Clepper 1975).

While these were only a few of the activities underway, what also emerged in the 1930s was a new framework of Federal and State policy in regard to forests. In general, it emphasized the protection of forests from wildfire and the protection of wildlife from overharvesting. It promoted the management of forests, farmlands, and wildlife with methods based on scientific principles and carried out most of its activities through a variety of cooperative arrangements that often involved several Federal, State, and local agencies (MacCleery 1992).

While there were many achievements of this new policy approach, one of the more notable was the dramatic reduction in annual wildfire area. By the end of the 1930s, cooperative fire suppression programs were beginning to be more effective, and wildfires, which had burned as much as 50 million acres a year, began a decline that lasted through the 1970s (MacCleery 1992). Another important cooperative achievement was the dramatic increase in tree planting programs.

TREE PLANTING—PUBLIC AND PRIVATE

Planned reforestation through tree planting had started in the South early in the 1900s through the work of pioneering landowners such as Henry Hardtner of Louisiana, who planted about 27,000 acres to southern pines under a 1913 contract, and the Goodyears of Bogalusa, who planted some 15,000 acres (Williams 1989). But these were the exceptions, not the rule, and it was not until the 1924 Clarke-McNary Act that authorized Federal cost-sharing support for State tree seed and nursery programs as well as increased educational and technical assistance to landowners, that the program was able to gain real momentum (Zimmerman 1976).

While the forest products industry, with its future hinging on new tree crops, was the most aggressive tree planter, public programs have played an important role in spurring private landowners to reforest their land. Recent increases in tree planting have been as significant as those produced by the CCC in the 1930s. (Moulton and Hernandez 1999). In 1936 through the creation of the Agricultural Adjustment Administration, Congress authorized cost sharing with private landowners for conservation purposes. Included in those purposes was tree planting for reforestation, windbreaks, and shelterbelts.

But in midcentury, the appraisal of the Forest Service was still that tree planting was a major national need. Citing more than 114 million acres (23 percent of the commercial forest area) as being nonstocked or poorly stocked, the Agency said that tree planting was one of the most effective ways of getting that vast acreage into production and keeping it productive (U.S. Department of Agriculture, Forest Service 1958).

In 1956, the first version of a conservation reserve—the Soil Bank—was enacted to help reduce crop surpluses through conversion of cropland into grass or trees. Under the program, USDA cost shared tree planting and paid land rental for 10 years. In 1985, a similar program—the Conservation Reserve Program—was launched. It is still in effect, and by 1992 it was estimated that more than 2.5 million acres of trees had resulted. The South has taken full advantage of these programs. Over the last 20 years, from 65 to 82 percent of the tree planting in the United States has occurred in the South (Moulton and Hernandez 1999).

CONSERVATION CHALLENGE SHIFTS GEARS

This rapid overview of the changes in forests, land, and people of the South over the last century has shown that an early concern for the mismanagement of rural lands, including forests, led to a major conservation revolution. By 2000, the science of forest management had progressed far enough so that it could be concerned with more than timber supply. It could aspire to produce sustainable forests—forest ecosystems that remain productive and intact over centuries, continuing to produce a full variety of economic and environmental goods and services—because of the management and care of skilled hands.

During that century of change, virtually everything has changed. The amount of total forest in the South is now around 214 million acres (Smith and Sheffield 2000). If the 1896 rough estimate was accurate, that's a reduction of some 20 to 50 million acres. More comparable data suggest that, since 1952 when the first reliable surveys were taken, the area of timberland has declined from 204.5 to 201 million acres in 2000 (Powell and others 1993, Smith and Sheffield 2000). While that acreage change was modest, the amount of timber growing on the land has increased significantly. Softwood timber volumes rose from 60.5 to 105 million cubic feet in the region, while hardwood timber volumes rose from 88 to 152 million cubic feet (Powell and others 1993, Smith and Sheffield 2000). Thus on a similar area, the amount of standing timber almost doubled, signaling a major achievement for forest management and conservation over the past half century.

Today, southern pines produce merchantable timber in < 25 years in many places. The efficiency of timber utilization is extremely high, and logs with 2-inch tops are being sent to the mill in some places. As a result, fewer acres of forest are harvested to obtain a similar amount of useful product.

High-flotation machines move through pine plantations, thinning out excess trees and sending them off to market without leaving soil ruts—in places without leaving a mark to show they have passed. Riparian buffers and streamside management zones protect the most productive habitats on the landscape and, as a result, plants and critters great and small share the forest with commercial timbering operations.

The forest products industry, once noted primarily for its cut-and-run strategies, is today the largest single employer of professional foresters (Society of American Foresters 2001) and a leader in defining and applying the principles of sustainable forest management (AF&PA 2001). There is much to be learned, but the science and art of forest management has clearly matured significantly.

The revolution in U.S. forestry has been compared with the transition made thousands of years ago by agriculture—from a foraging activity that simply harvested what nature had provided to a cropping activity involving planting, tending, and harvesting (Sedjo 1991).

Now, however, a new conservation question has emerged as a result of the enormous land use changes in the 20th century, and it may be the most challenging that the forestry profession has faced to date. That question, in short, is: "How much forest will be available for sustainable forest management in the future?" We may know how to manage the land, but if manageable land is not available, that skill is of little value.

There are, perhaps, three aspects to this threat to the future of forests and forestry in the South. First is the direct conversion of forest land to other uses. No longer is agriculture the major consumer of forest land as it was in the past. Today, it is urban development that moves land out of forest production (U.S. Department of Agriculture, Natural Resources Conservation Service 2001). The amount of land converted is fairly modest. Between 1992 and 1997, it amounted to about 1 million acres in the Nation according to the USDA's National Resource Inventories. Given the increases in forest productivity and efficiency that have emerged from forest science in the latter decades of the 1900s, that loss alone is probably not terribly significant.

But it is not just the loss of forest land, it is the pattern of that loss that leads to the second aspect of the change. Forests are being increasingly fragmented, and that has both environmental and economic consequences. From an environmental point of view, habitats may become disconnected, making normal movements of plants, animals, and genotypes more difficult. Those that become isolated may find it more difficult to thrive, or even survive. From an economic standpoint, every forestry operation becomes more expensive as forest tract size declines and, at some point, the prices received for forest products go down as well (Thorne and Sundquist 2001). All of these effects make forest production increasingly marginal and, at some point, landowners simply give up on using the forest as a production asset and either hold it as an amenity or sell it to the highest bidder. Either way, the area available for sustainable forest management is diminished.

Finally, however, is the third aspect of the pressure—the one that may be most difficult to identify and quantify. This can be labeled proximity pressure and it works like this—as urban populations move into a rural area, the opposition to rural land uses is almost certain to rise. For farmers, it is the objection of urban citizens to the smells of livestock or the dust and noise of farm operations. For forest managers, it is opposition to the sight of a clearcut harvest, the weight of log trucks on local roads, or the pressure of land taxes that respond to potential land sale value rather than forest production values (Sampson and DeCoster 1997). The pressures can be either direct or indirect, but they are cumulative. They make continued production seem risky, and when landowners decide that there is little or no future for production agriculture or forestry in their area, that decision becomes self-fulfilling. Long-term investments such as tree planting or timber stand improvement are no longer made, and even the most conscientious landowners become land speculators—waiting to turn their life's work and investment into cash for retirement.

As landowners reduce their forest management, either through land sales or simply slowing down, they produce less wood for local mills and less work for local contractors. At some point, usually when a market downturn makes things even more difficult, those mills close or those contractors decide to move or go out of the business. In return, the remaining landowners who are still trying to manage their forests find their economic opportunities diminishing, either through reduced market competition, reduced availability of contractors, or the total lack of one or the other.

Table 2.1—1980–99 population by State, southern region, and nationally with 2004 projection

State	1980	1990	1999	2004	Change 1980–99	
					number	*percent*
Alabama	3,893,267	4,040,587	4,385,470	4,591,457	492,203	13
Arkansas	2,284,614	2,350,725	2,568,170	2,725,840	283,556	12
Florida	9,744,073	12,937,926	15,018,424	16,085,294	5,274,351	54
Georgia	5,462,825	6,478,216	7,698,381	8,429,990	2,235,556	41
Kentucky	3,660,129	3,685,296	3,965,923	4,099,292	305,794	8
Louisiana	4,205,883	4,219,973	4,394,632	4,450,485	188,749	4
Mississippi	2,519,711	2,573,216	2,774,493	2,905,761	254,782	10
North Carolina	5,879,261	6,628,637	7,590,605	8,060,154	1,711,344	29
Oklahoma	3,024,740	3,145,585	3,361,437	3,478,481	336,697	11
South Carolina	3,121,614	3,486,703	3,855,261	4,019,194	733,647	24
Tennessee	4,585,757	4,877,185	5,485,923	5,818,327	900,166	20
Texas	14,218,841	16,986,510	19,989,393	21,714,566	5,770,552	41
Virginia	5,345,266	6,187,358	6,884,125	7,296,332	1,538,859	29
Southern region	67,945,981	77,597,917	87,972,237	93,675,173	20,026,256	29
National	225,169,362	247,051,601	270,361,877	282,490,898	45,192,515	20

The result is a continued downward spiral in the local opportunity to own and manage forest land for sustained production.

To some observers, that may sound like a scenario limited to the heavily populated areas of the Northeast but not likely to concern the rural South. The facts, however, are that the South is becoming increasingly urbanized, and as a result, the future of forestry is dubious in many areas. Look, for example, at table 2.1, taken from U.S. Census figures and projections for 1980 to 2004. Note that between 1980 and 1999, the population of the region rose by 20 million. That means that between 1980 and 2000—a period of 20 years—as many new people moved into the South as the total population of the region in 1900! So now there are some 90 million in the 13-State area—almost one-third of the Nation's population.

But how can we assess this population change in terms of its implications for production forestry? To address this question, we developed maps of the South using a Virginia Department of Forestry study published in 1997 that analyzed that State's commercial forest in terms of its availability for future forest production (Liu and Scrivani 1997). They found that while the amount of forested land in Virginia has been relatively stable for the last quarter-century, the future of forestry on much of that land is likely to be greatly different from its past. Population growth, urban and suburban sprawl, and changes in forest ownership have caused some 20 percent of the State's forests to be doubtful in terms of future timber production.

The basis for assessing population pressures came from research by Wear and others indicating that the probability of sustainable management approaches zero at 150 people per square mile (psm); that there is a 25-percent chance at 70 psm; a 50-percent chance at 45 psm; and a 75-percent chance at 20 psm.[3] Using those thresholds, we utilized a new population density analysis produced by Oak Ridge National Laboratory to do a coarse-screen analysis of the likely impacts of the current population densities on future forest management (Dobson and others 2000). We combined these data with a national coarse-scale map of land ownership and land cover to identify where forest cover was likely to coincide with increased population density and where private lands were most involved. The results indicate that significant areas of the South are at risk of losing the ability to manage forest lands for production forestry. That conclusion has been fortified by the Southern Forest Resource Assessment, which forecasts that urbanization will continue to expand in the South at the rate of around 1.1 million acres per year until 2020 (Wear and Greis 2002).

[3] Wear, D.N.; Liu, R.; Foreman, M. 1996. The effects of population growth on timber management and inventories in Virginia. [Number of pages unknown]. On file with: Southern Research Station, Forestry Sciences Laboratory, 3041 Cornwallis Road, Research Triangle Park, NC 27709.

NEW APPROACHES TO NEW REALITIES

If there is to be a healthy, viable, sustainable forest resource in the South through the 21st century, what does it need? And how can forest science contribute to that need? There may be several ways:

1. Help define and promote sustainable forestry in all its different expressions

   There are many programs emerging to promote sustainable forestry. Most will, it appears, have some sort of certification linkage, where the land management is audited by an independent third party and some sort of product mark tells consumers that the wood products they purchase have come from a sustainably managed forest. This is a new movement, marked by a full share of controversy and complication as different systems compete to win the attention of both forest owners and the public. My advice—do not get caught in the competition. It, in itself, is healthy, as it forces all the systems to seek improvement. Encourage all these systems so that a forest landowner, whether they are a small private owner or a large corporate owner, can find a system that fits their needs. When the end result is better forest management, the name of the system that brought it about is inconsequential.

2. Help find ways to reach urban audiences and help them appreciate the value of well-managed forests as part of the urban-wildland infrastructure

   We must quit thinking of urban areas as one thing and rural areas as another (Gordon and others, in press). There is a continuum of places that make up a landscape, and without the rural aspects, the value of many landscapes as a human habitat is reduced. But unless urban people value rural landscapes, including rural forests, those rural landscapes will disappear under the invisible pressures we have discussed.

3. Bring new forest management techniques into the urban-wildland intermix

   Urban people will appreciate and tolerate forest management more when that forest management is sensitive to their lifestyle needs. No longer can forest managers handle their land as if nobody is watching. The truth is, most places, lots of people are watching. And they are not uncritical. They expect forest managers to create situations, views, and environmental impacts that are acceptable. And the definition of "acceptable" is somewhat fluid. Expectations rise.

   So forest science cannot rest on the many laurels it has created in the 20th century. The questions coming up are equally, if not more, difficult, and the public pressure to "get it right" will steadily increase. The amount of good forest land available for sustainable management is decreasing while the need for forest products and services—both timber and nontimber—is rising. The margin for error is declining. The need for a vibrant, growing forest science in the South has never been higher.

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Chapter 3.

Southern Forest Resource Conditions and Management Practices from 1900–1950: Benefits of Research

James P. Barnett[1]

Abstract—*The vast harvest of the native forests of the South in the 19th and early 20th centuries created a great need for reforestation and silvicultural knowledge. An emphasis on forestry research that changed the face of the South began with the establishment of the Southern and Appalachian Forest Experiment Stations in 1921. Working under primitive conditions, early researchers provided the information that was used to restore the southern forests. A key to this success was the interaction and cooperation of workers in universities, State service, Federal service, and forest industry.*

INTRODUCTION

Although southern pines were the basis for the oldest forest industry in America, the forests of the Southern United States were little influenced by humans until the mid-19th century. Longleaf pine (*Pinus palustris* Mill.) was the focus of the early lumber business in the South—primarily for export. A decline in the supply of longleaf pine in the Carolinas was noted about 1860. However, intensive harvesting of this species continued to spread westward across the South throughout the early 1900s. As the harvesting of the 90 million acres of mature longleaf stands moved westward, the development of railroad logging continued to increase the efficiency of harvesting. Thus it is not surprising that in the west gulf region the supply of seed trees became insufficient to regenerate the species. Across the southern Coastal Plain, loblolly pine (*P. taeda* L.) began to naturally regenerate cutover longleaf pine sites. However, many millions of acres of forest land in both the mountains and Coastal Plains had already been converted to agriculture. Much of this land was found to be unsuitable for row crops and was abandoned. Other large areas of cutover lands that were not converted to agriculture needed reforestation. This cutover land was considered by many as open rangeland and was heavily grazed by cattle and hogs. These activities further increased the difficulty of reforestation. The rebuilding of the forest resource had become a major challenge as well as a silvicultural opportunity.

This chapter describes the initiation and the scope of forest research in the South through the World War II era. Because there is a great deal of information about the postwar period, it is necessary to limit the scope of the paper to the earliest part of the period. The objectives of the paper are to provide a sense of the research environment during the period, to describe the major scientific accomplishments of the period, and to identify some of the scientists who contributed to these accomplishments.

THE NEED FOR MANAGEMENT

George W. Vanderbilt was early to recognize the need for reforestation of cutover land, and hired Gifford Pinchot as a forester for his Biltmore Estate near Asheville, NC. Dr. Carl Schenck, who replaced Pinchot in 1885, established the first scientifically based forestry school in this country on the Biltmore Estate. Through his school and influence, Dr. Schenck became one of the founders of modern American forest management, and the Biltmore Forest School became known as the cradle of scientific forestry in America.

Northern investors came into the South following the Civil War. Late in the 1880s, they purchased land inexpensively and built mills for processing timber. For example, the Great Southern Lumber Company in Bogalusa, LA, ran four 8-foot band saws at full speed for more than two decades, producing 1 million board feet of lumber every 24 hours (Kerr 1958).

Late in the post-Civil War period while lumber production in the South was at an all-time high, a few farsighted individuals began to work on a reforestation program that would provide for a continuing forest resource. In 1913, Henry Hardtner, who became known as the "father of forestry in the South," established plots on the first reforestation reserve in Urania, LA, to

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support and guide pine reforestation (Wheeler 1963). Hardtner, as President of the Urania Lumber Company, placed 25,719 acres of his cutover forest lands under a reforestation contract with the State of Louisiana. It was Hardtner's belief that cutover lands offered long-term opportunities for profit (Maunder 1963). William G. Greeley, Chief Forester of the U.S. Forest Service, remarked that even by 1920 neither foresters nor lumbermen had any real concept of the reproductive vigor of logged-over forests, or of how the growth rate was increasing as young trees replaced old forests (Maunder 1963). In recognition of this situation, a Cut-Over Land Conference of the South held in New Orleans in 1917 promoted the sensible use of cutover lands in which forestry, farming, and grazing all had a place in the economic use of forest lands.

ESTABLISHMENT OF RESEARCH PROGRAMS

The need for additional research was becoming apparent in 1915 when Samuel T. Dana of the U.S. Forest Service, in an effort to identify problems that needed study, established large plots on Hardtner's reserve. In 1917, the Yale School of Forestry started sending its graduating classes to Urania for 3 months of practical training. This program continued for several decades. Students under the direction of Professor H.H. Chapman established longleaf pine thinning and fire plots as well as other related studies (Wheeler 1963). The early results of Chapman's Urania studies were summarized in "Factors Determining Natural Regeneration of Longleaf Pine on Cutover Lands in LaSalle Parish, Louisiana" (Chapman 1926).

In 1921, the Forest Service of the U.S. Department of Agriculture established the Southern and Appalachian Forest Experiment Stations at New Orleans, LA, and Asheville, NC, respectively. The Southern Forest Experiment Station (Southern Station) was primarily responsible for research in the southern pine types (from South Carolina to east Texas), and the Appalachian Forest Experiment Station (Appalachian Station) for the mountain hardwood types. The two research stations employed about two-thirds of the professional foresters working in the Southern United States. Although these foresters (Forbes, Hine, Shivery, Hadley, and Wyman of the Southern Station and Frothingham, McCarthy, Korstian, and Haasis of the Appalachian Station) worked under primitive conditions and with annual budgets of < $20,000 per station, they accomplished some remarkable things. A few other pioneering researchers joined the stations in the mid-twenties, but little expansion of the program occurred until Congressional passage of the McSweeney-McNary Forest Research Act of 1928. Passage of this act signaled a general appreciation of the need for forestry research efforts to deal with the many problems resulting from the large-scale harvesting of the native forests of the Southern United States.

Prior to World War II, there was little forestry research in the South apart from the programs established by the Federal Government. Notable exceptions were programs at the Biltmore Estate at Asheville, NC, and the Yale School of Forestry's training program at Urania, LA. Forestry programs at other universities in the South were just being established.

SUCCESSES OF EARLY RESEARCH

Reforestation

By conservative estimate, 13 million acres (about 10 percent) of southern forest land were in need of planting as late as 1954 (Wakeley 1954). The technology needed to undertake this massive effort was developed in the 1920s and 1930s with meager resources. Reforestation research began to flourish when Philip Wakeley arrived at the Southern Station in 1924 and was assigned to the Bogalusa, LA, substation, which was supported by the Great Southern Lumber Company. Following a visit to the thriving forestry project of the Urania Lumber Company, the Great Southern Lumber Company had initiated an historic planting program in 1920. The company planted 800 acres with loblolly pine seeds sown on ridges made with mule and plow. The success of this first large-scale commercial planting was the impetus for experimentation and observation that resulted in greatly improved technology (Heyward 1963b).

With help from Great Southern Lumber Company personnel, Philip Wakeley developed successful nursery production and outplanting techniques. Wakeley's collaborative research with Mary Nelson, Plant Physiologist, of the Southern Station (Nelson 1938) and Lela Barton of the Boyce Thompson Institute (Barton 1928) was critical to development of the needed understanding of pine seed testing, treating, and storing technology. J.K. Johnson, Great Southern Lumber Company forester and one of the Nation's first industrial foresters, supplied the labor and planting stock for many of the experiments. An

outstanding result was the publication "Artificial Reforestation in the Southern Pine Region," which has guided pine planting for the entire South since the Civilian Conservation Corps (CCC) days (Wakeley 1935a). This 1935 publication became the basis of an expanded version "Planting the Southern Pines," which was published after the war and became the primer for reforestation in the South (Wakeley 1954).

Reforestation research was transferred from Bogalusa to Alexandria, LA, during the CCC period with establishment of the Forest Service's Stuart Nursery at nearby Pollock. With the help of CCC crews, nearly two-thirds of a million seedlings were outplanted in research tests on the Palustris Experimental Forest and surrounding Kisatchie National Forest (Wakeley and Barnett, in press).

A colorful individual who made a unique contribution to the development of reforestation technology was F.O. (Red) Bateman, Chief Ranger of the Great Southern Lumber Company. Bateman had no formal training, but between 1921 and 1936, he made notable contributions to early fire-fighting practice and fire suppression work. He also developed the details of the first successful large-scale nursery and associated planting technology for the southern pines (Wakeley 1941, 1976). Wakeley (1976) said he was "one of the greatest silviculturists the South has known" and "thousands of acres of Great Southern's plantations, and in a real sense, most of the pine plantations in the South, stand as a monument to his genius."

In cases where some remnant seedlings or stands remained, the research R.R. Reynolds conducted at the Crossett Experimental Forest provided management guidelines for the use of uneven-aged and selection methods. This research program became recognized nationally and was an early example of a partnership between forest industry and Government research (Reynolds 1951).

Fire

The effect of fire in forests was a matter of great interest and controversy among early foresters. In 1916, results of observations in Henry Hardtner's reserve were published in the Louisiana Conservation Commission biennial report (Wheeler 1963). The findings are summarized as follows: (1) fires occurring from December 1 to March 1 are not destructive to longleaf pine; (2) fire will kill shortleaf pine (*P. echinata* Mill.) seedlings < 4 years of age, but not after that age; and (3) although longleaf seedlings will survive a fire, they will not survive damage by hogs.

Based on his observations at Urania, Professor Chapman of Yale advocated the use of fire in longleaf stands. He stated that fire controlled brown-spot needle disease (*Mycosphaerella dearnessii* Barr.) and promoted early height growth (Wakeley and Barnett, in press). Research station researchers did not agree with Chapman's conclusions. The Southern Station's study of a 1928 wildfire in an 800-acre longleaf pine plantation of the Great Southern Lumber Company indicated that brown-spot would quickly reinvade longleaf plantations, but that Chapman was correct in his contention that fire benefited initiation of longleaf pine seedling growth. Professor Chapman's research changed the prevailing opinion that all fire was bad. Chapman strongly supported the use of fire in longleaf pine reforestation and management, stating that ". . . prohibition of use of controlled fire will effectively exterminate this species in the region described" (Chapman 1941).

During the 1930s, other fire studies resulted in a tentative fire danger meter for the longleaf-slash pine (*P. elliottii* Engelm.) type. George Waltner, sociologist, and Dr. John Shea, psychologist, were contracted to study the forest fire-starting motives of local residents (Wheeler 1963). Dr. Shea reported that many of those who started fires craved excitement in "an environment otherwise barren of emotional outlets" (Kerr 1958).

Forest Survey

Early surveys of forest resources were mandated by Congress. In 1930, Congress appropriated funds to begin a forest survey of the southern hardwood region. "The Trees of the Bottom Lands of the Mississippi River Delta Region," by John Putman and Henry Bull (1932), was issued as the first in the Southern Station's Occasional Paper series. This publication was well received and later led to the establishment of the station's bottomland hardwood research center at Stoneville, MS.

The Southern Forest Survey was authorized by the McSweeney-McNary Act and began in 1931. I.F. "Cap" Eldredge assumed direction of this survey at the Southern Station and significant resources were allocated to the work. Beginning in 1934, a series of releases established the value of the effort. New releases were eagerly awaited, and these became the basis for the pulp industry's move into the South (Wheeler 1963). By the end of 1942, the Southern Forest Survey had "grid-ironed the States from South Carolina and part of Tennessee south and west to the western boundaries of the southern trees, and 53 releases had been issued, which in turn were reworked into formal State reports issued from the Government Printing Office" (Wakeley and Barnett, in press). This was a tremendous task (more than 215 million acres were inventoried) and its results provided the basis for the development of forest industry across the South.

Hardwood Management

Early hardwood research was focused at the Appalachian Station's Bent Creek Experimental Forest, which was established in 1925 on a portion of land that the Forest Service purchased from George Vanderbilt. Most of the land purchased from Vanderbilt became the Pisgah National Forest, but a portion was set aside for the experimental forest. Earl Frothingham and F.W. Haasis assumed responsibility for experimental tests established by Pinchot and Schenck on Vanderbilt's Biltmore Estate. Jesse Buell arrived in the mid-1920s and initiated studies to determine how the cutover areas of the Southern Appalachians could be managed. Buell published information dealing with silvicultural practices needed to manage hardwoods, and with Margaret Abell published reports of methods for estimating future volumes of Appalachian hardwoods and the effect of fire on hardwood quality (Buell 1928, Buell and Abell 1935). Fire was found to play a significant role in the introduction of heart rot in hardwoods (Haig 1946). Margaret S. Abell, for many years the only woman to be employed as a professional forester by the Forest Service, was stationed at Bent Creek during the 1930s.

There was little other hardwoods research in the South before the World War II period. The Southern Station was not allowed to conduct hardwood research before late 1928 when the State of Louisiana provided $5,000 for the salary and expenses of G.H. Lentz of New York State College of Forestry, assisted by John Putman, to begin an economic survey of the hardwood situation in Louisiana.

Insects and Diseases

In 1925, the Bureau of Entomology established a small insectary at Bent Creek in the Appalachian Station and assigned R.A. St. George to breed and observe generation after generation of such "public enemies" as the southern pine beetle (*Dendroctonus frontalis* Zimmermann). T.E. Snyder of the Southern Station began to publish information about the influence of environmental factors on the development of southern pine beetle populations in the mid-1930s (Snyder 1935).

At Bogalusa, Wakeley (1935b) worked out the life history of the Nantucket pine tip moth (*Rhyacionia frustrana* Comstock) in 1927–28, a significant accomplishment since he had little entomological training.

Brown-spot needle blight was a major disease affecting longleaf pine seedlings in nurseries and after outplanting. At the suggestion of Dr. Carl Hartley of the Bureau of Plant Industry in Washington, DC, Wakeley initiated a study evaluating the use of the fungicide Bordeaux as a potential control. The tests were very successful, and a Bordeaux mixture became the standard spray treatment for brown-spot. The assignment of Paul V. Siggers to the Southern Station in 1928 to conduct research on brown-spot needle blight and fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) began a period of significant accomplishment. His research culminated in papers such as "The Brown-Spot Needle Blight of Longleaf Pine" (Siggers 1932) and "Weather and Outbreaks of the Fusiform Rust of Southern Pines" (Siggers 1949). Siggers (1940) also proposed the name "little-leaf disease of pines" for the diseased condition of shortleaf pine in northcentral Alabama.

The valuable chestnut [*Castanea dentata* (Marsh.) Borkh.] was eliminated from the Appalachian forests by the blight caused by *Endothia parasitica* (Murrill) Anderson & Anderson. The blight swept southward and westward into the forests of the Southern Appalachian Mountains in the 1920s effectively eliminating the species from these forests (Frothingham 1924). Studies were established to determine how long the dead trees would be useful as sources of tannin and pulpwood. It was found that their insect-and-disease-resistant wood would ordinarily be useful for about 30 years after death of the trees (Haig 1946).

Products

An early problem experienced in the use of second-growth lumber was the rapid development of a blue stain fungus that greatly reduced the value of unseasoned (not kiln dried) lumber. Ralph Lindgren reported in 1928 and 1929 that treatment of lumber with ethyl mercuric chloride eliminated the blue stain problem (Wheeler 1963). Lindgren's accomplishment had a great impact on the forest products industry. Within 2 years, the results were applied in over 200 pine and hardwood mills across the country and were being put into use abroad (Lindgren and Verrall 1950).

Another early effort focused on improvements to chipping for resin production in the naval stores industry. Len Wyman was assigned to a substation in Stark, FL, in 1921. Wyman's work changed the gum naval stores industry across the South. He worked effectively with industry to reduce the size of the chipping streak. This reduction resulted in a substantial saving in labor and in tree mortality and also increased considerably the length of time a tree could be worked (Wakeley and Barnett, in press). To increase production of gum naval stores for war needs, the station intensified experiments with chemical stimulation, and in a few years again revolutionized naval stores techniques by introducing developments in this field. As old-growth stands suitable for chipping were cut, the stumps resulting from harvesting were distilled for naval stores products (Kerr 1958).

In 1937, the South had a total of 38 pulpmills in operation or under construction. Much of the credit for the rapid expansion of pulping southern wood goes to Dr. Charles Herty (Heyward 1963a). Herty served as head of the Department of Chemistry at the University of North Carolina and was elected president of the American Chemical Society in 1915. He became enthralled with the prospect of producing newsprint from southern pines and established a laboratory (Industrial Committee of Savannah, Inc.) in Savannah, GA, to evaluate pulping technology. He traveled widely to promote the use of second-growth timber as a source of pulp for newsprint. His showmanship and genius for publicity developed confidence in the potential to produce paper from southern pine pulp.

Mensuration and Statistics

One of the earliest studies undertaken by the Southern Station made use of temporary sample plots in even-aged, second-growth stands throughout the South. The data obtained were compiled into normal volume, stand, and yield tables for unmanaged second-growth loblolly, shortleaf, longleaf, and slash pines. The tables were published in 1929 as Miscellaneous Publication 50 of the U.S. Department of Agriculture (U.S. Department of Agriculture, Forest Service 1929). They were used widely and contributed greatly to an understanding of the growth potential of the four principal southern pines and the practical forest management of the pine types (Wakeley and Barnett, in press). This publication was long out of print and copies were virtually museum pieces when it was reprinted as a result of customer demand in the 1970s.

A number of spacing and thinning studies were established with both pines and hardwoods. Early on, there was no replication in these or any other studies. Nevertheless, they did begin to provide good management guidelines. With the assignment of Roy Chapman to the Southern Station in 1927, practical statistical techniques began to be more widely applied. Chapman was assigned to train under Francis X. Schumacher for 3 years and developed a friendship with R.A. (later Sir Ronald) Fisher, one of the founders of modern statistics, whose published works and personal advice did much to shape Chapman's and the station's scientific direction (Wakeley and Barnett, in press).

Genetics and Tree Improvement

In 1922, Professor H.H. Chapman published his remarkable treatise on studies establishing the existence of a natural hybrid between longleaf and loblolly pine, Sonderegger pine (*P.* × *sondereggeri* H.H. Chapm.) (Chapman 1922). He named the hybrid after V.H. Sonderegger, who was then Louisiana State Forester.

In 1929, Wakeley performed the first controlled hybridization of southern pines, a cross of longleaf and slash pine (Wakeley 1981). He also established the first provenance test of southern pine. Planted in 1926–27 and remeasured at 15 years of age, loblolly pine from four different seed sources showed a striking range in wood production (Wakeley 1944). Because of the detailed original descriptions, the 23 acres of these early experimental plantings became a valuable asset in forest genetics research. This research was aggressively pursued by a number of organizations after World War II and in 1954 led to the founding of the Southern Institute of Forest Genetics on the Harrison Experimental Forest.

Watersheds

H.G. Meginnis reported to the Southern Station in 1929 and began work in an erosion control program. The effort was centered in northern Mississippi where 35 percent of two counties was covered with gullies as much as 100 feet deep

(Wakeley and Barnett, in press). Meginnis quantified erosion and runoff by soil type, compared use of planted pines and other species for erosion control, and applied litter and organic matter to paired watersheds. His research established the protocols used across the South for managing eroded soils and restoring productivity (Meginnis 1933).

Charles Hursh began work at the Appalachian Station in 1926 and led research dealing with erosion control and methods of stabilizing road banks and abandoned agricultural land. In 1932, plots were established at the Bent Creek Experimental Forest near Asheville, NC, to study surface runoff from five representative types of forested or agricultural cover, and an infiltrometer was used successfully with artificial rainfall. These studies led to recognition of the need to establish complete watershed instrumentation to provide for continuous measurements of stream flow and precipitation. As a result, the Coweeta Experimental Forest was established near Franklin, NC, in 1933. Appalachian Station Director C.L. Forsling required a period of standardization of the gauged watersheds. An intensive program of weir construction began in 1934, and a network of 56 standard rain gauges, numerous ground-water wells, and meteorological stations was created. By 1939, calibration of watersheds had progressed enough so that experimentation could begin (Stickney and others 1994). Early studies documented the harmful effects of mountain farming, woodland grazing, and unrestricted logging on soil and water resources (Douglass and Hoover 1988).

Forest Economics

In July 1929, the Southern Station began work in forest economics, having received a special appropriation of $22,800 from Congress for initiating investigations of financial aspects of timber growing in the southern pine region. E.L. Demmon, Director, in summarizing the early evaluations in "Economics of Our Southern Forests," stated that the value of forest resources in the South greatly exceeded that of any other agricultural crop (Demmon 1937).

The War Years

During the early to mid-1940s, younger men left for military service and older ones spread themselves thin to make measurements and consolidate gains. Many experimental forest areas were closed, and most regular research was postponed for the duration of the war. The stations had major programs for gathering information about supplies, output, and requirements of forest products for defense for the War Production Board. The stations also assisted war agencies in establishing cork oak (*Quercus sober* L.) plantations, developing Russian dandelion (*Taraxacum kok-saghyz* Rodin) and goldenrod (*Oligoneuron* Small) plants for rubber production, freeing airfields of undesirable vegetation, measuring infiltration rates of soils in connection with airfield drainage, camouflaging military installations, evaluating priority requests for logging and milling equipment, improving fire protection of critical areas, and controlling termites and decay in wood structures (Wheeler 1963).

At the end of World War II (1946), the boundaries of the two stations were realigned. The Southern Station assumed responsibility for research in Tennessee and relinquished Georgia and Florida (South Carolina had already been transferred to the Appalachian Station) to the newly formed Southeastern Forest Experiment Station (formerly the Appalachian Forest Experiment Station).

SIGNIFICANCE OF THIS RESEARCH

With only a handful of professional foresters, and despite little technical support and primitive working conditions, forestry in the South has made tremendous gains. Researchers developed reforestation techniques, studied and began to understand the role of fire in forests, began surveys of the southern forests that led to development and expansion of forest industries, and learned how to control important insect pests and diseases. They also developed an understanding of the importance of the use of statistical design and the value of tree improvement, developed methods for controlling soil erosion, and improved the efficiency of producing forest products. In < 20 years, they provided the basic management guidelines that have resulted in great progress in the restoration of the South's forest lands. In more recent decades, forestry research has refined this knowledge and filled gaps in it. Researchers continue to build on the strong scientific understanding provided by those who preceded them. As a result, our restored southern forest lands are now a primary economic resource in all Southern States.

LESSONS LEARNED

How did our early research professionals with limited resources accomplish so much in a relatively short period of time? Dedication, cooperation, and teamwork were characteristics of the early research program. Not only did the individuals support each other's efforts, they developed excellent relationships with scientists in universities and other agencies, as well as with foresters in forest industry and State organizations dedicated to solving problems common to all organizations. Wakeley and Barnett (in press) quote a passage in Macaulay's "Horatius" that describes their attitude:

> For Romans in Rome's quarrel
> Spared neither goods nor gold
> Nor son nor wife nor limb nor life
> In the brave days of old.
> Then none was for the party.
> Then all were for the State.
> Then the rich man helped the poor
> And the poor man loved the great.
> Then lands were fairly portioned.
> Then spoils were fairly sold.
> The Romans were like brothers
> In the brave days of old!

CONCLUSIONS

The South's forests were largely overexploited during the early 1900s. Vast areas had been converted to agriculture and then abandoned or were harvested and not regenerated. The knowledge needed for the restoration of these forests was sorely lacking. The establishment of the Southern and Appalachian Stations in 1921 provided the impetus to develop the scientific base for this restoration effort. An important component of this effort was interaction and cooperation with those in universities and forest industry that had the same intense motivation to restore the southern forest lands.

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Chapter 4.

Southern Forest Resource Conditions and Management Practices from 1950–2000: Benefits of Research

Jacek P. Siry[1]

Abstract—*Over the past five decades, research progress and implementation have been the leading factors supporting the rapid development of southern forestry. The South has become the leading timber-supplying region in the United States, taking advantage of a large accumulation of growing stock and a substantial investment in intensive, research-based management treatments. This chapter focuses primarily on intensive management of planted pine forests. Plantations commonly receive high levels of all inputs and are major beneficiaries of research advances. High plantation growth rates are essential if our increasing demand for wood is to be met and if harvest pressure on the remaining natural forests is to be reduced.*

INTRODUCTION

During the first half of the 20th century, forest researchers established the basic management guidelines for forest management in the South. They developed reforestation techniques, learned how to control forest fires, carried out surveys of southern forest resources, learned how to protect forests from insects and diseases, developed soil protection techniques, and introduced new technologies that greatly increased the efficiency of wood products manufacturing. These achievements were essential not only for restoring southern forests but also for making possible their future expansion.

During the second half of the 20th century, these basic forest management guidelines were refined on the basis of new knowledge, and more importantly, many of them were implemented on a very large scale in the South. Although this chapter provides a brief overview of major advances in forestry research, it focuses on research related to management of planted pine (*Pinus* spp.). Research findings have influenced planted pine management in the South in important ways.

Over the past five decades, the South has experienced rapid growth in planted pine area and productivity. These gains were made possible in part by research that paved the way for the development and widespread application of new technologies including genetic improvement and application of fertilizers and herbicides. Today the South is the leading U.S. regional and global supplier of softwood timber. Extensive forest management that emphasized the exploitation of existing resources has been abandoned in the South and has been replaced by an intensive, primarily softwood-producing industry propelled by implementation of research.

OVERVIEW OF SOUTHERN FOREST RESEARCH AND MANAGEMENT: 1950–2000

The contributions to southern forestry made by forest scientists employed by the U.S. Department of Agriculture Forest Service (Forest Service), forestry schools and departments, forest industries, and other forestry organizations during the past half-century were enormous. Scientists developed knowledge and technologies that constituted an essential basis for rapid gains in the production of timber and nontimber goods. Extensive cooperation among scientists at various organizations and the combination of research and implementation made possible by Federal, State, and industrial programs were of great importance in the development of southern forestry. The following brief overview of major research advances in southern forestry is based largely on Johnston's (1989) record of a great history of forestry research in the South.

Growing demand for wood and research in forest products manufacturing were important factors in increasing utilization of southern forests. Research led to the development of technology for producing kraft pulps from the wood of southern pines, and the availability of this technology resulted in the rapid expansion of the southern pulp and paper industry. New technologies

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created new uses for southern pines, increasing their commercial value and leading to the rapid development of wood-manufacturing industries. For example, the development of plywood technology for southern pines in the 1960s was followed by the development of a variety of panel products, such as fiberboard, particleboard, and oriented strand board. Research also improved sawmilling efficiency by developing new equipment and cutting practices that increased lumber yields, especially from small logs. New equipment for logging operations, such as tree harvesters and machines for in-woods chipping, was also developed.

Increasing demand for small wood coincided with the exhaustion of convenient supplies from natural forests and encouraged the development of pine plantation programs at a time when land was abundant. Planting programs required large quantities of good seedlings, effective site-preparation methods, and protection from fires, pests, and diseases. Research provided the knowledge needed to secure seed sources, establish productive tree nurseries, develop effective planting methods, and protect forests. Fire research, for example, helped reduce area burned and damage caused by wildfire while it demonstrated the value of controlled burning. The area burned by wildfire averaged 38 million acres per year from 1931 to 1935; this was reduced to about 2 million acres per year by the mid-1960s (Southern Forest Resources Analysis Committee 1969). This progress permitted large gains in timber growth and encouraged investment in timber growing.

Timber management research has always been important in the South. Forest scientists developed guidelines for the management of all major species and forest types in the region. Research provided better knowledge of silvicultural practices, vegetation control, soils and fertilizers, and nutrient cycling. Scientists developed and used models for analyzing timber growth, yields, and effects of thinning and other management practices. Economic research identified promising investment opportunities and needs, stimulating the development of intensive pine management. By demonstrating that even small owners can benefit from intensified management, economic research helped establish a number of forest assistance programs. Further, researchers analyzed present and future timber supply conditions. Biometric and economic research combined with advanced forest surveys provided better information about forest inventory, growth, mortality, and utilization, helping guide investments in land acquisition and intensive management to support industrial expansion.

Hardwood forests, which cover more than half of the South's forest land, also attracted substantial research efforts. Research provided guidelines for regeneration and culture of hardwood forests in both natural and planted stands. Plantations of cottonwood (*Populus* spp.), sycamore (*Platanus occidentalis* L.), and yellow-poplar (*Liriodendron tulipifera* L.) have shown much promise of increased productivity. But there has been much less research and investment in hardwood management than in pine management (Hicks and others 2001, Kellison 2001). One reason for this is that hardwoods have been in ample supply, and returns from managing them actively have generally been insufficient to justify widely applied intensive silviculture.

Research produced hardwood pulp technology, however, and the availability of this technology has fostered increased utilization of southern hardwoods and has provided incentives for expanded research in their silviculture and natural regeneration. As available hardwood inventories dwindle and hardwood prices and management returns increase, more research effort and applications can be expected. Trials of early silvicultural interventions in natural hardwood stands show promise of providing substantial and profitable growth increases (North Carolina State Hardwood Research Cooperative 2001).

Finally, growing demand for forest recreation and wildlife stirred considerable research interest in these areas. For example, scientists investigated the impact of intensive forest management practices on recreation opportunities and developed guidelines for use of thinning and prescribed burning to improve the quality and increase the availability of wildlife habitat. Growing environmental concerns led to expanded investigation of the impact of forest management practices on water quality and to the development of best management practices.

Substantial research efforts had a great impact on the character of southern forests. In the 1950s, southern forests were managed primarily with low intensity in natural stands. More than 7 million acres of the region's timberland were nonstocked and in need of regeneration. Only 2 million acres were in planted pine forests. The area planted in pine had expanded to about 30 million

acres by 1997, along with rapidly intensifying management and increasing productivity (Smith and others 2001).

Planted pine management has changed southern forestry dramatically. While the South accounts for only 40 percent of the Nation's forest land area and 22 percent of its softwood growing stock, it supplies 64 percent of all softwood harvested in the United States. Today, the South's pine plantations account for nearly 19 percent of the world's area of fast-grown industrial wood plantations. While the region's planted and natural pine forests represent < 3 percent of global conifer forest cover, they supply nearly 19 percent of global industrial softwood roundwood harvests (Food and Agriculture Organization of the United Nations 2002, Smith and others 2001). No other region or country in the world supplies more softwood timber than the U.S. South.

INTENSIVE PLANTED PINE MANAGEMENT IN THE 1990S

Pine plantations are managed much more intensively now than they were formerly, when management consisted primarily of site preparation and planting. Today's intensive management relies heavily on the widespread application of research-based approaches such as the planting of genetically improved seedlings and the application of fertilizers and herbicides. The management of industrial pine plantations is a particularly good example of the contribution of intensive management technologies to greater growth because such management involves high levels of all inputs and because industrial plantations benefit greatly from research advances.

The results of a forest industry management survey[2] were used to estimate current operational results of intensive management of planted pine. The survey was designed by the American Forest and Paper Association's Resource Planning Act (RPA) Task Group and was used to collect data about industry land and management practices for use in the 2000 RPA Timber Assessment. The survey covered the 13 Southern States and collected data on tree planting, genetic improvement, control of vegetation and stocking, nutrition, thinning, harvest age, and the management of future stands on leased and company-owned forest land. Participating companies accounted for 16.3 million acres of planted pine, or about 90 percent of pine plantation area in forest industry ownership in the region.

The survey provided the basis for the development of five management intensity classes (MIC) for planted pine (Siry and others 2001). MIC 1 represents traditional management consisting only of site preparation and planting. MIC 2 represents low intensity that involves site preparation and planting of genetically improved seedlings. MIC 3 describes moderate intensity with fertilizer application. MIC 4 stands for high intensity in which herbicide use is added to MIC 3 treatments. Finally, MIC 5 represents very high intensity, with multiple applications of fertilizers and herbicides.

Table 4.1 presents total and average annual yields of merchantable wood for planted pine on medium-quality sites at age 25. Total yields range from about 2,700 cubic feet per acre for MIC 1 to nearly 4,600 cubic feet per acre for MIC 5 (Siry and others 2001). These total yields translate into average annual growth rates ranging from 109 cubic feet per acre for MIC 1 to 183 cubic feet per acre for MIC 5. These data show that very intensive management can produce almost 70 percent more volume than traditional management produces.

Table 4.1—Intensively managed planted pine growth and yield data (wood volume) for medium sites and 25-year rotation

Management intensity class	Total wood yield at age 25	Average annual growth rate
	ft^3/ac	*$ft^3/ac/yr$*
MIC 1 - traditional	2,716	109
MIC 2 - genetics	3,135	125
MIC 3 - MIC 2 + F	3,433	137
MIC 4 - MIC 3 + H	4,033	161
MIC 5 - MIC 4 + 2nd F and H	4,587	183

MIC 1 = site preparation and planting; MIC 2 = site preparation and planting of genetically improved seedlings; MIC 3 = moderate intensity with fertilizer application; MIC 4 = high intensity in which herbicide use is added to MIC 3 treatments; MIC 5 = very high intensity with multiple applications of fertilizers and herbicides; F = fertilization; H = herbicide application.

[2] Goetzl, A. 1998. AF&PA southern forest management intensity survey: data summary and survey results. [Number of pages unknown]. On file with: American Forest and Paper Association, 1111 Nineteenth Street, NW, Suite 800, Washington, DC 20036.

INTENSIVE TIMBER GROWING METHODS

Genetic Improvement

The forest industry survey indicates that use of genetically improved growing stock increases wood volume by about 15 percent, or nearly 420 cubic feet per acre at age 25. Such increases were made possible by genetic research and industrial tree improvement programs that began in the South as early as the 1950s.

Genetic improvement of pines was focused on site adaptability, disease tolerance, growth rates, tree form, and wood quality (Zobel 1974). Rapidly expanding planting programs demanded large quantities of pine seed, and this demand stimulated the establishment of seed orchards. Most tree improvement effort was directed at slash (*Pinus elliottii* Engelm.) and loblolly pine (*P. taeda* L.), but some emphasis was also put on longleaf pine (*P. palustris* Mill.). Continued interest in genetic improvement has resulted in the establishment of industry-university cooperative tree improvement programs at Texas Agricultural and Mechanical University, the University of Florida, and North Carolina State University. Hardwood tree improvement work began after the work on pines started and later subsided. Very few hardwood plantations were established.

The 42 years of loblolly pine improvement studies carried out by the North Carolina State University-Industry Cooperative Tree Improvement Program have yielded 7- to 12-percent volume increases in trees grown from first-generation seed orchards (Zobel and Talbert 1984). Second-generation tree breeding produced wood volume gains of 17 to 30 percent over unimproved seeds (Li and others 1998). Genetically improved trees also display improved stem quality and fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) infection rates that are reduced by as much as 25 percent. The history of tree improvement research in the South is summarized in Zobel and Sprague (1993).

Fertilization

Pine fertilization research trials were established in the South as early as the mid-1940s. Foresters, however, showed little interest in this work until 20 years later, when remedial fertilization of slash pine forests growing on phosphorus-deficient sites produced spectacular responses (Pritchett and Comerford 1982). On such sites, phosphorus fertilization resulted in great volume and value gains, as phosphorus shortages virtually precluded the establishment of viable pine plantations. Volume gains were as high as 50 cubic feet per acre per year for up to 20 years in response to a single phosphorus addition at or near planting.

Growing interest in forest fertilization led in the late 1960s to the establishment of industry-funded research cooperatives at the University of Florida and North Carolina State University. The Florida program focused on slash pine and the North Carolina program on loblolly pine. Both programs researched possibilities of increasing growth by applying fertilizers and developed technologies for operational use of fertilizers in forestry.

Fertilizers are now applied at planting, at young ages, and in midrotation. Two of the most commonly supplied nutrients are phosphorus and nitrogen. Fertilization at planting is frequently aimed at ameliorating phosphorus deficiencies, while applications in established stands usually supply additional nitrogen and phosphorus. Operational data from the forest industry survey indicate that midrotation applications of 25 pounds per acre of phosphorus and 200 pounds per acre of nitrogen increase yield by 400 cubic feet per acre, or 15 percent per application, for a 25-year rotation. To date, fertilizers are applied almost exclusively in intensively managed pine plantations; they have been used very little in hardwood stands.

Scientists have moved to investigate interactions of fertilization with other silvicultural treatments that may influence nutrient availability, the effects of applications of nutrients such as potassium and boron, and interactions between nutrient additions and tree resistance to pests and diseases (Allen 1983, Ballard 1984). Presently, research focuses on developing more integrated approaches to site nutrient management (Allen 2001).

Herbicide Application

The largest problem in intensive pine culture in the South is the difficulty of controlling hardwoods that invade pine sites (Waldstad 1976). Natural succession, when accompanied by reduced fire frequency and increased pine harvesting, favors hardwood development. Hardwood competition can overtop young pines and greatly reduce the availability of moisture, nutrients, and sunlight to pine trees, resulting in higher seedling mortality and slower growth (Clason 1993, Glover and Zutter 1993).

Foresters did not initially consider herbaceous competition a major impediment to pine growth, so early forest herbicide research focused on control of hardwoods in pine stands (Gjerstad and Barber 1987). Research developed rules for herbicide selection, dosage, timing, and application methods. In the 1980s, research trials indicated that herbaceous vegetation does compete with young pine seedlings and that its elimination can increase survival and growth rates of young pines (Creighton and others 1987, Lauer and others 1993, Yeiser and Williams 1996, Zutter and Miller 1998). This has led to the development of approaches for controlling both woody and herbaceous vegetation.

The forest industry survey indicates that control of vegetation has the largest impact on wood volume growth. In MIC 4, woody plant treatment in year 1 increased yield by about 600 cubic feet per acre at age 25. In MIC 5, herbicides were applied twice; herbaceous plant treatment at planting was followed by woody plant treatment in year 3. These applications increased yield by as much as 750 cubic feet per acre at age 25, or by nearly 28 percent over untreated stands.

Herbicides are used for site preparation before stand establishment, release from hardwood and herbaceous competition in young stands, and timber stand improvement in midrotation. Herbicide treatments gain popularity because they are cheaper, more effective, and easier to apply than others. To date, herbicide research and applications have been limited primarily to intensively managed southern pines, but there is growing interest in herbicide applications in hardwood forests. Fitzgerald (1980) provides an historical overview of herbicide research and use in forestry.

RETURNS FROM INTENSIVE MANAGEMENT

While intensive management can greatly increase pine growth and yield, investment returns will largely determine how widely it will be applied and how intensive it will become. The costs of genetically improved seedlings, herbicides, fertilizers, and other treatments increase the total management costs per acre. However, production rates may increase sufficiently to decrease average production costs and justify increased investment in timber management. Real rates of return for planted pine management now vary from nearly 10 percent (MIC 1) to 12 percent (MIC 5) (Siry and others 2001). Net present values and soil expectation values also indicate that intensive management offers attractive returns—values associated with very intensive management (MIC 5) are more than 1.6 times higher than returns associated with traditional management (MIC 1). The increased returns reflect higher production values resulting from increases in timber volume and quality. These returns are sufficient to justify investment in improved timber management practices on a large scale.

EXTENT OF INTENSIVE FOREST MANAGEMENT PRACTICES

Forest Service, Forest Inventory and Analysis (FIA) data spanning from 1982 to 1999 show increases in rates of harvesting, planting and natural regeneration, timber stand improvement, and chemical application in the South (Siry 2002). Intensive management is practiced primarily in planted pine forests, where most planting, site preparation, fertilizer and herbicide use, and thinning occur. The FIA data also indicate that natural pine, oak (*Quercus* spp.)-pine, and upland and bottomland hardwood forests are managed with considerably lower intensity.

Several authors have presented survey information that shows what forest management practices are employed, and how extensively they are employed, by important owner groups in the South (Moffat and others 1998, Siry and Cubbage 2001, Siry and others 2001). Table 4.2 summarizes this information and information provided by other sources that are described subsequently.

Table 4.2—Extent of intensive forest management practices in the South

Forest type	Management treatment	Forest land area
		million acres
Planted pine	Genetic improvement	26
	Fertilization	11
	Herbicide use	11+
Natural pine	Some practices such as fertilization and/or thinning were or will be used	6
Oak-pine		3
Upland hardwood		5
Bottomland hardwood		3

In the South, only about 4 million acres of pine plantations were established under management consisting only of site preparation and planting of seedlings that were not genetically improved. Pine plantations on 26 million acres were established using genetically improved seedlings. Today, virtually all seedlings of pine species planted in the South are genetically improved (Li and others 1998).

Data collected by the North Carolina State Forest Nutrition Cooperative (2001) indicate that almost 1.6 million acres of southern pine stands were fertilized in 2000. Since 1969 slightly more than 11 million acres have been fertilized in the South. This area is estimated to exceed the sum of forest acreage fertilized in the rest of the world. While midrotation fertilization is most common, the area fertilized at planting and at young tree ages is increasing. If current planting trends continue and pine plantations are fertilized at least twice throughout the rotation, then the area on which fertilizers are applied will at least double.

It is difficult to obtain reliable information about the extent of herbicide use. However, herbicides have a long history of use in pine management, and it is clear that they are employed widely in the South. Pesticide-use patterns (Michael 2000) indicate that nearly 1 percent of forest land in the United States is treated annually. If these patterns hold for herbicide use in the South, approximately 2 million acres of southern forest land receive herbicide treatments each year.

Natural pine, oak-pine, and hardwood stands are often managed custodially on an even-aged basis and receive no treatments. Management at higher levels of intensity, which includes the application of treatments such as fertilization or thinning of even-aged stands to promote growth and quality, is limited. Survey results indicate that only about 6 million acres of existing natural pine forests have received or are scheduled to receive such treatments. Following harvesting, natural pine forests are often replanted with pine seedlings and managed more intensively. Growth-promoting treatments have been applied on or are planned for 3 million acres of oak-pine forests and 8 million acres of hardwood forests.

EFFECTS OF INTENSIVE FOREST MANAGEMENT PRACTICES

Table 4.3 compares the growth rate of very intensively managed planted pine (MIC 5) with empirical rates used in the Subregional Timber Supply (SRTS) model, which analyzes and forecasts southern timber supply conditions (Abt and others 2000). The empirical growth-and-yield estimates employed are based on FIA data. Across all sites, management intensities, and owners in the South, growth of planted pine averages 94 cubic feet per acre per year for a 25-year rotation (Abt and others 2000, Siry and others 1999). Industrial yields are from about 15 percent (for MIC 1) to 95 percent (for MIC 5) above current SRTS model values for average sites at age 25. This implies that very intensive planted pine management (MIC 5) has the potential to double recently observed production rates. Very intensively managed pine plantations (MIC 5) can grow more than twice as fast as natural pine stands, which grow at an average rate of 72 cubic feet per acre per year.

An analysis based on FIA data indicates that average annual pine growth in the South (for planted and natural stands combined) increased by 22 percent from the mid-1980s to the mid-1990s (Siry and Bailey 2003). This increase added about 26 million tons per year to the region's softwood production. The analysis also indicates that pine growth increases are positively correlated with the area of intensively managed pine plantations.

Table 4.3—Growth rates (wood volume) for intensively managed planted pine (MIC 5) and SRTS-FIA forest management types

Management type	Average annual growth rate
	$ft^3/ac/yr$
Planted pine (MIC 5)	183
SRTS-FIA[a]	
Planted pine	94
Natural pine	72
Oak-pine	51
Upland hardwood	42
Bottomland hardwood	42

MIC 5 = very high intensity with multiple applications of fertilizers and herbicides; SRTS = Subregional Timber Supply model; FIA = Forest Inventory and Analysis.
[a] SRTS-FIA data are average values for all site indexes.

From the mid-1980s to the mid-1990s, planted pine area increased by 7 million acres to about 30 million acres while natural pine area decreased by 5 million acres to 33.5 million acres.

Growth rates for oak-pine and hardwood forests are substantially lower than those for planted pine. Oak-pine growth rates average about 51 cubic feet per acre per year for 60-year rotations. Growth rates for hardwood forests are still lower, averaging 42 cubic feet per acre per year for 60-year rotations. Growth rates in very intensively managed pine plantations (MIC 5) are nearly 3.6 times as great as average oak-pine growth rates and nearly 4.4 times as great as average upland and bottomland hardwood growth rates. Intensively managed plantations of hybrid poplars and other hardwood species grow rapidly, but their area is very small.

DISCUSSION AND CONCLUSIONS

Planted pine forests account only for about 15 percent of southern timberland but for a much greater share of softwood growth and harvests. The SRTS model indicates that pine plantations now account for about 56 percent of total softwood growth in the South (Prestemon and Abt 2002). The model indicates that pine plantations will overtake natural pine forests in supplying softwood timber between 2000 and 2005 as planted trees mature and reach merchantable size. Within a decade, harvests from pine plantations will amount to nearly a third of total softwood and hardwood timber production in the South.

The ability of pine plantations to supply the majority of softwood harvests is a clear indication of their great relevance for sustainable wood supply and conservation of the remaining natural forests. Since the area of commercial timberland is expected to remain relatively stable, existing forests will have to be utilized more intensively to satisfy timber demand. Intensive management of planted pine makes it possible to grow more wood on less land. Plantation success means that harvesting pressure on natural forests, old-growth forests, and environmentally sensitive areas will be reduced as timber demand is met primarily by wood grown on plantations. This creates new opportunities for conservation of the natural forests.

Ever-increasing demands for wood and other forest products and services imply that the productivity of pine plantations will have to continue to grow. Progress made in recent years indicates that this is entirely possible. Today's challenge is to develop approaches that combine various intensive management treatments in ways that generate the maximum returns in an environmentally responsible manner.

More frequent and more widespread application of fertilizers and herbicides could increase productivity substantially. Nearly half of the South's forest acreage would benefit from timber stand improvement, including herbicide use (Waldstad 1976). Nutrient-deficient sites are also widespread, and even sites previously thought not to be nutrient deficient can benefit from fertilization (Allen 2001). There is also abundant evidence that appropriate repeated fertilizer applications produce additional response from forest stands (Ballard 1984). For example, annual fertilization and multiple applications of herbicides resulting in total control of competing vegetation on loblolly pine research sites in Georgia produced annual growth rates ranging from 325 to 490 cubic feet per acre (Borders and Bailey 2001). Such growth rates are about twice as high as current rates in intensively managed industrial pine plantations (MIC 5).

Genetic improvement of trees appears to hold the greatest long-term promise. Although realized genetic-related gains in wood volume have not averaged more than 30 percent to date, the best second-generation loblolly families have shown volume increases of up to 66 percent and improved stem straightness, wood quality, and resistance to diseases (Li and others 1998). Continuing progress in breeding technologies, including controlled mass pollination and vegetative propagation (rooted cutting and tissue culture), and eventually genetic engineering of trees, promises even greater gains in wood volume and quality. The limits of such gains are today largely unknown.

Over the past five decades, forest research has developed powerful new timber-growing technologies. The use of genetically improved seedlings, fertilizers, and herbicides in intensively managed pine plantations now results in growth rates that are nearly twice as high as those associated with traditional management consisting of site preparation and planting. Wider and more intensive application of growth technologies now in use could double or triple the current production levels for intensively managed pine. Such increases will be essential for sustaining and expanding southern timber harvests while limiting pressures on the remaining natural forests.

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Chapter 5.

The Southern Forest Resource Assessment: What We Learned

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Abstract—*The Southern Forest Resource Assessment was initiated in the spring of 1999 to address broad questions concerning the status, trends, and possible future of southern forests. The overall objective of the assessment was to develop a thorough and objective description of forest conditions and trends in the South, and to present it in a way that would help the public understand a complex and dynamic resource. Findings of the assessment highlight the forces of change at work in southern forests and potential ecological and economic implications.*

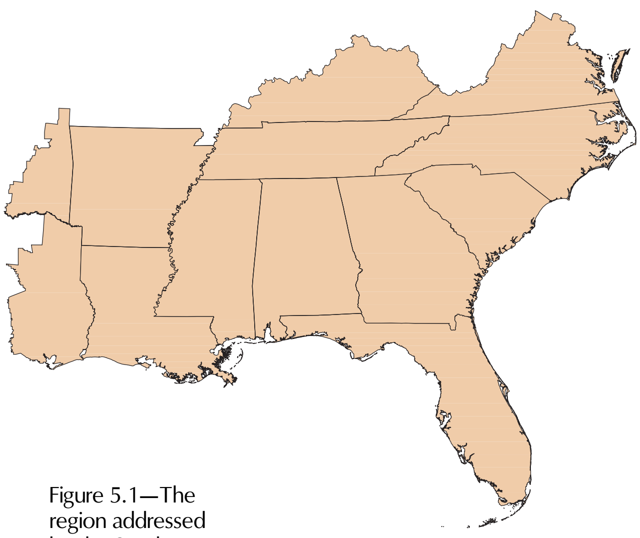

Figure 5.1—The region addressed by the Southern Forest Resource Assessment (Wear and Greis 2002a).

INTRODUCTION

The forests of the Southeastern United States are diverse and dynamic. They have been utilized heavily since European settlement, and their current condition reflects a long history of land use. At the beginning of the 20th century, a 100-year period of intensive agricultural exploitation gave way to a period of forest recovery and growth. In the last quarter of the 20th century, however, timber harvesting and land development for urban uses increased substantially. As a result, questions have emerged regarding the health, productivity, and ultimately the sustainability of the South's forests and the benefits they provide.

The Southern Forest Resource Assessment (SFRA) was initiated in the spring of 1999 to address broad questions about the status, trends, and potential future of southern forests (fig. 5.1). The assessment was chartered by southern offices of the U.S. Department of Agriculture Forest Service, the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service, and the Tennessee Valley Authority; and it was conducted in collaboration with State agencies represented by the Southern Group of State Foresters and the Southeastern Association of Fish and Wildlife Agencies.

Approximately 89 percent of the South's forests are held by private owners. The assessment was, thus, a somewhat unusual undertaking, one in which Government agencies evaluated the status and future of a largely private sector of the economy. For this reason, the assessment was chartered as an information-gathering activity. The overall objective of the assessment was to develop a thorough and objective description of forest conditions and trends in the South, and to present this description in a way that would help the public understand a complex and dynamic resource situation. This role, i.e., monitoring change at a broad scale and describing cumulative change, has been described by the National Research Council (1998) as a logical and important role for Government in the area of private forestry.

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A descriptive assessment such as the SFRA can be used to highlight the major dynamics and uncertainties at play within a region's forested ecosystems, thereby focusing public discourse on the changes affecting these systems and on associated policy issues. Because the assessment has only recently been completed, it is too early to examine its effectiveness on such terms. In this chapter, we (1) examine the process that was used to structure and to conduct the assessment, (2) discuss the major findings of the assessment, and (3) examine the implications of these findings for the conduct of forestry and forest science in the South.

ASSESSMENT PROCESS

The SFRA can be viewed as an exercise in what Lee (1993) has called "civic science." It was designed to be accessible to the public and to utilize considerable amounts of public input in the definition of issues, scope, analysis protocols, and review of outputs. It was designed to provide the public with a platform of current knowledge and data upon which to discuss and debate current and future issues regarding the South's forests.

Defining the Questions

The first step in conducting the assessment was to define the set of questions that would be addressed. This was done by employing an approach utilized in the Southern Appalachian Assessment (Southern Appalachian Man and the Biosphere 1996). Initial sets of concerns were drafted by a group of about 75 experts from participating Government agencies using a workshop format and organized around 4 broad topic areas: (1) social-economic, (2) terrestrial ecosystems, (3) water and aquatic ecosystems, and (4) forest conditions and health. These concerns were then summarized into an initial set of questions that provided a framework for organizing public input.

To gather public input on the initial questions, two public workshops were conducted at each of five locations in the South. At each location, one workshop was conducted in the afternoon and the other in the evening. After presenting the audience with an overview of the project's objectives and general design, the group was divided into four separate sessions, each concentrating on one of four broad topic areas. In each of these sessions, the participants were encouraged to raise any concerns and issues that they felt needed to be addressed by the assessment, and these were recorded and compiled. The initial questions were also posted on the SFRA Web site, and public comments were taken by mail and email.

The comments were then compiled using content-analysis software and were posted on the SFRA Web site. The assessment leaders then developed a preliminary set of questions that would address public concerns to the extent practical and consistent with overall objectives. Each of these questions was linked to the set of major concerns (labeled subpoints) on which the question was based. The questions summarized input from more than 700 participants, and the subpoints recorded the details of the major points summarized by the question. These preliminary questions and subpoints were posted on the SFRA Web site and were again reviewed by the public. The additional review input was used to further refine the questions.

Conducting the Analysis

Each question defined the objective of an analysis of a resource or social issue related to southern forests. An individual scientist or analyst was selected by the SFRA planning team to conduct the analysis for each question. These individuals, who were called question managers, constituted the assessment team. The team was convened for an initial meeting with the objective of assessing the feasibility of and methods for addressing each question. Because of the potential for overlap of the analyses, question managers discussed their questions and approaches in groups organized by broad categories. Members of the public participated in these discussions and provided input regarding the question managers' interpretation of the questions and their proposed approaches.

Following the initial assessment team meeting, question managers prepared study plans that were posted on the SFRA Web site. These were also subject to public review and were eventually finalized. Analysis of the questions then commenced. Each question manager had the latitude to consult with various colleagues or to build a research team to conduct the work. During the course of the analysis, two assessment team meetings were held to discuss progress, share data, and to coordinate work to the extent possible. These meetings were also open to the public and were structured in a way that allowed the team to conduct its business and to solicit public input and reactions to the team's efforts.

Preliminary findings were not discussed in open assessment team meetings. This was consistent with a policy that findings would not be released without careful peer review. A closed meeting of the assessment team was held in January 2001 to discuss preliminary findings and to improve the coordination of analyses of related questions.

Reviewing the Results

Answers to the questions were drafted as separate reports and summarized in a summary report, which compiled and synthesized major findings from the separate reports. These findings were then evaluated using a peer-review process patterned after standard approaches utilized by scientific journals. For each report, a number of experts (peers) were selected to review and comment on the accuracy and adequacy of the response. These experts were selected from a set of candidates provided by members of the public, by agency representatives on the planning team, and by the question managers themselves. A single-blind peer-review procedure was employed; i.e., the identities of the reviewers were kept confidential in order to obtain candid remarks on the reports. Reviews were compiled and returned to the authors of each report for consideration as they revised their chapters. The assessment coleaders managed the peer-review process, including evaluation of responses to reviews by the authors.

After the individual chapters were revised to address comments raised through peer review, they were released as draft reports. The draft reports (including the draft summary report) were published via the SFRA Web site, and the draft summary report was printed for distribution upon request (Wear and Greis 2001).

Draft reports were reviewed over a 90-day comment period. Comments were taken via a threaded message board organized by individual reports on the SFRA Web site and through the mail. As public comments were received, they were classified by specific points raised, were organized by chapter, and were distributed to authors. Comments were used to revise reports and to identify additional relevant data and research that had a bearing on the assessment questions.

Final products of the assessment include a technical report that addresses the individual questions (Wear and Greis 2002b) and the final summary report (Wear and Greis 2002a). They also include all data used in the analyses and complete documentation of data sources and analyses. The availability of data and documentation is intended to enable the public to conduct followup analysis and to replicate the work conducted within the assessment. The data could also provide a benchmark for future updating of assessment findings.

ASSESSMENT FINDINGS

The full suite of assessment findings is contained in the 23 technical reports that constitute the chapters of the SFRA technical report (Wear and Greis 2002b). The following sections summarize the major findings described in the SFRA summary report.

FORCES OF CHANGE

We evaluated the forces of change that have reshaped and continue to reshape forests in five categories: (1) land markets, (2) timber markets, (3) social institutions, (4) biological factors, and (5) physical factors. While each of these areas defines important mechanisms of change, it is clear that they interact in their effects on southern forests. In each area, we examined the history and status of these changes and, where possible, explicitly projected potential changes.

Land Markets

From 1700 to 1930, land clearing for agriculture and timber production completely restructured southern ecosystems. Clearing for agriculture greatly diminished the area of forested wetlands, especially in the Mississippi River Alluvial Valley. Agricultural uses reached their zenith in the late 19th century. Wholesale land abandonment then set the stage for a long period of forest reestablishment and growth.

Since the 1940s, there has been little net change in forest area in the South. Current forest area is 214 million acres, or about 91 percent of that recorded in 1907. However, there have been large offsetting changes: forest land has been converted to urban and agricultural uses in some places, and agricultural land has been converted to forest in others.

Forecasting models indicate that 12 million forest acres will be lost to urbanization between 1992 and 2020. An additional 19 million acres are forecast to be developed between 2020 and 2040. Forecasts also indicate conversion of 10 million acres from agricultural land to forest between 1992 and 2020 and conversion of another 15 million acres by 2040. Most forest loss is expected to be concentrated in the eastern part of the South; forest gains are expected to be concentrated in the west.

Timber Markets

Between 1952 and 1996, the South's timber production more than doubled. Its share of U.S. production increased from 41 to 58 percent, and its share of world production increased from 6.3 to 15.8 percent. The region now produces more timber than any other country in the world (fig. 5.2).

The South produces a great variety of timber products, including softwood saw logs (28 percent of the region's wood output), softwood pulpwood (25 percent), and hardwood pulpwood (16 percent). Since 1952, hardwood pulpwood has experienced the greatest increase in product share, growing from 3 to 16 percent of output.

Models of timber markets forecast that timber production in the United States will increase by about one-third between 1995 and 2040. Nearly all of this growth will come from the South, where production is forecast to increase by 56 percent for softwoods and 47 percent for hardwoods.

Social Institutions

Laws, regulations, and Government programs are frameworks within which forests are managed. The current income tax code has mixed impacts on long-term investments in forestry, and inheritance taxes encourage owners to liquidate or split up forest properties.

Forest incentive programs that subsidize the planting of trees have had a long and successful history in the South. More recent programs focus on multiple values obtained from forests.

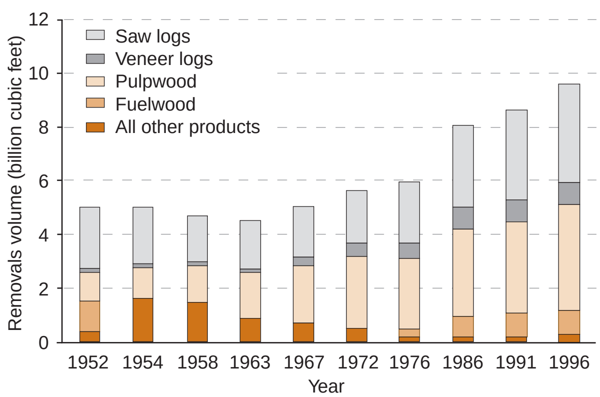

Figure 5.2—Removals by destination product, southwide, all species, 1952 to 1996 (Wear and Greis 2002a).

Direct regulation of forestry is limited in the rural South. However, in areas that are becoming more urbanized, a proliferation of local regulations has markedly affected land use and forest management. The number of such regulations nearly doubled between 1992 and 2000.

Funding of forest incentive programs is likely to vary depending on State and Federal priorities. The expansion of local regulations appears to be closely linked to population growth and urbanization. The number of regulations affecting forest treatments will likely continue to expand in high-growth areas.

Biological Factors

Native plant diseases and insects affecting pines have become problematic for forest managers in the South as the species composition and configuration of pine forests has changed. Southern pine beetle (*Dendroctonus frontalis* Zimmermann) and fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) are economically significant pests.

Nonnative diseases and insects have altered and continue to alter southern forests, especially hardwood forests. Chestnut blight {*Cryphonectria parasitica* (Murrill) Barr [formerly *Endothia parasitica* (Murrill) Anderson & Anderson]} removed an important canopy species beginning in the 1930s. Several other species-specific diseases have been introduced to the South. These include dogwood anthracnose (*Discula destructiva*), oak wilt [*Ceratocystis fagacearum* (T.W. Bretz) J. Hunt], and butternut canker (*Sirococcus clavigignenti-juglandacearum*). Among the nonnative insects that have been introduced are the gypsy moth (*Lymantria dispar* Linnaeus), balsam woolly adelgid (*Adelges piceae* Ratzeburg), and hemlock adelgid (*Adelges tsugae* Annand).

Nonnative trees, shrubs, vines, birds, and mammals are also having large impacts on southern ecosystems.

The southern pine beetle is expected to continue to cause substantial economic damage and ecological change in the South, especially on heavily stocked nonindustrial private and aging public forests. Multiple nonnative diseases and insects affecting hardwoods will continue to spread from the North. Expansion of urban areas is likely to increase the spread of nonnative plants and animals and to affect native plant and wildlife communities.

Physical Factors

Many southern forest types are fire adapted, and exclusion of fire has altered their species composition, flammability, and management. The reintroduction and continued use of fire will present challenges as concerns related to urbanization and air pollution become more important. The ambient environment influences forest growth and vigor. Ozone pollution is forecast to increase by 20 to 50 percent between 1990 and 2025, and growth reductions in southern pines are expected as a result. Future changes in temperatures could positively or negatively affect forest growth and species ranges depending on the extent of the change and the availability of moisture. Acid deposition is expected to significantly impact the region's forests only in the Southern Appalachians.

SOUTHERN FOREST CONDITIONS

We also examined the current status and potential future of various aspects of forest conditions and the services and direct benefits that forests provide. We examined southern forest conditions from four different perspectives: (1) social and economic systems; (2) forest area and condition; (3) terrestrial ecosystems; and (4) water quality, wetlands, and aquatic ecosystems.

Social and Economic Systems

Social context—The population of the South has grown faster than the national average (fig. 5.3). As a result, the share of the U.S. population residing in the South has increased to more than 32 percent. Although population growth occurred largely in urban areas through 1980, it has now spread across nearly all southern counties.

The South's population has also become more urban. These changes are reflected in values that have shifted away from a strong commodity orientation to a more biocentric view.

The South's population is forecast to continue growing, both absolutely and in relation to that of the United States as a whole, thus putting increasing pressure on forests, especially in urbanizing areas.

People and forests—Comparisons of the distribution of population and forests indicate areas in which access to forests and their benefits is especially limited. These areas are concentrated in Florida, in northern Virginia and northern Kentucky, and along interstate highway corridors I-85 from Raleigh, NC, to Atlanta, GA; I-65 from Birmingham, AL, to Nashville, TN; and I-81 from Chattanooga, TN, to Wytheville, VA.

Forecasts for the period 1992 to 2020 indicate that there will be outward growth and increased human impacts on forests surrounding urban centers such as Atlanta, Nashville, and Charlotte and along the Atlantic and gulf coasts. These wildland-urban interfaces have effects on many forest values.

Wood products—With expansion in forest production has come an expansion in jobs and income derived from the wood products industry. In 1997, timber harvests led to more than 700,000 jobs in the wood products sector and more than \$118 billion in total industry output. Total economic impacts of these activities were about 2.2 million jobs (5.5 percent of total jobs) and \$251 billion of total industry output (7.5 percent of industry output).

Timber harvesting and management of timber production are prevalent in all parts of the region but are especially concentrated on the Atlantic and Gulf Coastal Plains.

It is predicted that timber production will increase most in areas to the north and west of the traditional timber production core of the South—that is, into Tennessee, North Carolina, Arkansas, and western Virginia (fig. 5.4).

Increases in timber harvests are not expected to deplete inventories, but there is considerable variability among States and forest types. Softwood inventories are forecast to increase gradually between 1995 and 2040. Hardwood inventories are forecast to expand between 1995 and 2025, but to fall slightly between 2025 and

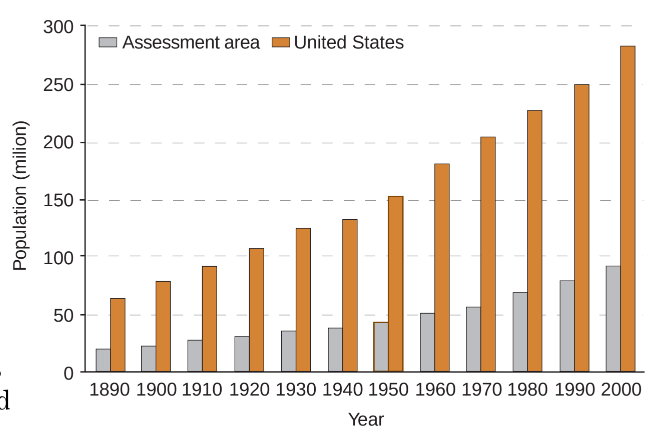

Figure 5.3—Population, in millions, for the United States and for the 13 States in the assessment area (Wear and Greis 2002a).

2040. This reflects forecasts that show hardwood removals exceeding growth regionally by about 2025, and sooner in some States.

Recreation—Southern forests provide opportunities for a broad array of recreational activities. Driven by a growing population and changes in income and other demographics, recreational uses of all types have increased. Recreation is an important source of employment and income in the South. In 1997, tourism based on outdoor recreation contributed between 0.64 and 2.88 percent of southern jobs. Recreation-based tourism on public lands represented 56 percent of this contribution. Much private land is unavailable for public recreation, and the trend is toward less access. Consequently, there is considerable pressure for increased recreational use of public lands.

Given current land ownership patterns, there appears to be limited capacity to expand forest-based recreational opportunities in the South. Recreational activities on public land are expected to be increasingly congested, and competition among various recreation groups will increase.

Quality of life—Forests contribute to quality of life in several ways. They provide for production of wealth by supplying wood products and recreational opportunities, they protect and enhance environmental quality, and they meet aesthetic needs.

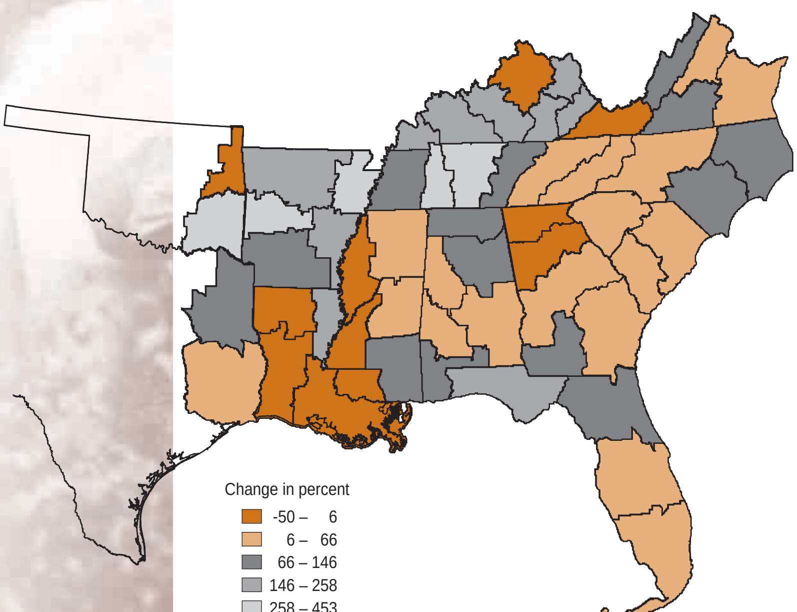

Figure 5.4—Forecast percent change in annual softwood harvest levels, 1995–2040, by survey unit of the Forest Inventory and Analysis Program of the U.S. Department of Agriculture Forest Service (Wear and Greis 2002a).

Changes in the use of forests will affect the quality of life for local residents. Predicted increases in harvesting in areas outside the production core of the South may generate increased wealth for some persons, but loss of aesthetic and environmental benefits for others. This will probably lead to debate about forest uses in local areas.

Forest Area and Conditions

Forest area and ownership—The South now has more than 214 million acres of forest land (fig. 5.5), 60 percent of the total in 1630 and 91 percent of the total in 1907 (fig. 5.6). Forest area has been relatively stable since the 1970s. Eleven percent of timberland (21.4 million acres) is managed by various Government agencies. The remaining 89 percent is privately owned. Twenty-two percent of private timberland is owned by forest industry, 21 percent by farmers, 12 percent by other corporations, and 45 percent by other individuals.

Ownership is changing with a decrease in forest industry ownership between the 1980s and 1990s and an increase in other corporate ownership, including ownership by timber investment management organizations.

Total area of forest land is forecast to decline by only 2 percent between 1995 and 2040. Preliminary results of the most recent forest inventories indicate that decreases in forest industry ownership are continuing.

Broad forest types—While total forest area has remained relatively constant, the distribution of forest types changed from the 1950s to the 1990s. The area of upland forest increased gradually. The area of lowland hardwood forest declined somewhat between the 1950s and 1970s but has leveled off. The area of naturally regenerated pine stands decreased by about half as the result of natural succession to upland hardwoods, harvesting of the pine component, or conversion to nonforest uses or planted stands following harvesting. The area in planted pine increased from about 2 million acres in 1953 to 32 million acres in 1999. In the 1980s and 1990s, pine plantations were established on land that previously supported hardwood or mixed pine-hardwood forests (47 percent), natural pine forests (28 percent), and agricultural fields (25 percent).

The area of pine plantations is forecast to increase by 67 percent to 54 million acres in 2040 (fig. 5.7). Areas of all other forest types are

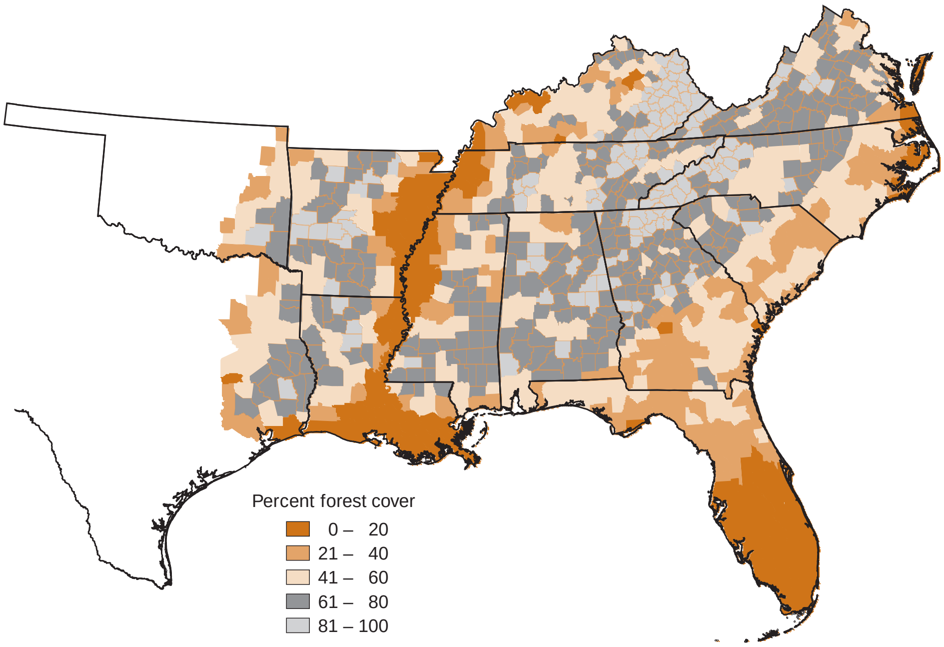

Figure 5.5—Percent of forest cover by county, 1992 (Wear and Greis 2002a).

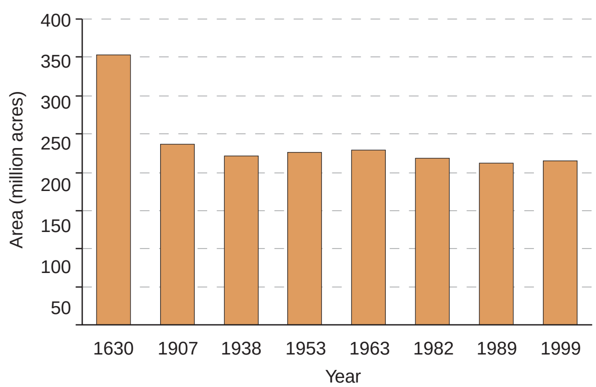

Figure 5.6—Forest area in the Southern United States, 1630 to 1999 (Wear and Greis 2002a).

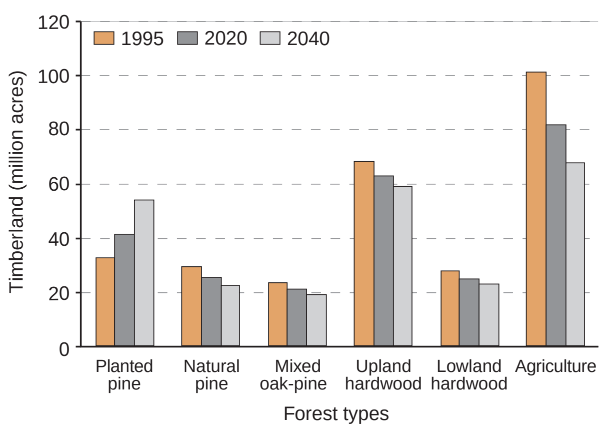

Figure 5.7—Forecast of the area timberland by forest types, 1995 to 2040 (Wear and Greis 2002a).

expected to decline gradually over this period. Forests of all types will be lost to urban uses and gains in acreage in planted pine will come mainly from planting of agricultural fields.

Landscape structure—Satellite images of forest cover in the early 1990s indicate areas where forest is highly contiguous. These areas include the Blue Ridge Mountains, the Cumberland Plateau, the Allegheny Mountains, the Ozark-Ouachita Highlands region, and some coastal areas. Areas where forest cover is highly fragmented include the Piedmont, central Tennessee, and the Ridge and Valley ecoregion.

Population growth and other factors are expected to make Piedmont forests especially susceptible to increased fragmentation through 2040.

Forest inventory—Southern forests accumulated considerable volumes of timber between the 1950s and 1990s. Inventory grew from 148 to 256 billion cubic feet, reflecting rapid growth of stands established since the 1930s. Recent inventories indicate a general slowing in the rate of accumulation for hardwoods and a leveling off of accumulation for softwoods.

Forecasts indicate that softwood growth will overtake and exceed removals by a slight margin in the next few years. As a result, softwood inventories are predicted to increase steadily between 1995 and 2040. Hardwood removals are expected to outstrip growth by about 2025. Hardwood inventories are forecast to peak in about 2025 and then decline to levels just exceeding current ones by 2040.

Timberland productivity—Intensive management has increased southern timber yields. Yields associated with high-intensity management can be 65 percent greater than those associated with standard site preparation and planting, and more than double the yields from naturally regenerated forests.

Future productivity is a key determinant of both future forest conditions and future of timber market conditions. For example, models suggest that if anticipated productivity gains were not realized, more pine plantations would be established to supply timber products. The effects of climate change, other environmental change, and pest-related mortality on productivity are less certain.

Terrestrial Ecosystems

Abundant forest communities—Upland hardwood and pine forest types remain plentiful in the South but are subject to several health problems. Southern pine beetle has had a greater economic impact than any forest pest over the past 30 years. The chain of forest changes begun by the chestnut blight continues; the latest of these changes may be a disease complex called oak decline, which is especially severe in the Southern Appalachians and the Ozarks.

Southern pine beetle will continue to be an economically important pest of pine forests. Epidemics are likely where pines have been planted outside of their natural range and in the absence of active management. Spillover epidemics from public land may continue to be a problem in the South. The complex of nonnative insects and diseases affecting hardwoods has the potential to restructure forests, especially in the northern part of the region.

Rare forest communities—Many concerns about southern wildlife and plant species focus on rare forest communities. Fourteen critically endangered communities have lost more than 98 percent of their habitat since European settlement. Most of these communities are in seven classes: (1) old growth; (2) spruce-fir (*Picea* spp.-*Abies* spp.); (3) wetlands, bog complexes, and pocosins; (4) bottomland and flood plain forests; (5) glades, barrens, and prairies; (6) longleaf pine (*Pinus palustris* Mill.) forests; and (7) Atlantic white-cedar [*Chamaecyparis thyoides* (L.) B.S.P.] swamps.

Two of the seven classes—old-growth and spruce-fir forests—are found largely on public land. The remainder are generally in private ownership, so their future depends on the decisions of numerous owners. Spruce-fir appears to be under the greatest stress—stress caused mainly by air pollution and a nonnative insect. Remnant longleaf pine forests are threatened by land development and fire exclusion.

Effects of land use changes—Urbanization affects bird populations by fragmenting or eliminating habitat and by increasing disturbances. Nonnative animals, for example, feral cats, dogs, and pigs, influence wildlife through predation, displacement of native species, and habitat modification.

Predicted changes in land use may affect bird species most adversely in the Piedmont, where population declines are anticipated for neotropical migrants and forest interior specialists.

Effects of forest management—Forest management can have important implications for wildlife. Impacts depend on specific site conditions and the management practices employed. Broader landscape patterns can influence mobile wildlife species. Fragmentation effects of certain practices are likely to be lower in heavily forested areas than in areas where urban and agricultural uses predominate such as the Piedmont, Interior Low Plateau, and Mississippi Alluvial Plain. Effects of landscape configuration and forest management may be especially important for some species, especially certain amphibians. Across the South, more species are threatened by increased isolation of shrub-scrub and grassland habitats than are affected by scarcity or fragmentation of mature forests.

The ultimate future challenge for forest management is to support the array of grassland, shrub-scrub, and mature forest species occurring within the same landscapes.

Wildlife species of concern—Of the 1,208 vertebrate species known to exist in the South, 132 are considered to be of conservation concern and 28 are classified as critically imperiled. The South is the center of amphibian biodiversity in the United States. Fifty-four amphibians are classified as species of concern, and 19 are critically imperiled. Areas where the concentration of endangered species is high include the Southern Appalachians, the Atlantic and Eastern gulf coast flatwoods, the gulf coast marsh and prairie, and peninsular Florida (fig. 5.8). Loss of habitat is the primary cause of species endangerment.

Habitat protection will be difficult in view of the rapid urbanization forecast for the South. Forestry operations can have impacts on certain amphibians, especially those that depend on both wet and upland habitats.

Conservation issues—Public land is relatively scarce in the South (11 percent of forest acreage) but plays an important role in conservation of specific forest types and wildlife species. More often, the management of private land determines the future of imperiled species and rare forest communities. Effective conservation often requires collaboration, giving rise to multiple-owner consortiums.

Although scarce, public land has unique ecological value because it can provide a dependable supply of interior forest habitat and older forests. In areas that are becoming urban, public tracts can serve as anchors for conservation strategies pursued by multiple owners. The effective reintroduction of fire to many forest ecosystems will remain a critical forest conservation challenge.

Water Quality, Wetlands, and Aquatic Ecosystems

Water quality—About 30 percent of the South has relatively good water quality, 36 percent has moderate water-quality problems, and 15 percent has serious water-quality problems. The leading causes of water-quality impairment have been siltation, pathogens, and nutrients. Of the 11 major sources of water-quality impairment, agriculture and urbanization have ranked highest, with silviculture ranking next to last. When properly implemented, best management practices (BMP) are effective in controlling pollution from silvicultural activities. Twelve of the thirteen Southern States have monitored BMP compliance and reported results. Because different States employ different survey methods, regional trends cannot be identified. However, consistency among States is improving; six States have adopted similar procedures since 1997.

As timber production increases in the South, effective BMP implementation will become even more crucial for protecting water quality.

Wetlands—Approximately 32.6 million acres of forested wetlands occur in 10 Southern States (those that constitute the assessment area minus Virginia, Texas, and Oklahoma). These wetlands account for 64 percent of the total forested wetland area in the conterminous United States. Losses of forested wetlands have been quite widespread, but have been noticeably concentrated in the Mississippi Alluvial Valley and the Coastal Plain of the Carolinas. Rates of loss have declined since the 1970s, but impacts and functional changes continue to occur.

Land management practices and urbanization are expected to continue to alter the function of wetlands. Wetland restoration efforts will continue, but their likelihood of success is not clear. Forest management practices will play an important role in the persistence of certain amphibian species.

Aquatic species of concern—The South supports a great diversity of aquatic species. Several hundred species of concern are found among the amphibians, mussels, crustaceans, fish, snails, and aquatic insects of the region. Especially high numbers of mussel, fish, and amphibian species are critically imperiled as a result of modification to aquatic and wetland habitats (fig. 5.9).

For many mussels and certain other species, declines will continue because of the effects of essentially irreversible actions such as dam construction, agricultural conversions, and the introduction of nonnative species. Many aquatic species of concern are narrow endemics. The effects of development and management activities may be disproportionately large for the small areas they occupy.

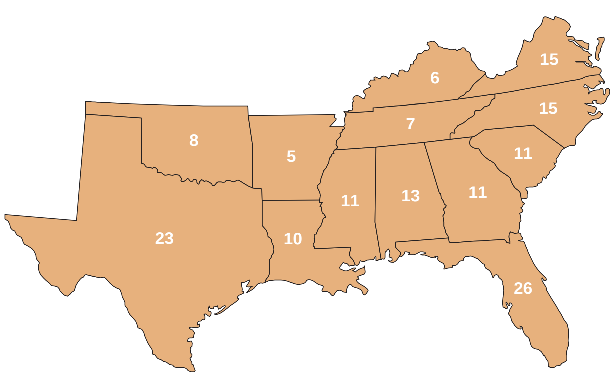

Figure 5.8—Number of terrestrial vertebrates in Southern States listed as endangered (Wear and Greis 2002a).

DISCUSSION

The findings of the assessment led us to some broad observations regarding the present and future status of southern forests.

1. The South is an economically, culturally, and ecologically complex region, and a number of forces of change are affecting its forests.

2. Urbanization presents a substantial threat to the extent, condition, and health of forests. Of the various forces of change, urbanization will have the most direct, immediate, and permanent effects on the extent, condition, and health of forests.

3. The population of the South is growing, and the social context of forest management is changing. These changes have implications for the nature of values and demands that people place on forests as well as on the uses of forests.

4. Total forest area will remain stable, but subregional and compositional changes will continue. We forecast little net change in the total area of forests between 1995 and 2040. Losses of forest area to urban uses are expected to be offset by shifts from agricultural to forest uses. Urban development is forecast to be concentrated in eastern areas, while afforestation of agricultural land is expected to take place largely in the western part of the South. Overall, the southern region will experience a westward shift in its forest area.

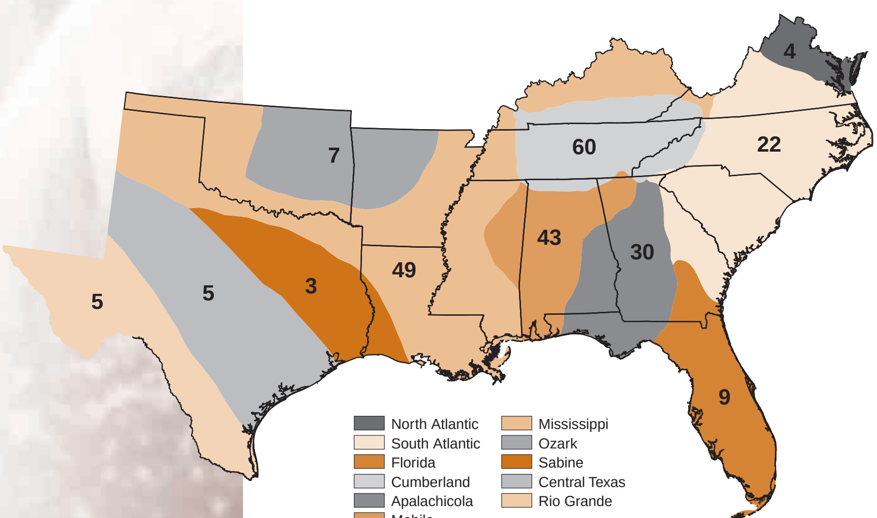

Figure 5.9—Distribution of mussel species by aquatic fauna provinces (Wear and Greis 2002a).

5. Timber production is forecast to expand, but it is not expected to deplete forest inventories below current levels. Between 1995 and 2040, softwood outputs will expand by 56 percent and hardwood outputs by 47 percent. Softwood inventories will continue to expand throughout that period. Hardwood inventories will expand until 2025 and then decline slightly between 2025 and 2040.

6. Investment in pine plantations is forecast to expand to meet increased softwood demand. This will have implications for the ecological characteristics of southern forests. Pine plantations enhance timber productivity. For example, planted forests accounted for only 15 percent of timberland, but they contributed 35 percent of annual softwood removals during the 1980s and 1990s. Increases in pine plantation acreage could also result in varying ecological changes, depending on stand origin and management. These effects are better documented at the forest stand level than at a broader landscape scale.

7. Changing patterns of land use and harvesting will have important effects on the lives of the people of the South. The wood products industry now accounts for about 6 percent of jobs and 8 percent of income in the region. In some rural parts of the South, these percentages are much higher and forest-related industry has represented more than half of the local base economy. Forests also contribute to the quality of life in the region by providing opportunities for recreation, visual backdrops, and environmental quality. Forecasts of increasing timber harvests imply more jobs in the wood products sector. However, abrupt changes in forest conditions could lead to increased costs for some people, increased benefits for others, and increased debate over forest uses in areas outside the traditional production core of the South.

8. Southern forests have proved to be resilient, but some components are scarce and are, therefore, at risk. Through the 20th century, the South has recovered from a largely cutover, exhausted, and eroded condition to become one of the most productive forest regions in the world. However, there are reasons for concern. Among these are the presence of numerous imperiled animal species (28 terrestrial vertebrates are critically imperiled) and increasingly rare

forest communities (14 communities have been reduced to < 2 percent of their area at the time of European settlement).

9. To borrow the adage from economics, scarcity defines value. The rare forest communities in the South have disproportionately high ecological value. Thus, much concern about biodiversity is focused on these relatively small shares of the forest landscape.

Subregions of Concern

The assessment also allowed us to define where change and the potential implications of change are focused within the South. In particular, we identified three areas in the region where concerns regarding forest sustainability may be especially high. These are (1) the Southern Appalachians, (2) the Piedmont, and (3) the Lower Atlantic and Gulf Coastal Plains. In the following discussion, these regions are considered individually.

Southern Appalachians—This region will be influenced by a combination of human, biological, and physical factors over the next two decades. Population growth and land use changes will increase the human presence in many forests. Demands for forest-based recreation are focused on the Southern Appalachians, and increased competition among recreation user groups is anticipated. A complex of forest health issues is affecting all forest types in this region and has the potential to restructure forest ecosystems there.

Piedmont—The Piedmont, from Virginia to Georgia, is expected to lose more forest area than any other part of the South. This heavily forested region already has a very low ratio of interior forest to total forest, indicating a high degree of forest fragmentation. Fragmentation is likely to continue with growth of populations in urban counties and interspersed rural counties. Consequently, wildlife habitats will be altered for certain neotropical migrant and other important bird species. Because populations will grow and forest area will decline, we also expect an increasing scarcity of forest-based recreational opportunities for city dwellers.

Lower Atlantic and Gulf Coastal Plains—Coastal flatwoods areas are forecast to lose much of their forest area to urban development. Forest loss combined with intensified forest management could have cumulative negative effects on coastal wetlands, both through direct wetland loss and through modification of hydrological regimes. The flatwoods, one of two areas in the South with the highest concentrations of endangered animal and plant species, contain many imperiled amphibians, crustaceans, and reptiles. These problems are of especially great concern in the Florida Panhandle.

Implications of the Assessment for Forest Research

At the conclusion of an effort such as the SFRA, it is important to consider what we were unable to do. In contrast to most bioregional assessments conducted in the United States to date, which have been motivated by a crisis of one sort or another (Gordon 1999), the SFRA can be viewed as an “anticipatory assessment” (Johnson and others 1999). It was intended to provide a complement of information to illuminate a dynamic resource situation and illustrate critical areas before an actual crisis erupted.

The assessment was successful in describing several emerging issues that could affect the sustainability of the South’s forests, but more information is needed to better identify problems and potential solutions. Each technical chapter of the assessment identifies research needs, and eight broad areas of investigation were highlighted. The following are some key areas of uncertainty:

- The effects of population growth on forest ecosystems
- The influence of changing market and other values on land use and management choices
- The determinants of overall forest productivity for all benefits
- Forecasts of changes in ecological structure and functions
- Broadening the scale of forest research to better address questions at regional levels
- The role of fire in forests and the effective use of fire
- The influence of changing forest structure, and especially the influence of pine plantations, on ecosystem function and wildlife
- Developing new forest management strategies for a variety of settings

A finding from the assessment as a whole is the inability to fully link findings into an integrated multidisciplinary analysis of forest ecosystems. The assessment highlights the fact

that fundamental knowledge in various disciplines cannot yet be readily integrated to address the full complexity of a dynamic and highly diverse region.

Such an analysis would, for example, allow us to directly evaluate the impacts of expanded demand for wood products on the distribution and condition of wetlands and subsequently on the distribution and persistence of related species. Our inability to make these causal links reflects a shortcoming of ecosystem and resource science in general that is at its root the result of the form of scientific investigation. This defines an important challenge for the South's forest research community.

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Productivity

Chapter 6.

Productivity

***Thomas R. Fox and Ray R. Hicks, Jr.*[1]**

The South is blessed with abundant and diverse forest resources. Today, forests cover approximately 215 million acres in the South, which represents 29 percent of the forest land in the United States (Conner and Hartsell 2002). Maintaining the productivity of these forests is essential to the economic, environmental, and social well being of the South and the Nation. The forest products industry ranks among the top industries in most Southern States and is the largest industry in several. The wood products sector contributed 770,000 direct jobs and over $120 billion in total industry output in 1997 (Abt and others 2002).

The diversity of forest ecosystems in the South is also large, ranging from mixed, mesophytic hardwood forests of the Southern Appalachians, to the planted pine forests of the Coastal Plain and Piedmont, to the bottomland hardwood forests along major rivers throughout the region. In 1999 there were 65 million acres of upland hardwood forests, 30 million acres of lowland hardwoods, 29 million acres of mixed pine-hardwood forests, 33 million acres of natural pine, and 30 million acres of pine plantations in the South excluding Kentucky (Conner and Hartsell 2002). These forests provide a wide variety of goods and services other than timber, including a diverse range of habitat for wildlife, recreational opportunities, and clean air and water. These goods and services contribute to an improved quality of life for an increasing population that has become more urbanized. Modern forest management regimes must provide these noncommodity benefits.

Management practices have been developed and refined for each of the major forest types in the South since the advent of scientific forestry at the Biltmore Estate led by the work of Olmstead, Pinchot, and Schenck in the 1890s. Although tremendous strides have been made in the management of most forest types, progress has been uneven. Economic factors associated with the development of southern pine-based pulp and paper industry, which started in the 1920s and 1930s, fostered the development of pine plantation management using an agronomic approach. The work of research scientists and practicing foresters in the U.S. Department of Agriculture Forest Service (Forest Service), southern forestry schools and universities, State forestry agencies, and private industry in pine tree improvement and intensive silvicultural practices has greatly improved the productivity of southern pine plantations. Similar but less sustained efforts were periodically directed toward intensive management of plantation hardwoods, generally with mixed results. The research efforts directed toward the management of natural hardwood, pine, and mixed hardwood-pine stands have been less concerted than that associated with intensive pine plantation silviculture. However, individual research programs within the Forest Service and at several southern forestry schools have maintained a strong and consistent focus on these forest types. Most notable are the Forest Service research units at Bent Creek and Coweeta focused on upland hardwoods, the program at Mississippi State University on silviculture of bottomland hardwoods, the industry-sponsored Hardwood Research Cooperative at North Carolina State University, which has strong programs in both upland and bottomland hardwoods, and the Forest Service Research Work Unit at Crossett, AR, that has developed uneven-aged silvicultural systems for southern pines.

Six chapters are included in this section on productivity. Three of these chapters review and highlight the progress made on silviculture of the major forest types in the South. This is followed by a chapter on the history and accomplishments of tree improvement programs in both southern pine and hardwoods. The final chapter discusses the links that exist between silviculture and remote sensing, specifically focusing on the use of remote sensing as a mensurational technique.

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The second chapter of this section "Silviculture and Management Strategies Applicable to Southern Hardwoods" by Ray R. Hicks, Jr., William H. Conner, Robert C. Kellison, and David Van Lear addresses the management of upland and bottomland hardwood forests in the South. Hardwoods comprise a significant component of the southern landscape. Some southern forests are dominated by hardwoods, such as the mesophytic forests of the Southern Appalachians and the bottomland stands that border all the major river systems of the South. In addition, hardwoods form a significant component of many southern pine stands. Hardwoods play an important ecological and economic role in southern forests. They provide ecological and habitat diversity, valuable lumber and veneer, and fiber for pulp and paper.

The authors first summarize the physiographic, edaphic, and climatic factors that characterize the various types of hardwood forests in the South. They then address the land use history and ownership patterns and the role these forces play in determining the type of hardwood stands that exist and their influence on objectives of ownership. Emphasis is placed on our improved understanding of the role of fire in hardwood forests and how the extent and frequency of fires, both historical and current, influence the composition and structure of hardwood forests. A detailed description of the silvicultural techniques for regenerating and culturing the commercially valuable species of hardwoods is then presented. The authors also discuss how silvicultural practices in hardwood stands are complicated because many hardwood stands occur on sites that are difficult to operate equipment and contain a diversity of species that vary greatly in stumpage value. These factors, along with the fact that most hardwood stands occur on small, privately owned tracts, contribute to the fact that most hardwood stands are not actively managed and have historically been exploited and high-graded.

The third chapter in this section "The Evolution of Pine Plantation Silviculture in the Southern United States" by Thomas R. Fox, Eric J. Jokela, and H. Lee Allen reviews the historical development of intensive southern pine silviculture. The acreage in pine plantations has increased significantly over the last 50 years from < 2 million acres in 1952 to 32 million acres in 1999 (Wear and Greis 2002). More remarkable is the significant increase in per-acre productivity that has accompanied the rapid expansion of pine plantations. Mean annual increment of pine plantations has more than doubled, and rotation lengths have been cut by more than 50 percent. Although planted pine accounts for only 15 percent of the total forest land base in the South, it accounts for 35 percent of the annual harvest volume (Wear and Greis 2002).

The authors of this chapter highlight the changes in pine plantation silviculture that have occurred since 1950. The contributions to improved plantation yields of tree improvement, improved nursery practices, site preparation, competition control, fertilization, growth-and-yield modeling, and land classification are presented on a decade-by-decade basis. Current state-of-the-art silvicultural practices involving integrated, site-specific, rotation-long silvicultural manipulations are discussed. A vision of the future presented by the authors includes clonal deployment of elite genotypes produced through somatic embryogenesis and managed on a site-specific basis to optimize growth rates and financial returns in an environmentally sustainable manner. Precision silviculture of pine plantations in the 21st century in the South will embrace the advances coming out of precision agriculture. The role that cooperative research and technology transfer had in the successful development of intensive pine plantation silviculture is emphasized throughout the chapter. The take-home message from the authors is that no one single organization had the financial or intellectual resources required to develop the needed silvicultural technology in the past. As the level of complexity of pine plantation silviculture increases in the future, concerted, cooperative research efforts will continue to be needed.

The fourth chapter in this section "Reproduction Cutting Methods for Naturally Regenerated Pine Stands in the South" by James M. Guldin, discusses management practices in natural pine and mixed pine-hardwood stands. Although the acreage in pine plantations has increased significantly over the last 50 years, the author correctly points out that a large percentage of forest land in the South will remain in natural stands. There are currently 62 million acres of natural pine or mixed pine-hardwood forests in the South (Wear and Greis 2002). These stands must be managed using classical silvicultural practices that establish and maintain productive, healthy forests that provide a variety of goods and services required by society. Natural regeneration is frequently the only option financially available to nonindustrial landowners. Longer rotations required to produce large-diameter pine trees and other multiple-use benefits associated with them, such as aesthetics and wildlife habitat, may not be feasible in plantation systems. Certain landowners and segments of the general public may reject the clearcut and plant approach required in plantation silviculture. Regulatory requirements, including best management practices in all Southern States, prohibit clearcutting in streamside management zones. Management prescriptions involving natural regeneration that avoids high-grading and protects water quality must be developed for these sensitive, high-quality sites.

The author reviews silvicultural practices that establish and maintain naturally regenerated pine and pine-hardwood mixtures. He discusses both even-aged and uneven-aged reproduction cutting methods, including seed tree and shelterwood systems and group and single-tree selection. He illustrates how both even-aged and uneven-aged systems can be effective in southern pine stands depending upon which species are present, the site preparation practices, and the manner that required intermediate treatments, such as release, are employed to assure adequate seedling establishment and rapid stand development. The importance of residual overstory basal area, timing of harvests to take advantage of cone crops and seed production, appropriate site preparation to create suitable seed beds, control of competing vegetation, and control of stand density are emphasized as key components of a successful natural regeneration system in southern pine.

The fifth chapter in this section "The Role of Genetics and Tree Improvement in Southern Forest Productivity" by R.C. Schmidtling, T.L. Robison, S.E. McKeand, R.J. Rousseau, H.L. Allen, and B. Goldfarb documents the impacts that tree improvement activities have had in the South over the last 50 years. The contributions of applied tree improvement to the increased productivity of southern pine stands are recognized throughout the world as one of the major success stories of modern forestry. Beginning with the pioneering work of Wakeley on seed source variation in southern pine in the 1920s, research on tree improvement in southern pines has progressed to the point where loblolly pine (*Pinus taeda* L.) is today probably the most domesticated and best understood conifer in the world. Again, hardwood species have received less attention in the South than have pines. However, interest in hardwoods has recently increased because of work in the developing field of forest biotechnology. Hardwood species, most notably those in the genera *Populus* and *Eucalyptus*, are proving to be much easier to study and manipulate through tissue culture, genetic mapping, and genetic engineering techniques than conifers. Hardwoods will probably serve as model systems where the gains in biotechnology are first realized in forestry.

The authors of this chapter provide a thorough review of the history of forest tree improvement in the South from its infancy in the 1920s. They include a discussion of both southern pine and hardwood tree improvement programs. They illustrate how the observations and efforts of practicing foresters played an important role during the early phases of tree improvement. These initial efforts were superseded by well-coordinated, sophisticated, cooperative research programs involving Federal and State Governments, universities, and private industry. Today approximately 1 billion southern pine seedlings are planted annually, nearly all of them the product of tree improvement programs. The authors discuss the productivity gains made using first-generation slash (*Pinus elliottii* Engelm.) and loblolly pine. Gains are estimated to be 15 to 20 percent over unimproved, natural populations. Additional gains will be made from the deployment of advanced generation material from elite populations through techniques such as open-pollinated single-family block plantings, and full-sib deployment using control mass pollination. Clonal forestry looms on the horizon as an opportunity to exploit the full genetic potential of various commercial species through the development of tissue culture techniques, such as rooted cuttings and somatic embryogenesis. The science of genomics will provide improved tools such as marker-aided selection that will increase the efficiency of tree improvement programs. The authors conclude with a cautionary note on the need to conserve long-term genetic diversity while managing for short-term productivity gains.

The final chapter in this section, "Forest Mensuration with Remote Sensing: A Retrospective with a Vision for the Future," by Randolph H. Wynne, discusses the role of remote sensing as a tool that practicing foresters can use to improve forest productivity. As management practices intensify, foresters require more detailed information upon which to base their decisions. Forestry is moving toward the agricultural model of intensive, site-specific management that can be broadly characterized as precision forestry. Information from digital remote sensing can be quickly integrated into a forester's decision process to develop sophisticated, fully integrated rotation-long management regimes that best meet landowner objectives. Although forest management at this level of intensity is often associated with the desire to optimize financial returns, sophisticated management scenarios are needed by any forester attempting to meet the competing demands placed on forest resources today. For example, meeting the needs for aesthetics, recreation, wildlife habitat, water quality, endangered species, wilderness, and timber production is a much more complicated task than simply optimizing growth and associated financial returns from timber management.

The chapter begins with a retrospective discussion of remote sensing, which reviews the long use of aerial photos to improve forest management. A section on timber volume estimation using aerial photos is then presented. This section explains how tree and stand properties such as stand density, tree height, crown dimensions, and crown cover can be obtained from conventional aerial photos and used to create photo volume tables. Historically, the variation in stand-volume estimates based on aerial photos was too high (often exceeding 25 percent) to be of great value for many uses. The most widespread use of remotely sensed data in forestry has been, and continues to be, to stratify and map stands, calculate land area, and simplify navigation. The value of aerial photos as a navigation tool used by foresters to increase the efficiency of their day-to-day activities in the woods should not be overlooked. The author then discusses new developments in remote sensing and computer technologies, and explains how they are being used to improve volume estimates of stands. The developing tool of lidar (light detecting and ranging), which uses an airborne laser to accurately estimate canopy height, crown density, and stand density is discussed. Lidar-based measurements are proving to be more accurate and less biased than conventional photo-based estimates of tree and stand parameters. The author is optimistic that the high cost of cost data acquired with these new techniques will decrease and that the combination of decreasing cost and increasing efficiency will improve the cost/benefit ratio of this technology. The chapter concludes with a discussion of how remote sensing utilizing these new techniques and tools will be an integral component of the new precision forestry paradigm.

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Chapter 7.

Silviculture and Management Strategies Applicable to Southern Hardwoods

Ray R. Hicks, Jr., William H. Conner, Robert C. Kellison, and David Van Lear[1]

Abstract—*Southern hardwood forests stretch from the Virginias to Florida and from the mid-Atlantic to Missouri. They can generally be grouped into upland forests and bottomland forests. The upland hardwood forests of the southern region are usually associated with the mountainous topography of the Appalachians and Ozarks. Bottomland hardwoods are found along the floodplains of larger rivers in the Atlantic and Gulf Coastal Plains, including the Mississippi River floodplain. Southern hardwood forests are owned by a variety of governmental and private owners, but the vast majority of owners are nonindustrial private individuals. These owners seldom engage in intensive forest management, often exploiting the resource. The silvicultural systems applicable to the management of hardwoods are the same as those recommended for pines, but in hardwood management, reliance on natural regeneration is more common than use of plantation silviculture. Oak species are very important in the southern hardwood forests, and lack of oak regeneration in present-day forests is a major concern. Lack of fire and the resurgence of white-tailed deer throughout the southern region are proposed as reasons for poor oak regeneration. Many stands, either due to their stage of development or neglect, are in need of intermediate management operations such as thinning and improvement cutting. Crop-tree management is a method that is particularly useful in southern hardwoods. It was concluded that although hardwoods make up a significant part of the southern forest resource, they are generally managed with less intensity than pines, and hardwood management is an opportunity area for the South in the future.*

INTRODUCTION

In this chapter, we discuss the silviculture and management of upland and bottomland hardwoods in the Southeastern United States. We begin by briefly describing the physiographic, edaphic, and climatic conditions for each forest type. Land use history and ownership patterns are then discussed because these factors are important in determining what types of stands occur and the objectives of landowners. Finally we describe the appropriate silvicultural techniques for regenerating and culturing the commercially valuable species in each management type.

Upland Hardwoods

The southern upland hardwoods occur extensively in the Southern Appalachians, on the Cumberland Plateau, and in the Ozark region. A diverse array of hardwood species is represented by genera such as *Acer, Carya, Fraxinus, Liquidambar, Liriodendron, Prunus,* and *Quercus*. The southern upland hardwoods include pine-hardwood mixtures in the Piedmont and southern Coastal Plains, but by far the most commercially significant upland hardwoods in the South occur in the Southern Appalachian region. For purposes of this discussion, the Southern Appalachian region includes the hilly or mountainous area west and north of the Piedmont and south of the glaciated portion of Pennsylvania. Using Fenneman's (1938) classification, this region is termed the "Appalachian Highlands," and contains parts of the Blue Ridge, Ridge and Valley, and Appalachian Plateau physiographic provinces. The Appalachian Highlands are classified as being in the Eastern Broadleaf Forest Province (Bailey 1996). The climate is continental and part of the Humid Temperate Domain (Bailey 1996). Rainfall is favorable for plant growth and is well distributed throughout the year. Highest precipitation rates occur in the southern Blue

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Ridge of the Carolinas and north Georgia, where annual precipitation averages 60 to 80 inches per year (Hicks 1998). Across most of the region, annual precipitation averages 40 to 50 inches. The geology of the Appalachian Highlands region is predominantly sedimentary. Sandstones of the Pennsylvanian period cap the highest mountains throughout the Appalachian Plateau Province, and limestones and shales predominate in the sharply folded Ridge and Valley Province. The Blue Ridge is composed primarily of metamorphic rock substrates with some igneous intrusions and small areas with sedimentary rock. At higher elevations of the southern Blue Ridge, Precambrian rock outcrops can be found. Faulting, folding, and geologic weathering have interacted with the geologic materials to produce the complex, steep, and rocky terrain found in the Appalachian Highlands.

Deciduous hardwood species predominate in the Appalachian Highlands. These include several oaks (*Quercus* spp.), hickories (*Carya* spp.), maples (*Acer* spp.), yellow-poplar (*Liriodendron tulipifera* L.), black cherry (*Prunus serotina* Ehrh.), and American beech (*Fagus grandifolia* Ehrh.). The area was also a prime range for American chestnut [*Castanea dentata* (Marsh.) Borkh.], a species that was all but eliminated by the chestnut blight {*Cryphonectria parasitica* (Murrill) Barr [formerly *Endothia parasitica* (Murrill) Anderson & Anderson]} during the early part of the 20th century. Braun (1950) classified a substantial portion of the Appalachian Highlands as being in the oak-chestnut forest region. Most of the forests of the Appalachian Highlands are second growth, resulting from previous logging and fires or from revegetation of abandoned fields.

Bottomland Hardwoods

Southern bottomland hardwoods occur mainly in the broad, Lowland Coastal Plain Province of the Atlantic Plain physiographic division and the gulf lowlands (Fenneman 1938) extending from the eastern tip of Pennsylvania south along the Atlantic coast and west along the gulf coast to the Rio Grande River. They also occur north along the Mississippi River floodplain to southern Illinois and to some extent along all the major and minor rivers east of the Great Plains (Hodges 1995). Despite the dense tree cover and the difficulty of clearing land, this ecosystem was the first in the Southern United States to be converted to agricultural crops. It was taken for agricultural use because it occupied level terrain with inherently fertile soils. The Coastal Plain is underlain by alluvial and marine sediments of mostly Cretaceous, Tertiary, and Quaternary age. Sediments were laid down in various onshore, nearshore, and offshore environments (Stanturf and Schoenholtz 1998). Annual precipitation in the major alluvial floodplains ranges from 48 to 64 inches and is generally greater during the warm season (Kellison and others 1998, Muller and Grymes 1998). The amount of rainfall received, however, is not a reliable indicator of the magnitude and duration of the flooding that can occur. Upstream precipitation in large watersheds (some cover hundreds of thousands of acres) has a larger impact on downstream flooding than local precipitation does (Kellison and others 1998).

Bottomland forests are extremely diverse, including more than 70 tree species (Putnam and others 1960) of which 40 are of commercial value (Hosner 1962). Angiosperms predominate, but a few gymnosperms occur. A number of tree species are common throughout southern bottomlands; these include red maple (*A. rubrum* L.), water hickory [*C. aquatica* (Michx. f.) Nutt.], sugarberry (*Celtis laevigata* Willd.), persimmon (*Diospyros virginiana* L.), green ash (*Fraxinus pennsylvanica* Marsh.), sweetgum (*Liquidambar styraciflua* L.), swamp chestnut oak (*Q. michauxii* Nutt.), water oak (*Q. nigra* L.), American elm (*Ulmus americana* L.), and baldcypress [*Taxodium distichum* (L.) Rich.] (Kellison and others 1998). Bottomland hardwood forests occur in the portions of the floodplain that are free from flooding for most of the year. These areas support the most diverse forests and sustain excellent growth (Smith 1995). Areas that are flooded for extended periods every year have fewer species, which have evolved special adaptations to these conditions (McKevlin and others 1998). Growth rates in the more flooded areas can be high, but they are highly variable (Conner 1994, Conner and Buford 1998, Megonigal and others 1997).

The quality and composition of bottomland forests have been influenced dramatically by past timber harvesting, agricultural use, grazing, and uncontrolled fires. The overall result of these influences has been a general degradation of composition and quality, even though volumes are increasing (Hodges 1995).

Pre-European Forests

Both upland and bottomland hardwood forests of the Southeastern United States were manipulated by Native Americans for thousands of years prior to the advent of Europeans (Carroll and others 2002). Native Americans used fire for many purposes. They controlled the composition and pattern of vegetation by frequently burning the southern landscape. They burned to manage wildlife habitat, ease travel, expose acorns and chestnuts, improve visibility, encourage fruiting, prepare their fields for planting, and to facilitate hunting and defense (Bonnicksen 2000, Pyne and others 1996, Williams 1989). Frequent low-intensity burning by Native Americans created a southern landscape of prairies, fields, savannas, woodlands, and dense forests. The southern hardwood forest was hardly a dense, old-growth landscape at the time of European discovery. The myth of low-impact management by Native Americans may have been reinforced by the fact that the major European occupation of interior America came after native populations had been devastated by diseases introduced by earlier European immigrants.

Some areas were burned on an annual basis and, if burning continued over long periods, became prairies or balds. Other areas, such as north-facing coves in the Southern Appalachians and frequently flooded bottomland forests, burned infrequently. Between these two extremes were forest communities that burned at varying intervals, thus creating a mosaic of forest conditions throughout the South. In the hardwood forests of the South, anthropogenic fires were complemented by occasional lightning-ignited fires (Carroll and others 2002).

Post-European Effects

The European settlers who displaced the Native Americans from the upland forests continued to burn the forest frequently to encourage forage production for their livestock (Pyne and others 1996). However with the advent of steam power for harvesting and processing of timber, wide-scale logging and the slash it produced created a different type of fire regime. High-intensity, stand-replacement fires ignited by sparks from locomotives followed logging and burned vast acreages of upland forests from the late 1880s though the early 1930s (Brose and others 2001).

Fire protection efforts begun early in the 20th century gradually became more effective and allowed the forests to develop—for the first time in millennia—in the absence of fire. However decades of fire exclusion had unintended consequences. The development of dense understories and midstories of shade-tolerant shrubs and trees is now a major contributor to the oak regeneration problem. In other areas, rhododendron (*Rhododendron maximum* L.) and mountain laurel (*Kalmia latifolia* L.) thickets have become so dense and expansive that the species diversity of cove forests is threatened. Because of these problems, there is renewed interest in using prescribed fire as a management tool in upland hardwood forests (Yaussy 2000).

Villages of early European colonists were almost always located along major streams. A rice culture developed, first in the vicinity of Charleston, SC, and then elsewhere along the Southeastern U.S. coast. On the fringes of the rice paddies and beyond, corn, wheat, and cotton supplanted hardwood forests.

Following attempts to control water flow in the major alluvial floodplains, first by private enterprise and then by public agencies, especially the U.S. Army Corps of Engineers, the forests were increasingly cleared for agricultural crops. Only about half of the original bottomland forests remained by the 1930s. From the 1930s to the 1980s, the bottomland forest area was further reduced from 11.8 to 4.3 million acres as a result of drainage and clearing for agriculture.[2] Conversion was especially rapid during the 1960s and 1970s when the price for farm crops, especially soybeans, reached unprecedented levels.

Land Ownership Characteristics

The majority of hardwood forest land (upland and bottomland) is in the hands of nonindustrial private forest (NIPF) ownership (MacCleery 1990), although a substantial portion of the Blue Ridge and Allegheny Highlands is in national forests and parks. The motivation for forest activity for most nonindustrial forest landowners appears to be income, although most of these owners do not rank commercial forest production as the number one reason for holding land (Egan and Jones 1993).

It is possible to combine commercial timber operations with forest stand improvement through application of appropriate silviculture in southern hardwoods. The development of new markets for smaller diameter and lower grade materials has enhanced the opportunity for producing revenue from heretofore noncommercial stands. Unfortunately, however, the type of timber harvesting often being practiced on NIPF lands amounts to high-grading of one type or another.

[2] Allen, J.A.; Kennedy, H.E., Jr. 1989. Bottomland hardwood reforestation in the Lower Mississippi Valley. [Not paged]. On file with: Southern Research Station, Southern Hardwoods Laboratory, P.O. Box 227, Stoneville, MS 38776.

Forest landowners share certain attributes that help to explain their behavior. Many are older and have lived during times when much of today's forest land was in fields, a condition that they worked hard to preserve. In addition, many people, accustomed to the practices of the past, believe that "timbering" is a once-in-a-lifetime affair. Thus many owners fail to see the value of managing their forest land.

It is incumbent on foresters who interact with landowners to begin their association by explaining what planned forest management means and what is and is not possible. Owners need to understand that even with relatively small tracts, it is possible to spread the income out over time while enhancing the future health, productivity, and value of the forest. It may be difficult to convince owners of such facts, since foresters are going against beliefs that have been years in the making. Owners may find it difficult to accept the fact that many second-growth forests are even-aged, and the larger trees are not older, but simply faster growing.

SILVICULTURE OF UPLAND HARDWOODS

Oaks, as a group, constitute the most significant hardwood forest resource in the southern uplands. Oaks, however, are losing their position in many upland forests, being replaced by aggressive species such as red maple and yellow-poplar (Abrams 1998, Brose and others 2001).

Exclusion of periodic, low-intensity surface fires from the hardwood forests of the Appalachian Highlands in the early decades of the 20th century has changed the character of these forests. Oaks thrive under a regime of periodic disturbance by surface fires (Brose and others 1999, Van Lear and Brose 2001). Because young oaks invest heavily in root development at the expense of height, they are at a competitive disadvantage with aggressive species like yellow-poplar and red maple, especially on above-average sites. However, when surface fires kill the aboveground portion of trees, the resulting seedling sprouts of oaks have a distinct advantage over their competitors. In the absence of periodic surface fires, oaks do not maintain a position of dominance in the advance regeneration pool. Thus as wind, ice, or partial harvesting disturbs the upper canopy, other species in the advance regeneration pool are poised to dominate.

This chapter uses concepts from Hicks' (1998) book "Ecology and Management of Central Hardwood Forests" to describe the silvicultural methods that are appropriate to most upland hardwood stands. It is our goal to demonstrate that properly designed commercial harvests can utilize silviculturally sound concepts, and to provide descriptions of relevant silvicultural methods and their application to NIPF stands. We also hope to discourage the use of loose terms such as "selective cutting," and to encourage foresters to develop a vocabulary that is appropriate and descriptive of the practices being recommended. Finally we want to stress that in hardwood stands, it is often necessary to apply several silvicultural methods simultaneously, and that management of hardwood stands must remain adaptable to changing market conditions, natural occurrences such as insect and disease outbreaks, and changing social pressures.

Most silviculture and forest management texts emphasize "traditional" approaches based on German methods that were developed for use in relatively simple coniferous ecosystems. Although a great deal of research on hardwood management has been conducted in North America, the information that has been produced must be presented in a form that is useful to managers.

Silvicultural methods can generally be grouped into treatments that are used to tend existing stands (intermediate operations) and those that are aimed at regenerating new stands. Hardwood silviculture differs markedly from pine silviculture in both areas. Topographic considerations, economic factors, and the abundance of natural regeneration usually prevent the application of plantation silviculture for upland hardwood management. Also, hardwoods almost always occur in mixed species stands in which commercially valuable trees are intermingled with trees of lower value. The objective of management is to work in concert with the natural ecosystem processes to favor the regeneration, growth, and quality of desirable trees. Intermediate cuttings that are most appropriate to hardwoods are crown thinning, improvement cutting, and crop-tree management. Among regeneration systems, those that are most appropriate to hardwoods are clearcutting, the shelterwood method, and related two-age systems. All of the foregoing create even-aged or two-age stands. The single-tree selection system and variations such as group selection will work well if the objective is to grow shade-tolerant species in multiage stands. However, none of the shade-tolerant commercial species in the southern forest region provide viable management opportunities.

Intermediate Operations

Crown thinning—The crown-thinning method is defined by Smith (1986) as thinning that involves the removal of trees in the upper strata of the canopy to favor desirable trees in the same canopy range. In crown thinning, the focus is on the better trees (crop trees) that are to be provided with additional growing space and resources. As with all thinning methods, crown thinning is applied at the stand level where residual stocking targets are an important consideration. Crown thinning seems particularly applicable to fully stocked or overstocked mixed oak or mixed mesophytic hardwood stands on above-average sites. Although species such as northern red oak (*Q. rubra* L.) are capable of responding to release at age 50 and older, appropriate candidate stands of shade-intolerant species such as yellow-poplar and black cherry should be treated earlier than oaks. Care should be given to residual stand density, understory composition, and stem wounding of residual trees. Excessive thinning can induce epicormic branching of residuals or release undesirable midstory or understory species, or both. Sonderman and Rast (1988) recommend thinnings of moderate-to-light intensity in mixed oak stands in order to minimize branch-related defects that typically result from heavier thinnings in such stands. Residual stand density should be maintained at a level above the "B" line and below the "A" line defined by Gingrich (1967).

Improvement cutting—Smith (1986) defines improvement cutting as cuttings done in stands past the sapling stage for the purpose of improving composition and quality by removing trees of undesirable species, form, or condition from the main canopy. Unlike crown thinning and crop-tree management, the focus of improvement cutting is on the "undesirable trees." Improvement cutting is widely applicable to southern upland hardwood stands. It is appropriate for use in mixed oak, oak-hickory, and mixed mesophytic hardwood stands. The silvical characteristics of the species present should be a prime consideration, but improvement cutting can generally be applied to stands well beyond age 50. Depending on the owner's objectives, species typically targeted for removal can include red maple, American beech, hickories, blackgum (*Nyssa sylvatica* Marsh.), scarlet oak (*Q. coccinea* Muenchh.), and black locust (*Robinia pseudoacacia* L.) in addition to poor-quality individuals of more favored species. Improvement cutting is widely applicable to current upland hardwood stands because of the age and current composition of many such stands, although marketing of trees removed may be difficult. Many upland hardwood stands have a past history of high-grading (Nyland 1992) which may limit the number of desirable trees available to leave in the residual stand. At some point, it becomes advisable to regenerate severely impoverished stands rather than apply intermediate management to them.

Crop-tree management—Crop-tree management is a technique that focuses on "individual" trees that have the potential to develop into high-value crop trees. Perkey and others (1993) emphasize that crop-tree value should be defined by the landowner's objectives. The two phases in crop-tree management are assessment and enhancement. Generally the assessment phase involves the selection of trees that have the potential for meeting the objectives defined by the landowner. Enhancement consists of activities that foster the attainment of those objectives. For example, if timber management was the objective, trees of desirable species with good stem quality and capable of responding to release would be selected as crop trees. The enhancement operation would release crop trees by removing some of the trees that compete with them for sunlight, water, and nutrients. The recommended method for releasing crop trees is the "crown-touching" method described by Lamson and others (1988). To apply this method, the crop-tree crown is divided into four quadrants (sides) and one determines whether the tree is free-to-grow on each of these sides. A three-sided release has been recommended by Lamson and others (1990) for use in younger stands. For older stands or for species with a tendency toward epicormic branching, a two-sided release is more appropriate. Cutting, girdling, or the use of herbicides (Miller 1984) can accomplish release of the crop tree. The advantages of crop-tree management are:

1. It permits crop-tree designation to fit landowner objectives
2. It is simple to apply and fits well with NIPF needs
3. It provides for an even flow of forest products over time
4. It allows for continuous forest cover until crop trees are harvested
5. Management efforts are concentrated on trees with the highest potential for future gain

Crop-tree management has disadvantages:

1. It does not provide for regeneration after removal of crop trees

2. Sometimes removal of low-grade interfering trees may not be a commercial operation and thus may constitute a cost to the landowner

However generally speaking, crop-tree management like improvement cutting is a widely applicable method that is appropriate to many mixed hardwood stands. The earlier the crop-tree enhancement can be applied to a stand, the longer the effect can benefit the crop trees. However, there are risks in attempting to assess crop trees and potential competitors at early ages.

Silvicultural Systems and Regeneration Methods

When a harvest is planned, an assessment should be made to determine how the stand would be regenerated. The information needed includes: (1) condition and size-class distribution of overstory trees by species; (2) quantity and condition of understory trees (desired initial and advanced reproduction); (3) kind and amount of competing vegetation; and (4) regeneration method, e.g., seeds, seedlings, or stump and root sprouts (Nyland 1996).

Clearcutting—In the clearcutting method, the overstory is completely removed in a single operation. The method is designed to regenerate even-aged, single-cohort stands, and generally favors relatively shade-intolerant species. Clearcutting mimics large-scale disturbances such as the fires and windstorms that have had a historic role in the creation of southern hardwood stands. In order to provide conditions that qualify as a clearcut, openings must be at least 1 to 2 acres in size (Sander 1992). In the southern uplands, clearcutting promotes regeneration of fast-growing, exploitive species such as yellow-poplar, sweetgum, and pines. On poorer sites (south- and west-facing slopes and ridges), clearcutting is effective in regenerating oaks. On the best sites in the Southern Appalachians (oak site index greater than 70), clearcutting favors yellow-poplar, often resulting in pure stands of that species. Successful regeneration can be delayed after clearcutting by the rapid development of competing vegetation such as ferns, brambles, and herbaceous species, as well as woody perennials such as sassafras [*Sassafras albidum* (Nutt.) Nees], dogwood (*Cornus florida* L.), rhododendron, and grapevine (*Vitis* spp.). In most cases, commercial woody species ultimately prevail, but other factors such as heavy browsing by white-tailed deer (*Odocoileus virginianus*) can delay the regeneration process even further. The early successional communities produced by clearcutting provide exceptionally good habitat for wildlife in the Southern Appalachians where maturing second-growth forests dominate the landscape (Harlow and others 1997).

Although clearcutting is a reliable way to regenerate a variety of hardwoods, many landowners regard it with disfavor. For a short time (1 to 10 years, depending on site quality), it produces a bare landscape that is not aesthetically acceptable to most owners. In addition, in the case of NIPF ownership, the property is often relatively small. A small owner who wants to attract a buyer for his or her timber may find it necessary to cut most or all of the timber at one time. This creates an undesirable situation in which income is produced only at very long intervals and the aesthetic value of the property is compromised for a long period. Conversely for larger ownership, clearcuts up to 20 to 30 acres might represent a relatively small percentage of their land base.

Shelterwood method—The shelterwood method is an even-aged management system that involves development of a standing crop of regeneration through a series of partial removals of the overstory (Smith 1986). In a three-cut shelterwood, the cuts are: (1) a preparatory cutting, designed to improve the quality and vigor of the residuals; (2) a seed cutting, designed to encourage regeneration; and (3) a removal cutting, designed to remove the overstory. The two-cut variation of the method eliminates the preparatory cutting and is appropriate where most of the trees in the current stand are of the desired species. The shelterwood method is often recommended for regenerating species that are intermediate in shade tolerance, such as oaks (Loftis 1990, 1993).

A shelterwood-burn technique developed by Brose and others (1999) takes advantage of basic differences between germination and root development strategies of oaks and many of their competitors to enhance the competitive position of oak regeneration on good sites. A few years after the initial shelterwood cut, a moderately hot growing-season burn is run through the developing advance regeneration to favor the oak reproduction. The reduction in competing vegetation by burning and the vigorous resprouting by oak reproduction shortens the time the shelterwood method requires. In the absence of fire, it may take 10 to 20 years to complete the shelterwood regeneration process, and this represents a longer commitment on the part of landowners and managers than they may be willing to make. Deer browsing can become a significant problem when applying the

shelterwood method, since deer often selectively browse species that are desired as regeneration.

Two-aged system—Leave-tree (deferment) cutting is receiving increasing attention for regeneration of southern upland and bottomland hardwoods. Implementation of the practice includes leaving 20 to 30 square feet per acre of basal area until the end of the following rotation in combination with the regeneration that develops in the openings created by partial harvesting of the parent stand. As opposed to the shelterwood system, where the residual overstory trees are removed to allow the regeneration to develop, leave-tree cutting maintains the overstory trees until the end of the rotation. At that time, the residual trees are removed together with about 75 percent of the basal area of the regenerated stand. The cycle is repeated in the next rotation and, thus, an overstory is present during all stages of stand development.

An additional benefit of this system is that a mixture of crop trees can be retained for the next rotation. Some of the trees might be selected for their timber value, and some for wildlife and other values. This system is equivalent to the "high forests with reserves" of European forestry (Matthews 1989). A major disadvantage of two-age systems is the vulnerability of leave trees to damage by windthrow, lightning strikes, and epicormic shoot development.

Selection system—The single-tree selection system is designed to develop a multicohort (all-age) stand of shade-tolerant species. In practice, however, it may be impractical to achieve this goal because it requires frequent stand entry and because the smallest diameter classes may not develop in the shade of trees of the larger diameter classes. Proper application of the selection system involves establishing several criteria, which include a residual basal area target, largest-tree-to-grow, a "q" factor, and a cutting cycle length (Smith and Lamson 1982). Single-tree selection is complex to apply, requires long-term commitment, and requires the presence of commercial species that are shade tolerant. In the Southern Appalachians, it may be applicable only in high-elevation stands that contain sugar maple (*A. saccharum* Marsh.). Because it has these limitations, professional foresters rarely apply the system.

Modifications of this method involve cutting trees in small groups or patches. These "group selection" systems may be more appropriate in the southern upland hardwoods than single-tree selection, although group selection, like single-tree selection, requires repeated entry into the stand. One of the common mistakes made by both foresters and landowners is to refer to "selective cutting" (cutting some trees and leaving others) as a legitimate silvicultural activity. The similarity between the terms "selective cutting" and "selection system" is unfortunate and leads to confusion.

SILVICULTURE OF BOTTOMLAND HARDWOODS

Bottomland hardwood forests are made up of an extremely heterogeneous mixture of species except in permanently flooded swamps and newly formed lands and old fields. Thirteen bottomland forest types are recognized by the Society of American Foresters (Eyre 1980). The U.S. Department of Agriculture Forest Service recognizes only two bottomland hardwood types for inventory purposes: oak-gum-cypress and elm-ash-cottonwood. The following discussion of silvicultural information draws heavily on Hodges (1995) and the chapter by Kellison and others (1998) in the book "Southern Forest Wetlands: Ecology and Management" (Messina and Conner 1998). Other primary sources include McKelvin (1992) and Kellison and Young (1997) who have compiled the findings of scientists regarding regeneration of bottomland hardwood forests.

Mixed hardwoods in the major alluvial floodplains generally have been logged one to several times since Dutch settlers (Heavrin 1981) built the first sawmill in the United States in 1633. Loggers have usually removed only the best and largest trees while leaving the smallest and least valuable trees to form the new stand. This form of timber harvesting, commonly known as selective harvesting, is in reality high-grading, a practice that should be condemned by foresters. This degenerative practice is not to be confused with the silviculturally sound selection system, in which the desired tree species mix of all size classes is maintained.

Diameter-limit cutting, improperly applied, is another form of high-grading. The principle is to harvest only those trees above a certain size, such as those 14 inches in diameter at breast height, and leave the remainder to develop into the succeeding stand. The assumption is that the small trees will grow into large trees of good quality in perpetuity. The problem is that natural stands of timber do not perpetuate themselves by like-producing-like. The openings created by removal of the larger trees will be occupied by the expanding crowns of the edge trees or by shade-tolerant understory trees that are already in place. The succeeding trees decrease the value of the stand for timber production and wildlife habitat with each partial harvest. In alluvial floodplains, cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.) would likely be succeeded by green ash; green ash would be replaced by sugarberry; and boxelder (*A. negundo* L.) and American hornbeam (*Carpinus caroliniana* Walt.) would finally supplant sugarberry. Generations of selective, incomplete harvests have reduced many bottomland hardwood stands to a poorly stocked, low-value condition.

The proper management procedure for major alluvial floodplain forests is to control the undesirable trees at the same time desired ones are harvested, and to maintain natural patterns and cycles of water flow (Kellison and others 1988). Fortunately, the practices best suited for accomplishing these goals are also those best suited for timber production, wildlife management, and maintenance of the flora and fauna associated with the alluvial forest.

Stands that have been harvested repeatedly often contain two, but rarely more than three age groups, with each age group dating to a previous harvest. Even though the species composition of the older age classes is usually desirable, a high component of the trees is culls with no timber value. Conversely, a high component of the youngest age class of timber is usually of poor species composition, resulting from the development of shade-tolerant trees in the understory of the residual crown classes. However, many of these stands, especially those occupying sites of high soil quality, are worthy of timber stand improvement, in which the undesirable trees are controlled to release the desirable trees in the intermediate crown class.

Even-Aged Systems

Experience has shown that stands occupying major alluvial floodplains will regenerate following complete harvesting of the timber in a single entry (clearcutting) or in two entries (shelterwood cutting). The regeneration from such harvested stands of trees less than about 100 years old will be largely from stump and root sprouts (Mader 1990). Stands of an older age class and those with altered hydrology will largely regenerate from seed in place at the time of harvest or transported to the site by wind, water, and fauna. The types of even-aged regeneration systems having application to major alluvial floodplains are clearcutting, patch clearcutting, shelterwood cutting, and seed-tree cutting.

Clearcutting—Clearcutting of hardwood forests that have the propensity to regenerate themselves from stump and root sprouts reduces species succession almost to the pioneering sere. It is only one stage short of a catastrophic event such as a hurricane in which stump and root sprouting of merchantable timber is severely limited because of windthrow and perhaps two stages short of a cleared bottomland field where all initial regeneration must be from seeds or planting.

In spite of its lack of aesthetic appeal, clearcutting is often the best way to regenerate hardwoods, especially degraded or impoverished stands. The regeneration will largely be from advanced reproduction and sprouts, but seedling reproduction will form a part of the succeeding stand in patches where sprout or advanced reproduction is absent. Seedling reproduction has little chance of developing into the succeeding stand if it occurs 3 or more years after sprout development. Species succession of advanced reproduction and sprouts proceeds much as it does with seedling reproduction, with shade-intolerant species showing fastest initial growth.

Opposition to clearcutting often results from the visual impact of the treatment and from wildlife considerations. We recommend that the size of clearcuts not exceed 20 acres. This maintains the silvicultural benefits of clearcutting while minimizing the adverse aesthetic effects. Additionally, it is desirable that (1) the harvested area should be configured to the landscape with scalloped edges; (2) declining, overmature, or hollow trees should be left standing for wildlife purposes (approximately 2 per acre); and (3) dead and downed trees should be left on site for associated flora and fauna.

Patch clearcutting—This system is a variation of clearcutting, with the size of the treated area being the major difference. The configuration implied is noncontiguous patches or strips. Areas of about 5 acres are usually considered optimum. Smaller areas are adversely affected by edge trees, the influence of which extends into the opening about the distance of the height of the dominant trees. The edge trees limit the growth of shade-intolerant species at the expense of shade-tolerant ones.

A significant limitation of patch clearcutting is that it requires frequent stand entry, which eventually results in many small patches. The small patches create innumerable problems in stand management and inventory, and they are poorly suited for forest interior-dwelling birds and certain other fauna (Sietz and Segers 1993).

Shelterwood cutting—When the shelterwood system is applied to bottomland hardwoods, best results are obtained when the overstory canopy is reduced to about 50 percent of its original cover. This level of reduction allows sufficient sunlight to reach the ground to promote seedling and sprout reproduction.

Experience has shown that clearcutting and shelterwood cutting initially give rise to similar types of reproduction, but that the intolerant species under a shelterwood will start to decline if the overstory trees are not removed within 5 to 10 years. Shelterwood cuts can help buffer against rising water tables in areas where the soil water table has risen as a result of altered hydrology. In some situations, the shelterwood system is advocated for the regeneration of oaks, especially cherrybark oak. Shelterwood cutting is not always essential for oak regeneration in alluvial floodplains because species such as water oak and willow oak (*Q. phellos* L.) can regenerate equally well with or without a partial overstory stand (Leach and Ryan 1987). In deeper water systems, such as muck swamps, shelterwood systems appear to be no more effective in developing the desired reproduction than clearcut systems (McKevlin and others 1998).

Seed-tree cutting—The prescription for seed-tree cutting is to leave four to eight seed trees per acre while removing all other overstory and understory trees. The theory is that seeds from the leave trees will be disseminated over the area, helping to ensure success in regeneration. However seed trees are usually a wasted effort in alluvial floodplains because most heavily harvested hardwood stands regenerate successfully from sprouts, from seeds buried in the duff, and from seeds disseminated by water, wind, and fauna. The primary reason for leaving such trees is for wildlife, ecological, and aesthetic values.

Uneven-Aged Systems

Stands of trees of widely different ages can be maintained by the selection system in which harvesting, regeneration, and intermediate stand treatments are applied at the same time. Stands are entered at intervals of from 1 year to perhaps every 10 years. Each cutting removes financially mature and high-risk trees, adjusts stand density to create room for the best trees to grow, and makes space for new reproduction. A specific stand structure is achieved by leaving the desired basal area levels in several diameter classes.

Single-tree selection—This is the system often advocated by the opponents of clearcutting or shelterwood cutting. The ecological basis of the system is sound, but the application is so difficult that, in practice, the exercise often approximates a selective or diameter-limit cut.

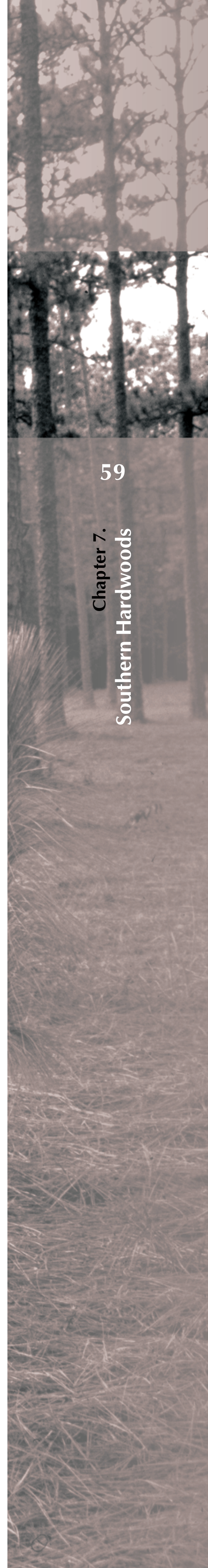
Group selection—This variant of single-tree selection involves removal of groups of trees of similar age, size, or species on an area usually not exceeding 0.25 acres. Care must be taken to remove undesirable as well as desirable trees. Group selection differs from patch clearcutting in that it employs small openings and frequent entries to promote a multiaged stand of shade-tolerant species. The necessity to enter the stand repeatedly at short intervals may make it impractical to implement the practice.

Two-aged system—We have discussed this method previously in connection with upland hardwoods. The method is similarly applicable to bottomland hardwoods and has the advantage on wet sites of requiring relatively few entries.

Plantation Management and Restoration

Procedures have been developed for establishing hardwood plantations on alluvial floodplains (Malac and Herren 1979). Industrial foresters have focused on developing eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) and sycamore (*Platanus occidentalis* L.) plantations. Eastern cottonwood has shown more promise than other species in the Mississippi River Delta, but sycamore—and to some extent sweetgum, green ash, water oak, and willow oak—have proven more adaptable than cottonwood to some of the other alluvial floodplains of the South. About 125,000 acres of commercial hardwood plantations currently exist in southern bottomlands. Despite successes on the floodplains, with growth rates of 3 to 4 cords per acre per year at rotations of 15 to 18 years, the trend is to establish hardwood plantations outside of the alluvial floodplains. The causes for this shift in site location include environmental concerns and the difficulty of managing and harvesting the resource in areas with episodic flooding. Few industrial forestry organizations are willing to invest in plantation forestry in alluvial floodplains when there is significant uncertainty about the implications of the Clean Water Act for such operations.

Floodplain forest restoration efforts have been limited, and most have focused on reestablishment of forest cover for timber, stream protection, or



wildlife habitat values (King and Keeland 1999, Stanturf and others 1998b). Typically forest managers have tended to increase the numbers of certain preferred tree species in the stands (Chambers and others 1987). In the past 10 to 15 years there has been a preference for planting oaks (Haynes and others 1995, King and Keeland 1999), and this practice could result in a greater occurrence of oak regionally than was typical of presettlement forests (The Nature Conservancy 1992). More recently, greater emphasis has been given to planting a wider variety of bottomland species (Allen and others 2001, King and Keeland 1999).

Several of the largest reforestation efforts today are in areas of the Lower Mississippi River Valley, including parts of the Yazoo National Wildlife Refuge, the Tensas National Wildlife Refuge, and the Ouachita Wildlife Management Area, and on privately owned land enrolled in the Wetland Reserve Program. About 193,000 acres have been seeded or planted, with the potential of 494,000 acres being returned to forest by the year 2005 (King and Keeland 1999). Many of the areas being reforested are on poorly drained lands cleared for agricultural crops in the 1960s and 1970s and abandoned later because of substandard crop yields and limited accessibility. Reforestation and restoration efforts are proving successful in reestablishing bottomland hardwood species that may provide commercial timber and wildlife habitat (Allen and Kennedy 1989, Clewell and Lea 1990, Haynes and Moore 1988).

Various forest establishment techniques have been used, including direct seeding of oaks and planting of seedlings or cuttings of several bottomland species (Stanturf and others 1998a). Although direct seeding is about half the cost of planting seedlings (Bullard and others 1992), the technique is reliable only for oaks and, to a lesser degree, other large-seeded species such as pecan [*Carya illinoensis* (Wangenh,) K. Koch]. Smaller seeds are more susceptible to damage by heat and dry soil. Allen (1990), who compared 4- to 8-year-old stands in the Yazoo National Wildlife Refuge, concluded that planting of tree seedlings was more effective than direct seeding in establishing wildlife habitat quickly. He reported extensive drought-caused mortality of newly germinated seeds, even though there was effective invasion of light-seeded species, especially sweetgum, green ash, and American elm.

CONCLUSIONS

Because of the ownership characteristics, age and composition of stands, and the silvical characteristics of the species present, many hardwood stands in the South are appropriately managed by means of intermediate cuttings (notably improvement cutting and crop-tree management). The method of harvest regulation that seems most appropriate to hardwood stands is volume regulation, since it is more compatible with partial cutting methods.

Selecting the method of regeneration is more troublesome. Shelterwood methods, or some modification of them, are often recommended for regenerating oaks. If prescribed fire is an option, it is possible to favor oak regeneration on better upland sites by employing a shelterwood-burn method.

Clearcutting is an effective way to regenerate a variety of hardwood species (generally shade-intolerant ones) in both upland and bottomland forests, while group selection can be used to regenerate and maintain multiaged hardwood stands. Plantation silviculture of bottomland species like cottonwood, sweetgum, and American sycamore has been successful, but plantations of upland hardwoods have had limited success. Maintaining an adaptive strategy to take advantage of bumper crops of advance regeneration and to capture value from market changes is important in hardwood management. As long as certain rules are followed, such as matching harvesting with periodic growth, avoiding high-grading, and providing for regeneration, southern hardwoods can be managed sustainably.

The array of premium-grade hardwoods in the eastern deciduous forest is second to none in the world (Hicks 1998). The timber from genera such as *Acer*, *Juglans*, *Prunus*, and *Quercus* is in demand for furniture in every developed country. Therefore the future will be to manage for premium-grade timber while using the residual for fiber products. The challenge will be for professional foresters to convince landowners, public officials, and environmental advocates to embrace the practice of proper timber harvesting on a region-wide scale. Failure to implement proper silviculture will result in continuation of the high-grading that has been normal practice since the inception of timber harvesting in the eastern deciduous forest. High-quality saw logs and veneer logs are among the most profitable markets for hardwoods, but a limitation to the strategy of managing hardwoods exclusively for premium-grade logs is that it could reduce the emphasis on hardwood fiber production. This will force many North American pulp and paper companies to rely on offshore suppliers for their wood, and eventually for their pulp. As North American pulp and paper manufacturing plants become obsolete from lack of capital investment, they may relocate closer to the source of the raw material.

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Chapter 8.

The Evolution of Pine Plantation Silviculture in the Southern United States

Thomas R. Fox, Eric J. Jokela, and H. Lee Allen[1]

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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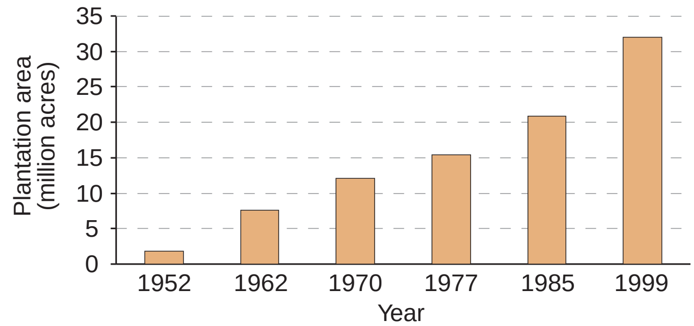

Figure 8.1—Number of acres of pine plantations in the Southern United States from 1952 to 1999 (data from U.S. Department of Agriculture 1988, Wear and Greis 2002).

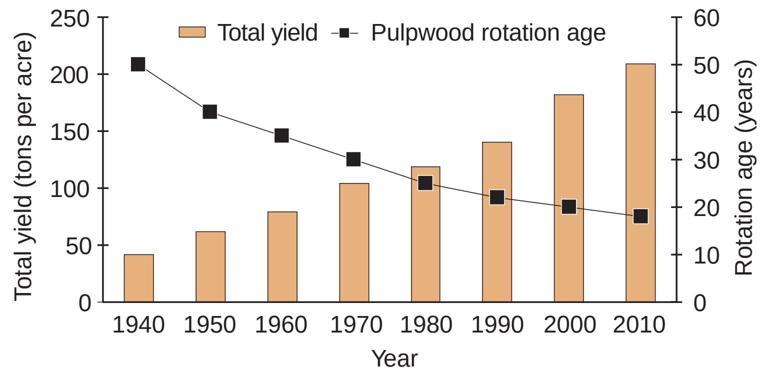

Figure 8.2—Estimated total yield and pulpwood rotation age in pine plantations in the Southern United States from 1940 through 2010.

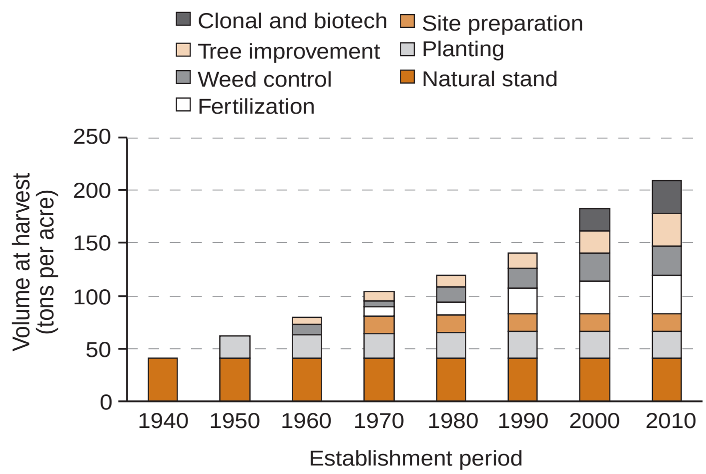

Figure 8.3—Estimated contributions of intensive management practices to productivity in pine plantations in the Southern United States from 1940 through 2010.

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

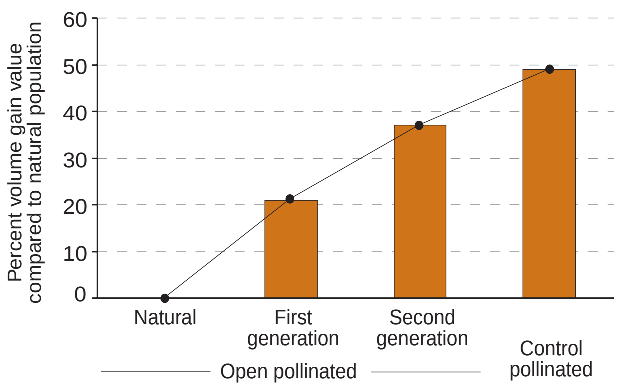

Figure 8.4—Growth increases in southern pine plantations due to tree improvement practices in the Southern United States (adapted from Li and others 1997, Todd and others 1995).

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.

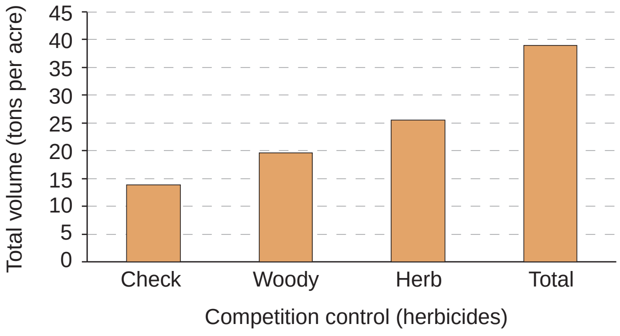

Figure 8.5—Effect of competition control on growth of loblolly pine at age 8 (adapted from Miller and others 1995).

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.

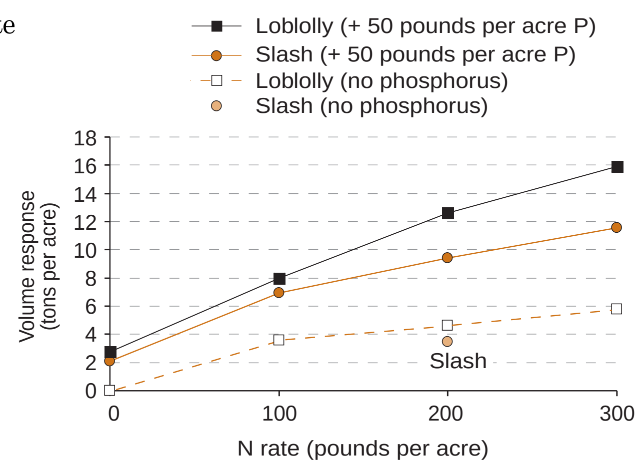

Figure 8.6—Growth response of loblolly and slash pine on a variety of soil types following midrotation application of nitrogen (N) and phosphorus (P) fertilizer (adapted from North Carolina State Forest Nutrition Cooperative 1997).

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.

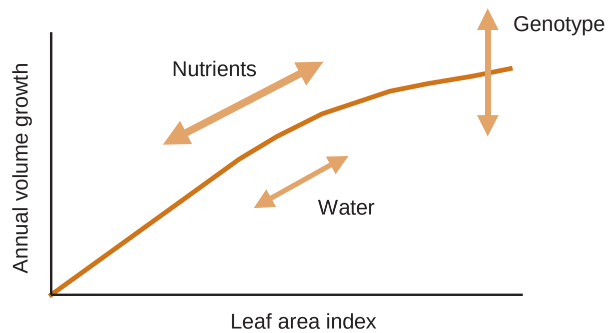

Figure 8.7—Relationship between leaf area index and growth rate in southern pine plantations.

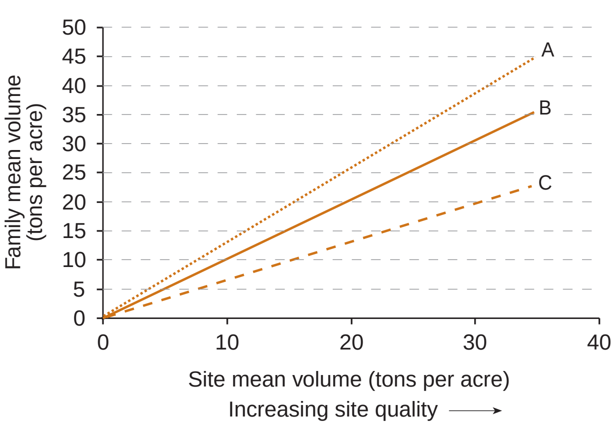

Figure 8.8—Performance of loblolly pine families [identifications are (A) 07–56, (B) 08–59, and (C) 01–64] as site quality increases (adapted from McKeand and others 1997).

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

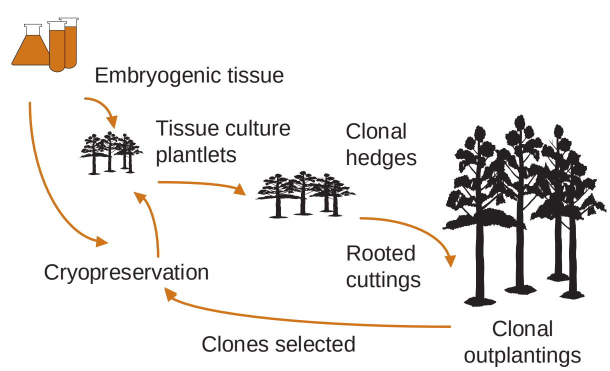

Figure 8.9—Integration of rooted cuttings and somatic embryogenesis into a clonal forestry program for southern pines in the United States.

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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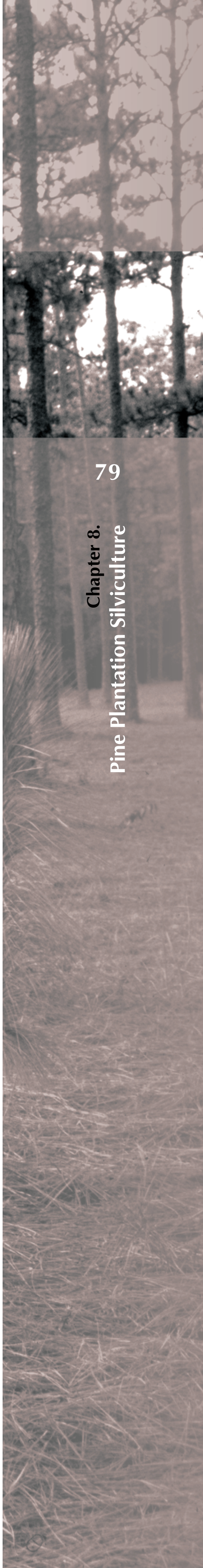

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Chapter 9.

Reproduction Cutting Methods
for Naturally Regenerated Pine Stands in the South

James M. Guldin[1]

Abstract—*It is projected that plantations will make up 25 percent of the South's forest land area by the year 2040. Thus the remaining 75 percent of that area will consist of naturally regenerated pine, pine-hardwood, and hardwood stands. Naturally regenerated pines can be managed successfully by even-aged and uneven-aged silvicultural systems when the reproduction cutting method is properly planned and executed, and when there is timely application of site preparation, release, and intermediate treatments to ensure seedling establishment and development. Attention to residual basal area, seed production, preparation of suitable seedbeds, control of competing vegetation, and timely density control are important to the successful management of naturally regenerated stands.*

INTRODUCTION

In the last half of the 20th century, the practice of silviculture in southern pine (*Pinus* spp.) stands has focused on one silvicultural system—clearcutting and planting. This focus has been made possible by two great advances during that time: (1) the development of genetically improved planting stock and (2) the advent of herbicide technology for control of unwanted vegetation in planted stands. The silvicultural system of clearcutting, planting, and associated herbicide treatments has come to define intensive forest management. Forest industry, nonindustrial private forest (NIPF) landowners, and Government agencies have all employed variations of this prescription, and as a result the area in plantations in the South has gone from virtually none to roughly 12.5 million ha (31 million acres) in the last 50 years (fig. 9.1).

This silvicultural system has become popular because of the large total merchantable volume of wood and wood fiber that can be obtained. In 1995, plantations occupied 15 percent of the forest land in the South but provided 35 percent of the harvested volume (Wear and Greis 2002). By 2040, pine plantations will occupy approximately 20 million ha (50 million acres), or 25 percent of the southern forest area. This will represent roughly half of the projected pine-dominated forest area at that time (Wear and Greis 2002).

On the other hand, these data also imply that by 2040, 75 percent of the South's forest land will not be plantations, but rather in stands of naturally regenerated origin. Currently more than half of the area in the South's pine-dominated forest types is managed by methods other than intensive plantation culture. Some of this area will not be managed at all in a professional sense; it will simply be allowed to grow as it will and will be high-graded when an operable commercial harvest becomes feasible. But other areas are, and will continue to be, managed using classical silvicultural practices that establish and maintain

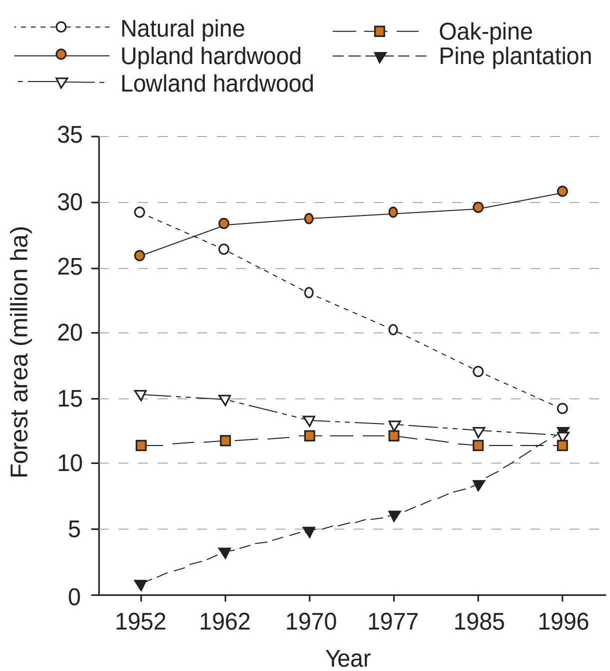

Figure 9.1—Trends in forest area occupied by forest type and year, 1952–96 (Sheffield and Dickson 1998).

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naturally regenerated pine stands. Specifically, these include even-aged reproduction cutting methods, such as the seed tree and shelterwood methods, and uneven-aged reproduction cutting methods, such as the group selection and single tree selection methods.

Management of naturally regenerated stands will have four prominent areas of application in the decades to come. The first of these is in management of the forest land owned by NIPF landowners. Many NIPF landowners choose not to employ clearcutting on their land, because clearcutting requires a large capital investment in stand establishment. Plantation establishment costs can quickly exceed $500/ha ($200 per acre), especially if intensive site preparation includes applications of chemicals and fertilizer (Dubois and others 2001). While such costs are easily borne by large companies, they are often difficult for NIPF owners of small properties to justify. Management prescriptions that rely on natural regeneration can be adapted to make stand establishment costs very low, although the tradeoff is that it takes longer to develop trees of merchantable size. However, many NIPF landowners find this acceptable, especially in light of the multiple management objectives they often seek, within which the aesthetic disadvantages associated with clearcutting do not fit.

The second prominent area of application is in management of large-diameter pine trees and the higher unit value that sawtimber brings relative to pulpwood when trees are harvested. For example, during the past 10 years in Louisiana, prices of softwood sawtimber averaged from 3.2 to 5.4 times those of pine pulpwood on an equivalent weight basis (Louisiana Department of Agriculture and Forestry 2002a, 2002b). In multiple-use settings, management of stands to large tree size can produce aesthetic, wildlife, and other benefits sought by a landowner. Finally, a part of the South's forest industry will continue to concentrate on the manufacture of high-quality dimension lumber, the best source of which is high-quality trees of sawtimber size.

The third area of application is within streamside management zones (SMZs), often among the most productive sites in a forested ownership. Clearcutting is generally avoided in SMZs, because it has adverse effects on water quality and aquatic systems. High-grading or selective cutting is often used to capture standing volume of desired species found in SMZs, but experience shows that such practices are neither sustainable nor grounded in sound silvicultural practice. One sensible approach to the management of SMZs is to employ management prescriptions that naturally regenerate desired species while maintaining forest cover within the SMZs.

Finally managers of public forest land in the South, especially those who manage national forest lands, are increasingly seeking alternatives to clearcutting (Guldin and Loewenstein 1999). This trend has its origins in the fact that the public does not like the appearance of clearcutting on public lands. But it also is seen in modern approaches to management of Government lands by means of silvicultural prescriptions designed to retain or restore forest stand conditions that benefit underrepresented plant and animal communities, such as the pine-bluestem habitat restoration in the western Ouachita Mountains (Stanturf and others 2004).

Research and practical experience suggest that both even-aged and uneven-aged reproduction cutting methods can be used in southern forest stands, depending on forest type, prevailing economic and ecological conditions, and ownership (Burns 1983). It is likely that the range of potential applications will grow wider rather than narrower as a wider variety of practitioners employ a wider variety of these methods on a wider variety of ownerships.

THE ECOLOGICAL BASIS OF NATURALLY REGENERATED PINE STANDS

Reproduction cutting methods that rely on natural regeneration emulate a continuum of intensity of natural disturbance. Clearcutting, with its total removal of all overstory vegetation, approximates the most severe stand-replacement disturbances, such as the main path of a tornado or the flare-up of a canopy-destroying wildfire. But few ecological conditions in nature are so severe that all living trees are removed. More commonly, some trees remain following disturbance, and they provide seed to reforest the disturbed area. Reproduction cutting methods that rely on natural regeneration imitate this dynamic directly.

The even-aged seed tree and shelterwood methods approximate disturbance events sufficiently severe that a new regeneration cohort is established across the entire stand. They differ in the number of residual trees remaining on the site and in the provision of shelter by residual trees. In the seed tree method, few overstory trees remain, and microecological conditions for seedlings are essentially the same as if the area were clearcut. In the shelterwood method, more overstory trees remain, and their presence slightly ameliorates the microecological condition for developing seedlings.

The uneven-aged methods approximate disturbance events that open up only part of a stand. Thus the new regeneration cohort will be found only in those portions of the stand within which the openings are found, rather than across the entire stand. The group selection method emulates disturbance events such as beetle spots or locally heavy windstorms that remove small groups of overstory trees within a stand; regeneration then occurs in that group opening. The single tree selection method imitates the smallest scale of disturbance, that of the mortality of one or two mature trees. This creates a small opening marginally sufficient for development of a very small cohort of regeneration, provided that the species being managed is sufficiently tolerant of shade to develop. Thus the entire gradient of natural disturbance events, from severe events that give rise to continuous regeneration cohorts across the stand to localized events that give rise to discontinuous regeneration cohorts within the stand, are reflected in the reproduction cutting methods used to naturally regenerate managed stands.

EVEN-AGED REPRODUCTION CUTTING METHODS

Clearcutting Method

The clearcutting method can be applied in a manner that relies on natural regeneration rather than on planted seedlings to reforest the clearcut site (Langdon 1981, Smith 1986a). However the circumstances under which the practice will succeed are highly specialized. One common approach is to configure the clearcut opening so that trees from adjacent stands can naturally seed all parts of the harvested site (fig. 9.2). The more risky practice in southern pines, clearcutting using seed-in-place (Smith 1986a), relies on the harvest of trees at the point in the growing season when cones are mature but not yet opened. Harvest will disperse those cones across the site, and the warm temperature regimes that result from clearcutting promote cone scale reflexion and seed dispersal (Shelton and Cain 2001). This method can succeed only if many conditions are concurrently met. Cones must be present and contain viable seed, harvest must occur within a 1-month window prior to the autumnal seed fall, seedbed conditions must be adequate within the slash resulting from the harvest, seed must remain present and viable

Figure 9.2—The strip clearcutting method demonstrated in a loblolly-shortleaf pine stand, Crossett Experimental Forest, near Crossett, AR. Photo courtesy of James M. Guldin 2003.

until germination occurs, and seedlings must become established and must develop properly. The major difficulty is that there is no room for accident or error, since there is no residual seed source in the event that the initial cohort does not become established.

Seed Tree Method

In the seed tree method, a small number of trees are retained on the site after harvest as a source of seed for the harvested area. Seed trees should be distributed uniformly across the site in such a way that the entire area of the harvested stand is within an acceptable dispersal distance of one or more of the residual seed trees. A reasonable estimate for the number of seed trees depends on tree size, but it is not unusual to reserve 10 to 25 pine seed trees/ha (4 to 10 trees per acre), with a corresponding residual basal area from 1 to 3 m^2/ha (5 to 15 square feet per acre). The harvest that takes all but the seed trees is called the seed cut, and the subsequent harvest that removes the seed trees is called the removal cut (Smith 1986a).

Professional application of the seed tree method bears little resemblance to retention of seed trees under the old seed tree laws. Those laws, which mandated retention of a few trees/ha after harvest, had the effect of leaving the poorest phenotypes of marginal size to reforest the site. Many attributes of interest to foresters, such as cone production, straightness, and branchiness, are highly inherited traits, and trees that display such attributes are likely to pass them along. Thus proper application of the seed tree method dictates the retention of trees with good form, acceptable branch characteristics, and evidence of past seed production. These attributes are easier to determine in some species than others. For example, in shortleaf pine (*P. echinata* Mill.), cones tend to persist for a number of years after seeds are shed (Lawson 1990), whereas loblolly pine (*P. taeda* L.) tends to drop its cones after seed fall (Baker and Langdon 1990). In shortleaf pine stands, marking crews can use this information about cone persistence to help determine which trees to retain.

The biggest limitation on the effective use of the seed tree method is the production of seed by the parent tree. Of the four major southern pines, the seed tree method works best in application to loblolly pine, especially in the west gulf region where abundant seeds are produced with great regularity (Cain and Shelton 2001). Adequate seed production translates to adequate seed fall and the likelihood of effective catch of seed by the site. Unfortunately, seed production in longleaf pine (*P. palustris* Mill.) is highly periodic, and use of the seed tree method is rarely successful with this species. One way to compensate for erratic cone production is to plan to retain seed trees for a long period of time, in the hope of continued recruitment into the regeneration cohort. Empirical evidence suggests that the seed tree method can also be made to work in shortleaf pine, which falls between loblolly and longleaf in periodicity of seed fall (Guldin and Loewenstein 1999).

As seed fall from seed trees becomes marginal, the need for effective site preparation increases. One main element of site preparation is the creation of a suitable seedbed. This, for southern pines, generally means the scarification of the forest floor to expose mineral soil. Typically, the logging activity associated with a seed tree harvest provides sufficient scarification for acceptable establishment of seedlings during bumper seed crops (Baker and others 1996). If seed crops are marginal, supplemental scarification may be required. However, no amount of supplemental scarification will help if seed crops are a failure. As a result, early detection of impending seed crops is important to help schedule the amount of site preparation necessary to ensure acceptable seedling establishment. Since pine cones take 2 years to develop, one can get an early estimate of cone production expected for given autumn by inspecting tree crowns for conelets in the spring of the previous year. While this approach offers only a rough prediction of adequate to bumper crops, one can easily see when a cone failure is imminent. That information can then be used to schedule or defer site preparation treatments in the summer or autumn immediately prior to seed fall.

When properly applied, the seed tree method has a number of advantages. Enough residual trees should be retained to allow an operable harvest of the parent trees 5 to 10 years after the seed cut. That operable harvest can also provide a desirable precommercial thinning in the regeneration cohort, by felling the seed trees amidst the regeneration and by the passage of the equipment used to harvest and skid the felled logs to the logging deck.

An outstanding example of the seed tree method in application to southern pines exists in the loblolly-shortleaf pine type in the upper west Gulf Coastal Plain (Zeide and Sharer 2000) (fig. 9.3). No southern pine is easier to regenerate

Figure 9.3—The seed tree reproduction cutting method applied operationally in a loblolly-shortleaf pine stand managed by forest industry, Ashley County, AR. Photo courtesy of James M. Guldin 1984.

naturally than loblolly pine, which dominates this forest type; seed crops that are adequate or better occur 15 years in 20 in mature loblolly-shortleaf pine stands (Cain and Shelton 2001). For a number of decades, the silvicultural guidelines for a major industrial forestry landowner in the region called for use of the seed tree method, leaving 2.3 to 4.5 m^2/ha (10 to 20 square feet per acre) of basal area of trees with good form and with diameter at breast height of 40 to 50 cm (16 to 20 inches).[2] The seed trees were usually taken in a removal cut 3 to 5 years later, which produced an operable harvest of from 2.9 to 8.8 m^3/ha (500 to 1,500 board feet per acre) of saw logs. Removal of the seed trees also thinned the excessive pine regeneration that was common in this forest type. The first commercial thinning occurred between the ages of 17 and 20 years, leaving about 16 m^2/ha (70 square feet per acre). The next thinning, at age 25, included some small saw logs, and subsequent thinnings on a 5-year cycle averaged 11.7 m^3/ha (2,000 board feet per acre) in each thinning. The final seed cut produced between 29.2 and 40.8 m^3/ha (5,000 to 7,000 board feet per acre). Thus growth for the rotation averaged > 1.75 m^3/ha (300 board feet per acre) annually. Late-rotation thinning also released the crowns of the seed trees, which increased cone and seed production. Regularly scheduled prescribed fires on a 3- to 5-year cycle, coupled with hardwood control on a 5- to 10-year cycle, promoted visibility within the stand that enhanced subsequent thinning treatments, and if carried through the end of the rotation, reduced the need for intensive site preparation in the subsequent rotation.

Shelterwood Method

The shelterwood method is similar to the seed tree method in that residual trees are retained to reforest the site after harvesting occurs, but more trees are retained. In his description of the shelterwood method, Smith (1986a) includes three specific elements: (1) the preparatory cut, (2) the seed cut, and (3) the removal cut.

The preparatory cut removes competitors of future seed trees, which then expand their crowns and root systems, thereby enhancing the potential for cone development. In southern pines, the late-rotation thinning commonly conducted in pine sawtimber stands generally fulfills the intent of the preparatory cut. During the seed cut, 35 to 75 pines/ha (15 to 30 trees per acre), having 4.5 to 9.0 m^2/ha (20 to 40 square feet per acre) of basal area, are selected for retention. Favorable traits for residual pines include stem form, windfirmness, and evidence of past seed production. The removal cut harvests the seed trees after the new stand has developed past the point of risk from seedling-related mortality.

One operational advantage of the shelterwood over the seed tree method in southern pines is that the volume of the residual trees in the shelterwood is greater than that of the seed tree method and is, thus, more likely to attract interest from loggers during the removal cut. Conversely, if carelessly done, logging during the removal cut can adversely affect stem density of the regeneration, especially at higher residual basal areas. Depending on management objectives, the final harvest may be deferred for half or more of the rotation length, resulting in a two-aged stand; this method is referred to as an irregular shelterwood (Helms 1998, Smith 1986a).

[2] Lovett, Ernest. 2003. Letter dated September 29 to James M. Guldin. On file with: Arkansas Forestry Sciences Laboratory, 114 Chamberlin Forestry Building, University of Arkansas at Monticello, Monticello, AR 71656.

Under traditional application of the shelterwood method, microclimatic ecological conditions are ameliorated relative to those found in fully open conditions; e.g., see Valigura and Messina 1993. Thus one reason to apply the shelterwood method is to moderate conditions that might be too harsh for seedlings to survive under a clearcut or a seed tree prescription. As a practical matter, the shelterwood method is popular for species in which seed production is erratic or unreliable; the added numbers of seed trees that remain in the shelterwood often make the difference between adequate stocking and less-than-adequate stocking.

Among the most prominent examples of the shelterwood method in southern pines is the experience with longleaf pine in southern Alabama (fig. 9.4). Longleaf pine has the deserved reputation of being the most difficult of the southern pines to regenerate naturally, but clever research has identified the practices needed to naturally regenerate the species using the shelterwood method (Boyer 1979, Croker and Boyer 1975). First, seed production in longleaf is optimal when the seed cut retains 6.9 to 9.2 m^2/ha (30 to 40 square feet per acre) of basal area (Maple 1977). Fewer trees result in fewer cones per unit area, and more trees do not enhance cone production. Second, prescribed fires are essential to control brown-spot needle blight (*Mycosphaerella dearnessii* Barr.) and, thereby, to release seedlings from the grass stage (Boyer 1979). Third, seedling mortality is highest beneath the crowns of residual trees, because the buildup of pine straw promotes prescribed fires sufficiently intense to kill them. All of these factors have led scientists to conclude that the need for available growing space, the need for frequent prescribed fire, the optimal development of cones in the canopy, and the ability to store seedlings in a seedling bank beneath the overstory of longleaf pine could be achieved using the shelterwood method.

Figure 9.4—The shelterwood reproduction cutting method applied in a research study on the Escambia Experimental Forest, near Brewton, AL. Photo courtesy of James M. Guldin 1982.

UNEVEN-AGED REPRODUCTION CUTTING METHODS

Prevailing wisdom suggests that uneven-aged reproduction cutting methods, especially the single tree selection method, are best for shade-tolerant species (Smith 1986a). As a result, the use of uneven-aged silviculture to manage shade-intolerant species such as the southern pines is often criticized. But historical experience suggests that the method can work with pines, subject to certain considerations. The Dauerwald, among the first applications of uneven-aged silviculture, was imposed in plantations of Scots pine (*P. sylvestris* L.) on poor sites in Germany (Troup 1952); some of its attributes still apply to current uneven-aged methods (Guldin 1996). Pearson (1950) applied a selection method to ponderosa pine (*P. ponderosa* Laws.) stands on the Fort Valley Experimental Forest in Arizona, thus laying the groundwork for contemporary application of that method in the American West (Becker and Corse 1997).

In the South, the best long-term uneven-aged dataset comes from the Good and Poor Farm Forestry Forties of the Crossett Experimental Forest (CEF) in southern Arkansas. Established in mixed loblolly-shortleaf pine stands on the west Gulf Coastal Plain in 1937, the Good and Poor Farm Forestry Forties have yielded data that were summarized after four decades (Baker 1986, Reynolds and others 1984). Other long-term examples are the quarter-century summary from the Farm Forestry Forties at Mississippi State University (Farrar and others 1989) and the 33-

year record from the University of Arkansas's Hope Farm Woodland at Hope, AR (Farrar and others 1984). Empirical evidence suggests that the selection method can be made to work with longleaf pine in the lower Coastal Plain of Florida and Alabama (Farrar 1996), and with shortleaf pine in the Interior Highlands of Arkansas and Oklahoma (Guldin and Loewenstein 1999, Lawson 1986). In short, the selection method can be adapted to southern pines if attention is paid to marking, regeneration, and stand structure (Guldin and Baker 1998).

Figure 9.5—The group selection method in application to longleaf pine in a Farm Forestry Forty demonstration on the Escambia Experimental Forest, near Brewton, AL. Photo courtesy of James M. Guldin 1982.

The general experience with uneven-aged silviculture in intolerant pines would lead one to suspect that group selection, with its larger openings (fig. 9.5), would be more effective than single tree selection, with its minimal canopy opening. Certainly some evidence suggests that in longleaf pine, group selection may be an effective reproduction cutting method (Brockway and Outcalt 1998, Farrar 1996, Farrar and Boyer 1991). On the other hand, Russ Reynolds, the scientist who pioneered the research at CEF, did not distinguish specifically between single tree selection and group selection; he spoke instead of using whatever size of openings was indicated by local stand conditions (fig. 9.6). Whether group selection or single tree selection is preferred, a number of considerations should receive special attention when selection methods are applied to southern pines: initial stand conditions, regeneration, developmental dynamics, application of marking rules, and residual stand structure.

Initial Stand Conditions

Circumstantial evidence suggests that early 20th century southern pine stands were largely even-aged before they were high-graded. Loblolly pine was known as old-field pine, and early photographs show that virgin upland pine-hardwood stands in the west gulf region had an open understory (Reynolds 1980).

Figure 9.6—Stand structure in a stand under management using the selection method, Good Farm Forestry Forty demonstration, Crossett Experimental Forest, near Crossett, AR. Photo courtesy of James M. Guldin 1984.

Similarly, virgin shortleaf pines in the Ouachita Mountains grew in open forest consisting of widely spaced overstory trees and little undergrowth (Smith 1986b).

Naturally occurring loblolly-shortleaf pine stands in the west gulf region originated after the first cutting of virgin forest in the early 1900s. In 1915, the Crossett Lumber Company, which owned the virgin forest land that would later become the CEF, harvested the area using a 38-cm (15-inch) stump limit cut, which was roughly equivalent to a 30-cm (12-inch) diameter limit cut. Between 1915 and 1934, no deliberate management was undertaken. The area supported occasional harvest of small hardwoods for chemical distillation and periodically was subject to arson fires. The company leased the 680-ha (1,680-acre) tract to the U.S. Department of Agriculture Forest Service (Forest Service) in 1934 for establishment of the CEF. While the company was interested in research information on management of second-growth forests, they also thought that Forest Service research staff could help prevent arson or control the resulting fires (Reynolds 1980).

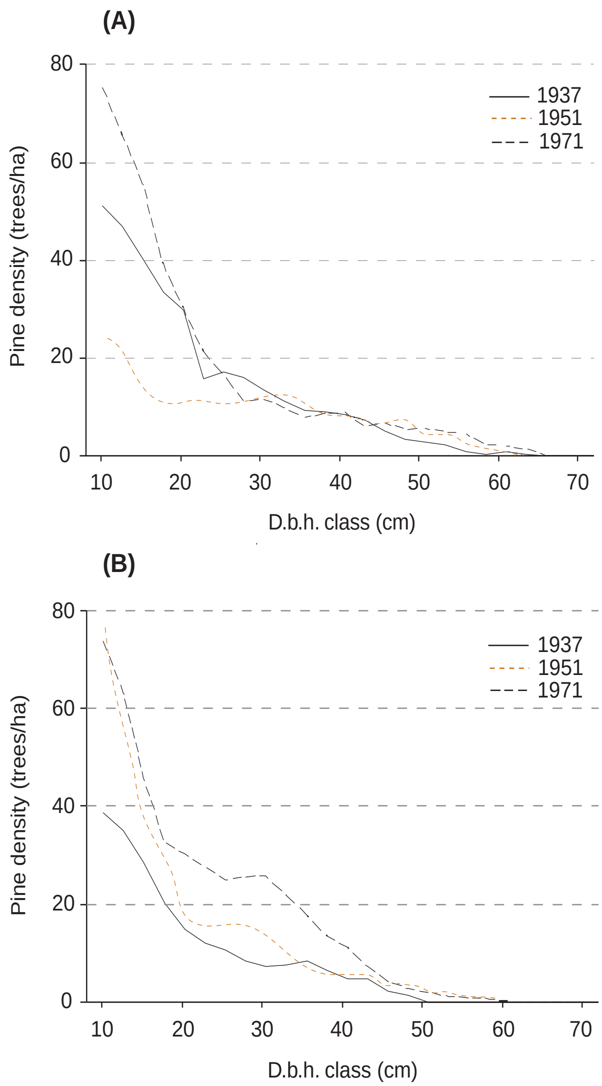

Figure 9.7—Diameter distributions of the Good Forty and the Poor Forty on the Crossett Experimental Forest in the first 35 years of the demonstration—(A) Good Forty in 1937, 1951, and 1971; (B) Poor Forty in 1937, 1951, and 1971.

Thus the use of uneven-aged silviculture in southern pines originated as a result of selective cutting. In 1937, the CEF Forties were stocked with scattered residual overstory trees that had survived the 30-cm (12-inch) diameter limit cutting in 1915, and the second-growth seedlings, saplings, and poles that seeded in after the cut and grew until 1937. On average, the stands were about 40 percent stocked by then (Reynolds 1969). The diameter distribution of the pine component in the CEF Good and Poor Forties in 1937 showed the reverse J-shaped curve typical of uneven-aged structure (fig. 9.7). This description of selective cutting and its effects on stand conditions at CEF was typical of that in the region; the stands in the Farm Forestry Forties and Hope Farm Woodland demonstrations had a similar history and initial condition. Because the stands in these demonstrations were relatively understocked when the selection method was initially applied to them, their rapid recovery to fully stocked conditions under the selection method shows that uneven-aged silviculture is a powerful tool for bringing understocked or cutover stands to full stocking within a short time (Baker and Bishop 1986; Farrar and others 1984, 1989).

Additional research illustrates not only the speed of the recovery, but also the degree of understocking from which recovery can occur. Baker and Shelton (1998a, 1998c) reported that stands with 20- to 30-percent stocking could develop acceptable stocking and basal area within 15 years, provided that competing vegetation is controlled with herbicide application. These threshold levels are lower than previously thought, and lower than threshold levels in the long-term demonstrations.

This suggests a strategy for implementing uneven-aged silviculture in southern pines across a forested ownership in the public or private sector. If the ownership supports both fully stocked even-aged stands and stands that for one reason or another are understocked, the best approach would be to convert the understocked stands rather than the fully stocked even-aged stands.

Regeneration

The importance of regeneration in these demonstrations is poorly documented for two reasons. First, there is no record of regeneration development in the 20- to 40-year period between the initial high-grading and demonstration establishment. Second, because regeneration was so abundant, the scientists who established the demonstrations paid little attention to it.

Reynolds (1959, 1969) reported that pine regeneration was established as a result of removal of poorer hardwoods of large and medium size, continuing fire protection, and control of small hardwood stems. He also noted that pine seedlings, saplings, and poles typically are found in small openings and often directly under high-crowned larger stems. This is apparent in the diameter distributions of the Good and Poor Forties during the first 20 years of management (fig. 9.7). The continued ingrowth into the 10-cm (4-inch) class during this period resulted from recruitment of saplings from the smaller diameter classes.

Thus obtaining regeneration and promoting its development through the seedling and sapling classes are critical for successful uneven-aged management (Shelton and Cain 2000). The initial cohort of reproduction should be established or released at the first cutting-cycle harvest in order to meet two goals: (1) the need for reproduction cutting to result in regeneration, and (2) the need to establish three or more distinct age classes in the uneven-aged stand (Helms 1998). If the establishment of the initial regeneration cohort is delayed, the conversion period will be correspondingly lengthened.

Residual Basal Area

In southern pines, regeneration establishment and development are strongly related to the basal area of the merchantable component of the stand. Data from the CEF and elsewhere suggest that uneven-aged stands can be managed successfully within a range of residual basal area from 10 to 17 m^2/ha (45 to 75 square feet per acre) (Baker and others 1996; Farrar 1996; Farrar and others 1984, 1989). At residual basal area levels < 10 m^2/ha (45 square feet per acre), the overstory is understocked and growth will not be optimal (although such stands can be rehabilitated to optimal production easily, as discussed earlier). At residual basal areas > 17 m^2/ha (75 square feet per acre) at the end of the cutting cycle, regeneration development is adversely affected.

The residual basal area target immediately after harvest must be established in conjunction with the expected length of the cutting cycle, the expected growth of the residual stand, and the upper basal area limit for the species. For example, basal area growth of uneven-aged loblolly-shortleaf pine stands at CEF is 0.5 to 0.7 m^2/ha (2 to 3 square feet per acre) annually. If a 5-year cutting cycle is planned, the target residual basal area immediately after the cutting cycle harvest must, therefore, be 14 to 15 m^2/ha (60 to 65 square feet per acre), so that stand basal area does not exceed 17 m^2/ha (75 square feet per acre) at the end of the cutting cycle. Longer cutting cycles require lower residual basal area levels.

Thus managing for the proper residual basal area is an important element of uneven-aged silviculture. This is one reason why structural regulation using the basal area, maximum diameter, and q-ratio or the BDq method (Baker and others 1996, Farrar 1996, Marquis 1978) has become popular. The CEF experience and other work suggest that BDq is more than an alphabetical ranking; this order reflects the priority for implementation (Baker and others 1996, Farrar 1996). The importance of maintenance of stand structure is based on obtaining the appropriate basal area; retaining a specified maximum diameter class or a given q is much less important (Guldin and Baker 1998).

Developmental Dynamics

By definition, uneven-aged stands have three or more distinct regeneration cohorts; so, if one begins with an even-aged stand or an understocked stand, conversion to an uneven-aged structure is a long-term proposition. A minimum of two cutting-cycle harvests will be needed to recruit two additional cohorts of regeneration, and a third cutting-cycle harvest will be needed to avoid suppressing this new regeneration, especially with shade-intolerant southern pines. For the 5- to 7-year cutting cycles used for loblolly-shortleaf pine stands at CEF and elsewhere, it will be 20 to 30 years before even-aged or understocked stands are minimally reconfigured to uneven-aged structure. For species such as shortleaf pine in the Interior Highlands, where 7- to 10-year cutting cycles are common, the conversion period will be 30 to 40 years. These estimates are confirmed in data from the CEF Good and Poor Forties, where the time from high-grading harvests in 1915 to initial development of full stocking was 36 years.

Marking Rules

When conducting a cutting-cycle harvest in an uneven-aged southern pine stand, the guidance given to field crews can be summarized by a simple rule: cut the worst trees and leave the best (Baker and others 1996; Farrar 1996; Farrar and others 1984, 1989; Guldin 1996; Reynolds 1959, 1969). When stands have developed an uneven-aged structure through time, tree size generally becomes correlated with age across the diameter distribution (Baker and others 1996). Marking a percentage of the poorest trees in each diameter class improves the average tree quality within each class, and over time only the best trees of highest quality attain the largest size. As a result, one attribute of the selection method is that over time, it produces large sawtimber that has high quality.

In stands being converted from even-aged to uneven-aged structure, size is not correlated with age, because the smaller trees may be of the same age as the larger trees. This means that most trees in the left-hand tail of a normal bell-shaped diameter distribution may in fact be the worst trees in the stand. Strict adherence to the rule of cutting the worst and leaving the best may result in an effect similar to thinning from below, where most of the smaller trees are removed. This is preferable to retaining poorer trees in smaller size classes at the expense of better trees in larger classes simply to achieve a target structure. If the best trees are being retained below the maximum diameter and are retained in a manner that allows development of subordinate stems and newly established regeneration cohorts, a perfectly balanced stand structure is immaterial.

Marking crews need guidance in judging whether an intermediate tree in the pulpwood size class can respond to release if it is allowed to remain in the stand. Reynolds (1959) noted that loblolly pine in the west gulf region could respond to release, even at advanced age. Baker and Shelton (1998b) observed that if a loblolly pine had a 20-percent live crown ratio and good apical dominance, it should satisfactorily respond to release, even if it developed in the lower crown classes of fully stocked, uneven-aged stands for up to 40 years; anecdotal evidence for longleaf pine is similar. Different standards would probably apply for other southern pine species and for trees from lower crown classes in even-aged stands.

To a certain extent, the group selection approach to management of uneven-aged stands violates the rule of cutting the worst trees and leaving the best. Group selection usually prescribes cutting of all trees, best and worst, if they are within the group. The degree of conflict depends on how the groups are located. If groups are identified independently of density or stocking, for example, by systematically installing groups of similar size and shape according to a predetermined pattern, the opportunity to cut the worst and leave the best is seriously compromised. Conversely, if groups are established in understocked portions of the stand, without regard for size, shape, or pattern of group opening, the number of best trees that must be cut will be reduced. Group selection with reserves (Helms 1998) is probably the best, though least often prescribed, method to minimize conflicts with the "cut the worst and leave the best" axiom, provided that reserved trees within the group are the best trees and do not adversely affect regeneration establishment or development.

OTHER ELEMENTS

Additional silvicultural considerations are important in the management of naturally regenerated stands by even-aged or uneven-aged methods.

Seedbed preparation is critical. Southern pine seeds germinate best on exposed mineral soil. In southern pine types that produce prolific seed crops, such as the loblolly-shortleaf pine type in the west gulf region, the scarification associated with logging provides enough exposure of mineral soil to promote establishment of regeneration. For other species, such as longleaf pine, supplemental mineral soil scarification is often recommended. Prescribed burning can also be used to prepare seedbeds.

The relative competitive abilities of pines and hardwoods after a harvest dictate that foresters must pay attention to relative growth rates and intervene if necessary. After a seed cut or cutting-cycle harvest, the intent is to allow pine seed to germinate on exposed mineral soil, become established, and be free to develop. However, hardwoods cut during harvest or subsequent site preparation will sprout and quickly outgrow seed-origin pines. Similarly, under certain circumstances grasses and other herbaceous plants may become sufficiently dense to impede pine seedling development, and control of grasses may also be necessary. Therefore site preparation or release treatments are often an integral part of effective silvicultural prescriptions for natural regeneration.

For example, competing hardwoods, as well as nonnatives such as privet (*Ligustrum vulgare* L.) and honeysuckle (*Lonicera japonica* Thunb.), commonly inhibit the development of pine regeneration (Shelton and Cain 2000). Given the slow rates of height growth of pine seedlings and the competition provided by hardwood sprouts and invasive nonnative plant species, herbicides are critically important in managing stands of naturally regenerated pines, and may be more important to the establishment and development of naturally regenerated pine seedlings than to the survival and development of planted pine seedlings. The use of herbicides has in fact been an element of every successful long-term demonstration of uneven-aged silviculture in southern pines, including the successful practical experience of which the author is aware. Periodic control of hardwoods by applying herbicides at roughly 10-year intervals was an element of uneven-aged silvicultural prescriptions at CEF (Baker 1986). Farrar and others (1984) noted that deficits in the smaller diameter classes in uneven-aged stands were due in part to the failure of recruitment from regeneration to pulpwood-size classes, which was attributable to hardwood competition and the presence of privet. Farrar and others (1989) reported that control of hardwoods by cutting, girdling, or herbicide treatments occurred in the past on the uneven-aged Mississippi State Farm Forestry Forties, and was recommended in the future for all hardwood stems > 1.0 cm (0.4 inch) in diameter. Prescribed fire and herbicides were used in much the same way in stands regenerated using the shelterwood method on the Escambia Experimental Forest (Croker and Boyer 1975). Their use has been recommended in industrial seed tree silvicultural guidelines for south Arkansas and north Louisiana (see footnote 2 and Zeide and Sharer 2000). Prescribed fire, which does not kill larger hardwoods, probably cannot completely eliminate the need for herbicides in naturally regenerated stands, especially in uneven-aged stands.

Finally control of regeneration density is fundamental to the successful application of natural regeneration in managed stands. Regeneration development in loblolly pine is improved by early precommercial thinnings to control stem density (Cain 1995). Nevertheless regeneration density will always be less uniformly distributed in naturally regenerated stands than in successfully established planted stands. Industry foresters in the west gulf region observed a long-term average rate of understocking of 7 percent of the stand area in managing naturally regenerated stands (see footnote 2). Invariably, one of the challenges in managing naturally regenerated stands is the likelihood of damage to regeneration when conducting removal cuts or subsequent cutting-cycle harvests. In situations where regeneration is far in excess of desired density, such logging-related precommercial thinning may actually be desirable. However, the situation is more critical when regeneration density is marginal prior to the removal cut or to subsequent cutting-cycle harvests. Careful supervision of logging operations is needed in such situations.

SUMMARY

Successful use of natural regeneration in managing southern pines depends on a number of factors. The establishment and development of pine regeneration is critical. Prescriptions must leave a sufficient number of seed trees to adequately regenerate the site during an average or better seed year. Sites must be properly prepared to be receptive to pine seed, and timing of harvests and site preparation must optimize the establishment and development of regeneration.

In even-aged stands, late-rotation thinnings or preparatory cutting is recommended to expand crowns of future seed trees and to promote cone production. The seed cut must create an appropriate balance of residual trees and seed production capacity per tree to ensure adequate seed fall, and site preparation must be timed to that seed crop. In uneven-aged stands, the first cutting-cycle harvest must be heavy enough not only to create conditions suitable for the establishment of regeneration, but also to prevent suppression of regeneration before the second cutting-cycle harvest occurs. Subsequent cutting-cycle harvests must continue this developmental pattern. Regardless of system, herbicides will almost certainly be needed to control competing vegetation and enable young pine cohorts to develop successfully.

Experience and research suggests that all four major southern pines can be managed using one or more of the even-aged or uneven-aged reproduction cutting methods that rely on natural regeneration. Certainly some forest types, such as the mixed loblolly-shortleaf pine type in the west gulf region, are amenable to any of the even-aged and uneven-aged prescriptions, whereas in other forest types, such as longleaf pine, the range of available options is perhaps narrower and requires greater care in application. Each of the systems must be implemented in a manner that takes into account the silvical characteristics of the species in question. Choosing which method to use in a particular forest type depends on proper application of available research and experience with the desired species in specific situations. Overall, these methods present feasible and economically viable alternatives to clearcutting and planting for public land managers, forest industry foresters, and NIPF landowners in the South.

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Chapter 10.

The Role of Genetics and Tree Improvement in Southern Forest Productivity

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Abstract—*Because of space limitations, a thorough discussion of the rich history of tree improvement in the Southeastern United States cannot be totally accomplished in this forum. However, a synopsis of key program highlights and the people who forged and directed these programs is presented, together with a discussion of current and future work. This discussion covers improvement programs for both southern pines and hardwoods. Comparisons of and contrasts between these two types of programs are discussed and punctuated by the reasons for successes and failures. Today, southern pine tree improvement programs are on the cutting edge of genetic technology, moving from open-pollinated seed to clonal programs encompassing molecular genetic features. Programs for southern hardwoods generally are much less advanced, because there are several limiting factors unique to hardwoods and because hardwood fiber is available at low cost.*

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INTRODUCTION

Consumption of forest products is expected to continue its rapid increase during the 21st century. In contrast, the land base used for wood production is expected to decline because of population pressures, environmental concerns, lack of adequate management by many landowners, and the divesture of lands deemed nonstrategic. Even today, removals equal or exceed growth rates in some areas (Wear and Greis 2002). However, models indicate that the potential productivity of forests in many regions can be much higher than is currently realized (Allen 2000, Bergh and others 1998, Sampson and Allen 1999). With investments in appropriate management systems, growth rates > 25 m^3/ha/year for pines are biologically possible and can be financially attractive for a broad range of site types in temperate, subtropical, and tropical regions.

In the early days of southern forestry, vast areas were clearcut with little or no regard for regeneration. Natural regeneration was satisfactory in some areas but totally lacking in others. Very little planting occurred before the Civilian Conservation Corps began wide-scale planting during the Great Depression. Wakeley (1944) estimated that < 500 acres of southern pines had been artificially regenerated successfully before 1920.

Historically, the practice of silviculture focused on controlling the composition, quantity, and structure of forest vegetation and the maintenance of site quality. As forest plantations have become important sources of fiber, fuel, and structural material, this custodial role has given way to active intervention to improve both plant and soil resources. Forest managers are recognizing that intensive plantation silviculture requires active management of both biotic and abiotic resources to optimize production. Silvicultural treatments including soil tillage, vegetation control, fertilization, fire, and thinning can dramatically affect soil resources. The key

to optimizing fiber production is to deploy the best genetic material available and to provide sufficient resources to allow the full genetic potential to be realized.

SOUTHERN PINE TREE IMPROVEMENT

Early Work

Before 1920, little was known about how seed source might affect forest plantation productivity in the United States. Since well before the turn of the 20th century, the importance of geographic seed source was known for European species. In this country, native seed collections for an extensive study of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] were initiated in 1912 (Kaufman 1961), and testing of ponderosa pine (*Pinus ponderosa* Laws.) seed sources in northern Idaho and Colorado began in 1916. Inspired by some of Luther Burbank's work with walnut (*Juglans* spp.) hybrids, James G. Eddy started the Eddy Tree Breeding Station (which later became the Institute of Forest Genetics) at Placerville, CA, in 1925.

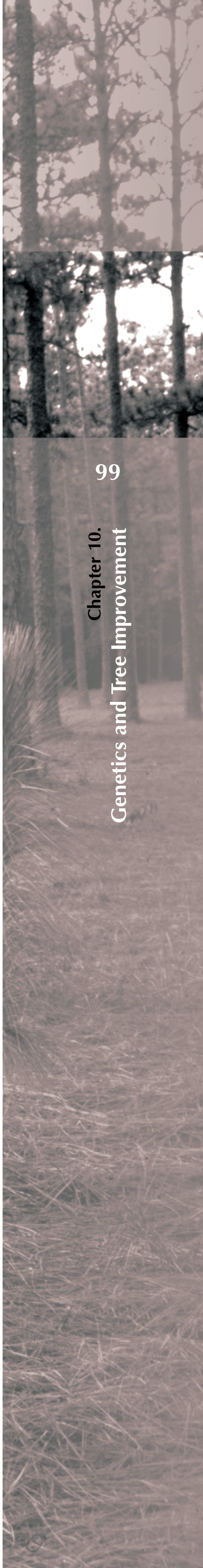
Although Chapman (1922) identified the first natural southern pine hybrid [longleaf pine (*P. palustris* Mill.) x loblolly pine (*P. taeda* L.)], the history of southern tree improvement began with Phil Wakeley, who came into the region in 1924. His undaunted drive led him to complete a monumental amount of research in basic silviculture, and his manual "Planting the Southern Pines" (Wakeley 1954) is still in use. Although he had little training in genetics, he was aware of seed source effects and in 1926 installed an important loblolly pine provenance test near Bogalusa, LA. This test was one of the first to clearly demonstrate genetic differences in a southern pine. The magnitude of the seed-source effect in southern pines was unknown before Wakeley published age-15 data indicating that growth and disease resistance varied widely among geographic races of loblolly pine (Wakeley 1944). Wakeley is also credited with creating the first artificial southern pine hybrid in 1929, a cross between longleaf and slash (*P. elliottii* Engelm.) pines (Dorman 1951).

Other early work included a large open-pollinated progeny test of loblolly pine installed in 1934 by A.L. McKinney and L.E. Chaiken of the U.S. Department of Agriculture Forest Service, Appalachian Station [now part of the U.S. Department of Agriculture Forest Service (Forest Service), Southern Research Station]. Substantial inherent differences were noted before the planting was flooded by the Santee-Cooper Power Project (Kaufman 1961).

In 1941, Mitchell, Dorman, and Schopmeyer, working at the research station in Lake City, FL, started selecting slash and longleaf pine for high gum yield. Open- and controlled-pollinated seedlings from these selections were used to establish the first progeny tests in southern pines demonstrating the existence of individual tree genetic variation.

Around 1949, L.T. Easly (1953), a forester with Westvaco, gave some high school students permission to collect cones from one of his saw-log operations and sell them to the State nursery. The students later told him that they preferred short, scrubby trees with lots of cones on them, rather than the sawtimber he was cutting. Aware of Dorman's work, Easly concluded that the dysgenic selection would result in poor-quality trees because of the student's preferred collecting methods. This prompted him to establish the first seed production areas in loblolly pine, which he referred to as orchards.

In 1951, the Southern Forest Tree Improvement Committee was formed to foster research and development in forest genetics and tree improvement. It has continued to be a guiding force in forest genetics and tree improvement research and technology transfer to the present day. According to Kaufman (1961), two events provided the impetus for the rapid expansion of genetics and tree improvement in the 1950s. The first was the influence of several prominent foresters who attended the World Forestry Congress in Helsinki in 1949, where they became aware of the tremendous progress being made by tree breeders in Europe. The 1950 meeting of the Appalachian Section of the Society of American Foresters was devoted to tree improvement. The second event was an exchange of correspondence beginning in the fall of 1949 between the Forestry Relations Division of the Tennessee Valley Authority (TVA) and the Forest Service's Southern Forest Experiment Station on the possibility of establishing a regional seed-source research program. The result was the first Southern Forest Tree Improvement Conference held in Atlanta, GA, in January of 1951. The organizers were surprised when > 80 people attended. Since then, the conferences have been



held every other year. The proceedings of the conferences are major sources of information in genetics and tree improvement, as is evident in the literature cited for the present chapter.[2]

One product of the first conference was the establishment of a subcommittee, headed by Phil Wakeley, to install the Southwide Southern Pine Seed Source Study (SSPSSS), one of the most comprehensive provenance tests ever established. The results from Wakeley's (1944) first test were dramatic, but the study was planted only at Bogalusa, LA. The local seed source from Livingston Parish, LA, was clearly the best not only for growth but also for disease resistance.

The SSPSSS, on the other hand, was much more comprehensive. It was a very large undertaking, involving many cooperators across the Southeastern United States who collected seed and provided planting sites. All four major southern pine species were included—loblolly, slash, longleaf, and shortleaf (*P. echinata* Mill.) pines. A total of 128 plantations were established, including seed from and plantations in 16 States, ranging from New Jersey and Pennsylvania south to Florida and west to Texas, Oklahoma, and Missouri (Wakeley 1961).

The results of the SSPSSS and some other more limited provenance tests showed that the local seed source was not always the best source. Seed sources from warmer climates tended to grow faster than local sources, if the warmer climate sources were not moved to areas with climates greatly unlike those where they originated. Unlike the other southern pines, loblolly has important east-west differences. Seed sources from west of the Mississippi River are slower growing but more resistant to disease and tolerant of drought than sources from east of the Mississippi. Sources from just east of the river, centered at Livingston Parish, LA, combine the rust resistance of the western sources with the faster growth of the eastern sources. Results of this study led to large-scale transfers of seed to increase productivity. Disease-resistant Livingston Parish, LA, seed was widely planted in locations to the east. For example, much of this seed was planted in Georgia, where disease had caused losses in productivity. Fast-growing coastal Carolina seed sources have been planted extensively in Arkansas, where they outgrow the local sources.

It was assumed, based on the loblolly results, that east-west differences would be important in longleaf and shortleaf pines, because they also occur on both sides of the Mississippi River. Recent analysis has shown that this is not so, and the latest seed-movement guidelines (Schmidtling 2001) stress the importance of minimum temperatures in seed transfer considerations for these two species.

Wise use of information about geographic variation has resulted in large increases in southern pine productivity. Further increases have been realized through breeding. Forest tree breeding in the South started in earnest with the formation of the tree improvement cooperatives in the 1950s, with the main emphasis on pines. The first cooperatives evolved in the early 1950s out of research programs at the University of Florida (headed by T.O. Perry) and at the Texas Forest Service (headed by Bruce Zobel). Zobel moved to North Carolina State University in 1956 to form the third and the largest of the tree improvement cooperatives that exist today.

Current Status

Productivity improvements from genetics have helped to make investments in intensive forestry very profitable throughout the world. In regions such as the Southeastern United States, managers of facilities for wood-based manufacturing facilities have realized that their future depends upon a reliable, ecologically sustainable, and economically affordable supply of wood. Plantations of genetically improved forest trees are critical to maintaining this supply. In the South, > 1 billion loblolly pine seedlings are planted each year, and nearly every seedling is a product of a tree improvement program. Because of the economies of scale, even modest genetic gains are worth millions of dollars to industrial landowners, and the small landowner benefits as well. Even through only one generation of improvement, gains have been substantial. For first-generation loblolly pine and slash pine, volume, stem quality, and disease resistance have been improved, and the gain in harvest value is estimated to be 15 to 20 percent over unimproved trees (Hodge and others 1989, Talbert and others 1985). Estimates from the second generation of improvement in loblolly pine are even more encouraging. Additional

[2] Copies of proceedings of the Southern Forest Tree Improvement Conferences are available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161, 800-553-6847 or 703-605-6000, fax 703-605-6900, orders@ntis.gov.

productivity gains over the first generation average 7 percent for unrogued orchards to 18 percent for rogued orchards, and improvement in quality should dramatically exceed what was seen in the first generation (Li and others 1999).

Because of the substantial improvements in forest productivity from both genetics and silvicultural manipulation (Allen 2000, McKeand and others 1997), the options available to foresters have increased greatly. Combining a thorough knowledge of soil productivity and optimal silvicultural techniques with use of the most advanced genetic material will dramatically increase productivity. It is estimated that 20 to 30 percent more wood can be produced per hectare by utilizing the most responsive families from the first-generation programs in conjunction with the best site preparation and nutrition management practices (McKeand and others 1997). Even greater gains are expected when the best second-generation families are deployed to the best sites (Li and others 1999).

Deployment options for further increasing the genetic quality of planting stock are also being pursued. Mass production of selected full-sib families (Bramlett 1997) will have significant impact on forest productivity, especially in areas where additional selection intensity for environmental concerns such as cold tolerance is necessary. Because more genetic gain can be realized if the best full-sib families are used for regeneration (Li and others 1999), foresters will have more options for increasing productivity and profitability. Limitations to utilizing the best full-sib families are the cost-efficient production of seed and the bulking of these families with vegetative propagation. Pollination methods for mass-producing full-sib seedlings are being developed in the South (Bramlett 1997, Goldfarb and others 1997) and have been used successfully in other pine regeneration programs around the world (Balocchi 1997, Carson 1996, Walker and others 1996).

A breeding program is the backbone of any deployment program, and to sustain genetic gains through time, the breeding program must be of sufficient size and diversity to provide new and improved genotypes. A general trend has been to supplement traditional mainline breeding populations with intensively managed and selected elite breeding populations (Cotterill 1989, McKeand and Bridgwater 1998, White 1993, White and others 1993). In the elite populations, financial benefits can be realized in the short term by breeding only the very best genotypes. Fewer trees are bred, so breeding generations cycle faster, and the gain per year is dramatically increased.

These elite, intensively managed breeding populations are complements to, and not replacements for, larger breeding populations where the long-term management of genetic resources is a primary objective. Tree breeders have a unique responsibility and opportunity compared to other plant and animal breeders. Most forest tree species remain as wild undomesticated populations, and those few species that are being bred have only been domesticated in the past few years. Forest trees generally have very high levels of genetic variation compared to other plants and animals (Hamrick and others 1992), and this variation is the foundation of the successful efforts to improve productivity through genetics.

SOUTHERN HARDWOOD TREE IMPROVEMENT

Early Work

Early studies in the South concentrated on establishing geographic variation patterns in growth and wood properties by means of provenance trials and sample collections from widely distributed natural stands. The earliest studies in the South date from the spring of 1936, when the forestry division of the TVA became involved in this work. This program included the breeding of walnuts (*Juglans* spp.), hickories (*Carya* spp.), chestnuts (*Castanea* spp.), oaks (*Quercus* spp.), honey locust (*Gleditsia triacanthos* L.), black locust (*Robinia pseudoacacia* L.), and persimmon (*Diospyros virginiana* L.) as a means of combining high productivity and quality of nuts, acorns, or other fruits with desirable timber quality (Schreiner 1938, Wakeley 1975). In the 1950s and early 1960s, trials of yellow-poplar (*Liriodendron tulipifera* L.) (Farmer and others 1967, Kellison 1965, Lotti 1955, Thorbjornsen 1961), sweetgum (*Liquidambar styraciflua* L.) (Webb 1964), and eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) (Farmer and Wilcox 1966, Maisenhelder 1961) were established. At this time, the Forest Service initiated a tree improvement program to help mitigate a shortage in timber resources in the United States expected in the mid-1980s (Tibbs and Windham 1999). Studies soon followed for other hardwood species, including northern red oak (*Q. rubra* L.) (Gall and Taft 1973), cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.) (Randall 1973), and sycamore (*Platanus occidentalis* L.)

(Land 1981, Webb and others 1973). By 1983 at least 27 hardwood species had been considered for tree improvement, and collections had been made for most of these (Purnell and Kellison 1983). Unlike southern pines, no one species or small group of species is suited to the various site types throughout the South, because hardwoods are very site specific. Understanding site specificity is essential to understanding and realizing genetic gain in hardwoods. However, the absence of economy of scale greatly limits the ability to develop a viable genetic program for most hardwood species.

Three early programs stood out for their longevity and contributions to hardwood genetics. These programs were established by the Forest Service, Southern Forest Experiment Station; the North Carolina State University Hardwood Research Cooperative (HRC); and the Texas Forest Service. The Southern Forest Experiment Station's program of hardwood tree improvement began in the early 1960s at the Southern Hardwoods Laboratory located in Stoneville, MS. Sweetgum, cherrybark oak, sycamore, and eastern cottonwood were studied initially, and other species added in the late 1970s and early 1980s just prior to the closing of the hardwood project in 1982 (Ferguson and others 1977, Mohn and others 1970). Eastern cottonwood, probably the most intensively studied hardwood species in the South, was the subject of testing from 1965 through 1980. Early tests indicated that local sources were superior to earlier introductions of European hybrids (Maisenhelder 1970). Testing eventually resulted in the release of the first and only certified genetically superior cottonwood clones in the country (Land 1974). Subsequently, collections were made from natural stands throughout the lower Mississippi River Valley, from coastal areas from North Carolina to Texas, and from other programs as far north as Minnesota. Large clonal tests were established with industry and university cooperators in Arkansas, Illinois, Kentucky, Louisiana, and Mississippi. Clones suitable for use in various portions of the Mississippi River Valley were identified, and data collected on vegetative propagation, controlled pollination, disease resistance, crown architecture, and selection strategies provided excellent information for industry and university programs to build upon (Cooper and Ferguson 1979; Cooper and Filer 1976, 1977; McKnight 1970). In general, clones originating up to 200 miles south of the plantation sites grew faster and had greater leaf rust resistance than local clones. Many of the cottonwood clones developed at Stoneville remain the backbone of plantation and breeding programs today.

Hardwood cooperatives were organized somewhat later than the pine cooperatives. The HRC began in 1963 with a combined program of intensive tree improvement and less intensive management of natural stands (Young 1996). Sweetgum, sycamore, yellow-poplar, green ash (*Fraxinus pennsylvanica* Marsh.), and water oak/willow oak (*Q. nigra* L./*Q. phellos* L.) received most of the attention during the early years because of their commercial importance across a majority of the Southern United States. Initially, a selection index was used to identify phenotypically superior trees, which were then grafted into clone banks and seed orchards with the oaks established in seedling seed orchards. In 1972, region-wide progeny testing was initiated by the HRC (Anon. 1999). Open-pollinated seed from phenotypically average or better than average sweetgum, sycamore, water oak, willow oak, and black walnut (*J. nigra* L.) were collected from natural stands throughout the South. The modified selection scheme was used because the index system proved inadequate for identifying genotypically superior southern hardwoods in natural stands (Purnell and Kellison 1983).

In 1971, the Texas Forest Service's Western Gulf Forest Tree Improvement Program formally added the Hardwood Cooperative Tree Improvement Program to their existing pine program (Byram and Lowe 1995). To date, 17 species-site trials and 188 open-pollinated progeny tests have been established with nearly 1,500 families (Byram and others 2000). After 20 years, sycamore, sweetgum, and green ash tests indicated that family differences were significant, but there were neither consistent provenance effects nor any meaningful genotype x environment interactions for hardwood species in the southern Coastal Plain (Byram and others 1998). A slight indication was found that sources from the western edge of the species range are slower growing. Families that performed well across the region could be identified as early as age 5 or 10.

Current Status

A survey of State tree improvement personnel indicated that most Southern States currently have hardwood tree improvement programs, and almost half are active members of one of the two hardwood cooperatives. Arkansas, Louisiana, Mississippi, and Texas benefit from their affiliation with the Western Gulf Forest Tree Improvement Program. North Carolina and South Carolina are currently members of the HRC. Sycamore and sweetgum are of primary importance in both programs, but other species have been added. Justification for research on a particular species sometimes results more from its importance to wildlife than from its importance to fiber production. Federal cost-sharing programs, e.g., the Conservation Reserve Program, drive planting of southern bottomland hardwoods on nonindustrial private land almost entirely. Demand is high now for hardwood seed to support Federal cost-share programs (Byram and others 2000), and if these programs are expanded through the extension of eligibility to additional lands, hardwood planting could increase substantially, and demand for improved seedlings would correspondingly increase.

Tree improvement efforts on Federal land in the South have shifted dramatically over the last 15 years. This is mainly because new laws have reduced the number of acres harvested and have subsequently reduced the number of acres planted annually. As rotations have lengthened and management programs have become less intensive, pine improvement programs are no longer justified for Federal lands (Tibbs and Windham 1999). Under current policy, only northern red oak and white oak (*Q. alba* L.) will have artificial regeneration programs, and these will rely on seedling seed orchards. Hardwood species that are difficult to maintain or are threatened by introduced pests such as American chestnut [*Castanea dentata* (Marsh.) Borkh.], butternut (*J. cinerea* L.), and dogwood (*Cornus florida* L.) receive special attention (Tibbs and Windham 1999) as gene conservation becomes a major focus of more programs (McCutchan 1999). The University of Tennessee and the Georgia Forestry Commission are partners with the Forest Service in these projects.

Genetic improvement of eastern cottonwood is probably more advanced than that of any species in the South. Ease of vegetative propagation, abundant seed production, and established techniques for controlled pollination have enabled programs to make significant advancements. Clones developed by the Southern Forest Experiment Station and the Texas Forest Service form the basis for several current programs, including the interspecific hybridization programs in the Pacific Northwest and around the world. Westvaco (now MeadWestvaco) probably has had the most consistent cottonwood program since the closure of the Stoneville project. Both clone and progeny tests were established throughout the 1980s. These were aimed at increasing realized gains, establishing a genetically diverse deployment population, and constructing a viable breeding population. Today, fiber farms (irrigated and fertilized plantation systems) are being investigated as a source of hardwood fiber for various southern mills. Improvement programs are targeting these sites for their specific needs.

The U.S. Department of Energy (DOE) is currently sponsoring research to develop *Populus* clones for the Southeast as part of their Biomass Fuels Program (Land and others 2000). Breeding and testing programs are active at Mississippi State University. New seed collections have been made from throughout Southeastern United States and clone tests have been established in Missouri (MeadWestvaco), Florida (University of Florida), Alabama (Boise Cascade), and North Carolina (International Paper).

Venture companies are exploring the possibilities for commercializing transformation products in a number of species. The Southeast will also benefit from work being accomplished at the Tree Genetic Engineering Research Cooperative at Oregon State University and the Poplar Molecular Genetics Cooperative at the University of Washington, especially in the genus *Populus*. The most exciting effort to date is the genomic sequencing work that is being done with *Populus*, which is being funded through the DOE (Anon. 2002). This effort is already developing projects aimed at increasing production of hemicellulose and auxin.

Unlike southern pine tree improvement, hardwood tree improvement has generally lacked a unified approach or the benefits of having a single-species focus. McKnight recognized this in 1975 when he characterized hardwood tree improvement as a "haphazard thing, a searching for meaning and direction." These words are still accurate when summarizing hardwood tree improvement efforts in not only the Southeast but throughout the United States. Numerous programs have been intensive at times only to be closed when demand lessens, when research dollars tighten, when raw material costs decrease, or when the perception of a hardwood shortage is replaced by problems of greater importance. This wavering has limited gains, mainly because it has necessitated the rebuilding of testing and breeding populations, something that has been avoided in

the continuous pine tree improvement programs of the South. Several major factors contribute to the unique aspects of hardwood tree improvement; these include the number of species, their site sensitivity, and their infrequent occurrence in even-aged monospecific stands (Land 1975).

As with past programs, current hardwood programs face a lack of long-term funding because hardwood furnish is perceived to be low in cost and accessible even though numerous southern mills are reaching further for their hardwood fiber supply. Even though large amounts of hardwood fiber are needed to sustain these mills, little has been invested in research to develop low-cost hardwood fiber sources that would provide substantially higher yields than natural stands do, and in less time. Industry funding has become even more restricted with the recent downturn in the paper industry. The funding crunch is also affecting long-term cooperatives through mergers and the capitalization of the supporting land base that is thought to be nonstrategic to a specific mill. Today's industrial programs are faced with a need to develop plantation schemes that will meet return-on-investment demands and build programs focused on one or two species that are adapted over a range of sites throughout the South.

THE FUTURE OF TREE IMPROVEMENT IN THE SOUTH

Many new tools are available to aid in efficiently manipulating the genes of forest trees. While traditional methods of quantitative genetics have been very effective, they can be enhanced with emerging technologies. There are exciting new possibilities for improvement through advances in biotechnology that allow incorporation of genes for traits such as herbicide resistance, insect resistance, increased cold tolerance, modified lignin, and growth. A requisite first step to applying biotechnology to plantations is the ability to vegetatively propagate selected clones. Rooted cuttings of many hardwood species and fewer conifers have been used in intensive forestry practices for decades and in a few situations for centuries. Classic examples include willows (*Salix* spp.), poplars, and sugi (*Cryptomeria japonica* D. Don), which has been clonally propagated for > 1,000 years and used in plantation forestry in Japan since around A.D. 1400 (Toda 1974). Unfortunately, most conifers and certain recalcitrant hardwoods have not been clonally propagated successfully. The primary obstacle to success is maturation. As seedlings of these species that are difficult to root mature, they undergo many morphological and physiological changes. One important trait that changes is the ability of severed stems to form adventitious roots. For these species, rooting of cuttings collected from very juvenile seedlings will often be high (> 80 percent), but rooting success of cuttings from open-grown trees typically drops to almost zero over a period of 2 to 10 years.

In many species, juvenility (the ability to form adventitious roots and rapid growth of rooted cuttings) can be maintained for several years through severe pruning (hedging) of stock plants to produce cuttings for rooting (Goldfarb and others 1997, Rowe and others 2002). Cuttings can be rooted at high frequencies even when taken from hedged loblolly pine that is several years old (Cooney and Goldfarb 1999). Rooted cuttings of this type grow as rapidly as seedlings from the same families (Frampton and others 2000, Stelzer and others 1998).

Other strategies exist for maintaining juvenility until clones can be selected and multiplied. One strategy employs establishing clone trials from stock plants while maintaining juvenility of the stock plants through selection age. A possible modification could include establishment of clones as axillary shoot cultures and maintaining the cultures at temperatures that are low but above freezing to delay maturation.

A second strategy being pursued consists of initiating somatic embryogenic cultures from candidate seeds. The cultures would be divided to generate somatic seedlings for clonal field tests while the remaining portions of the culture would be placed in liquid nitrogen for cryopreservation. When superior clones have been selected, preserved cultures could be recovered, multiplied, and used to generate somatic seedlings for reforestation. For the southern pines, all of these steps have been achieved, but there are limitations in the efficiencies of each step in the process. Also at this time, only a relatively low percentage of genotypes (families and clones) can be successfully propagated through all the steps.

Ultimately, the strategy most likely to be employed widely will be the one with the lowest cost per genetic gain delivered. Both technologies, though possible on a research scale, still require further development on an operational scale, so it is difficult to precisely predict gains and costs. Perhaps the ideal system would comprise elements of both technologies. That is, clones would be started as embryogenic cultures, cryopreserved, and clonally tested with somatic seedlings. Once selected, a moderate number of somatic seedlings could be turned into stock plants for large-scale, low-cost production of rooted cuttings for reforestation stock. Despite technological and strategic uncertainties, it appears likely that research advances in recent years, together with the potential genetic gains available and the widespread interest of many industrial landowners, will result in the development of some clonal system for the southern pines in the near future.

A third strategy, which may only be applicable to certain species, utilizes alternative explant sources from mature trees to initiate cultures. Pioneering work at the University of Georgia (Sommer and Brown 1980, Sommer and others 1985) has led to the propagation of mature trees via staminate inflorescence tissues (Merkle and others 1997). Sweetgum propagation has been an ongoing project at the University of Georgia since the mid-1970s. The development and refinement of asexual propagation techniques for sweetgum has been ongoing at North Carolina State University since the mid-1990s. Efforts have focused on optimizing the collection of cuttings, storage methods, basal auxin treatments, and transplanting times (Anon. 1998, 1999, 2000; Rieckermann 1995; Robison and others 1999). Recent success in both rooting and survival of sweetgum, however, has been tempered by poor shoot growth following rooting (Anon. 2001, Gocke and others 2001). Sweetgum would be more widely adaptable for use on southern sites than more easily propagated *Populus*, *Salix,* or *Eucalyptus* species.

True clonal forestry as is practiced with *Eucalyptus* species in many tropical countries (Zobel and others 1987), and with *Populus* species in temperate regions (e.g., Li and Wyckoff 1993, Stettler and others 1988), provides additional gains not possible through conventional breeding. When specific clones of any age tree can be propagated, the full genetic potential of the population can be utilized. Because no sexual recombination occurs when clones are propagated, there is no opportunity for specific gene combinations to be lost. If maturation can be reversed or at least arrested, clonal forestry for southern pines and recalcitrant hardwoods will likely become a reality.

Productivity increases from clonal forestry have often been dramatic. The best clones of *E. grandis* (Hill ex Maiden) in Brazil produce 70 m^3/ha/year, whereas unimproved seedlings produce only half this much volume (Zobel and others 1987). Similar benefits for hybrid poplars in the Pacific Northwest of the United States have also been realized. The best clones from hybrid crosses of *P. trichocarpa* x *P. deltoides* produce yields that are > 100 percent better than those produced by average seedlings (Stettler and others 1988). As clonal forestry becomes practical in more species, breeding will adapt from a population improvement approach to one that will capture heterosis by producing individual elite genotypes (Tuskan 1997).

Multiplication of specific full-sib families that have demonstrated proven performance has become operational with *Pinus radiata* D. Don and has had major economic impact on plantation programs in New Zealand, Australia, and Chile (Balocchi 1997). Several companies in the Southeastern United States are actively pursuing a similar strategy for the southern pines.

Deployment of genetically improved planting stock is the only opportunity breeders have to directly impact forest productivity. The number of methods to affect the type of propagule that will be deployed has increased and will continue to increase with the help of molecular genetics. Already molecular geneticists and breeders have collaborated to identify genes that are important in controlling economically important traits. In loblolly pine, for example, major genes for disease resistance (Wilcox and others 1996), specific gravity of wood (Groover and others 1994), and volume production (Kaya and others 1996) have been identified using DNA markers that are associated with the locus or loci controlling the economic trait.

Using marker-trait associations effectively is not straightforward (Bradshaw 1996, Johnson and others 2000, O'Malley and McKeand 1994, Williams and Byram 2001, Wu and others 2000). Marker-assisted selection will likely supplement traditional selection methods in some elite breeding programs. However, molecular markers are expensive, and determining the marker-trait association with field trials is even more expensive. It is very likely that markers associated with desirable traits in one parent will have different associations in other parents. Only if linkage disequilibrium is common in a population will marker-trait association be the same in each member of the population (O'Malley and McKeand 1994), and it is unlikely that this situation is common (Strauss and others 1992). In the future,

if the investment is made to map genotypes of all parents in an elite breeding program, the incremental cost of using the markers for selection in both breeding and deployment populations could be reduced. Again this promising technology awaits improvement in cost efficiency (Johnson and others 2000).

Molecular geneticists' greatest contribution to tree improvement may be a better understanding of the processes of wood formation and growth. With knowledge about processes such as lignin biosynthesis (e.g., MacKay and others 1997), molecular geneticists hope to manipulate the process to make pulping more efficient (e.g., Dimmel and others 2001). Genetic engineering, or the insertion of foreign genes into the genome of a desirable clone, has been realized in forestry. In species in which tissue culture via organogenesis or embryogenesis is feasible, insertion of genes has great potential. One of the major factors that will hamper hardwood molecular biology programs is the lack of highly sophisticated conventional breeding programs for most species.

Advances in mapping and transformation have been more rapid in hardwoods than in the pines because of their relative ease of culture and manipulation. Indeed, various *Populus* species and sweetgum have become model species for industrial and cooperative biotechnology programs. This is even more evident with the recent announcement of a project to sequence a *Populus* clone (Anon. 2002). Development of molecular resistance to more environmentally friendly herbicides would reduce establishment and early rotation maintenance costs that have plagued hardwood plantations. This possibility has tremendous potential, and transgenic tests throughout the United States are providing insights into it. While this trait alone would allow for a tremendous increase in hardwood plantation acreage in the South, the addition of other characteristics, such as reduced lignin content, would provide even more impetus.

It is unlikely that transformed [genetically modified (GM)] trees will be widely deployed until the negative public perception of their use can be changed. This issue is likely to be a serious impediment to tree improvement in general. Recent attacks by bioterrorists have resulted in the destruction of transformed trees, vehicles, laboratory buildings, and ordinary selected trees in a tree improvement program (Kaiser 2001, Service 2001). Most of the June 2002 issue of "Nature Biotechnology" (volume 20, number 6) was devoted to various aspects of the use of GM crops.

CONCLUSIONS

Genetic tree improvement and plantation management has had and will continue to have a positive impact on forestry and forest management worldwide. The demand for forest products will continue to increase, and intensive management will be needed to meet this demand. Plantation management of fiber farms can also alleviate pressure on ecologically sensitive forests and provide year-round accessibility to wood. Tree improvement can best promote the conservation of forest ecosystems by providing high-yielding, adaptable planting stock for these fiber farms.

Tree breeders must be cautious in the use of the genetic resources in breeding populations. The rich genetic variation in most tree improvement programs is an endowment that must be skillfully managed. Fortunately, breeders have learned to manage populations both for short-term financial benefit and long-term conservation of genetic variation. The future of tree improvement for both pines and hardwoods is bright, with more challenges, more available tools, and more opportunities for gain than ever before.

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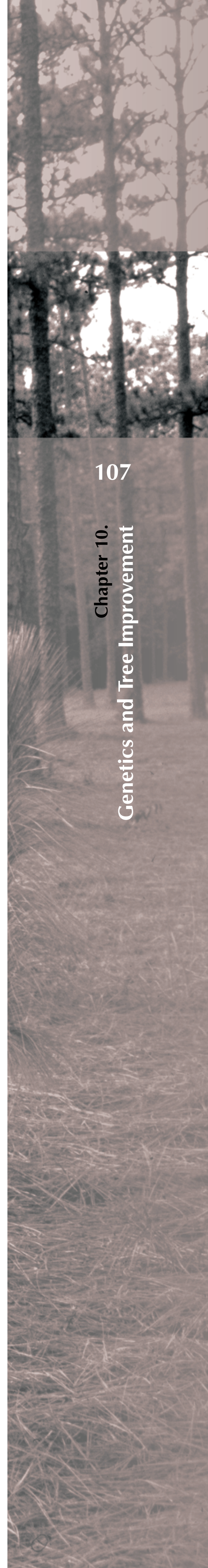

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Chapter 11.

Forest Mensuration with Remote Sensing:

A Retrospective and a Vision for the Future

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Abstract—Remote sensing, while occasionally oversold, has clear potential to reduce the overall cost of traditional forest inventories. Perhaps most important, some of the information needed for more intensive, rather than extensive, forest management is available from remote sensing. These new information needs may justify increased use—and the increased cost—of remote sensing.

INTRODUCTION

Forestry Information Needs of the 21st Century: Increasing Demand and a Changing Landscape

Demand for forest products is expected to increase rapidly during the 21st century. Population growth and economic development that increase the per capita consumption of forest products drive this trend. Global population, now approximately 6 billion, is estimated to increase by 900 million each decade for the next 50 years (Food and Agriculture Organization of the United Nations 1997). Most of this increase will occur in developing nations. Level of economic development strongly affects the demand for forest products. Worldwide income measured as gross domestic product increased by 109 percent between 1970 and 1994 (Food and Agriculture Organization of the United Nations 1997). Gross domestic product is estimated to rise from $20 trillion in 1990 to $69 trillion in 2030, with the most dramatic increases occurring in the developing nations (World Bank 1992).

Although the demand for forest products is increasing, global forest area is decreasing. Between 1985 and 1995, the area of the world's forests decreased by 180 million ha, an annual loss of 18 million ha (Food and Agriculture Organization of the United Nations 1997). Much of this loss resulted from the conversion of forest land to nonforest uses such as agriculture, pasture, or development. Environmental regulations and the desire to preserve native forests to maintain biodiversity further restrict harvesting of forest products. For example, harvest of timber from the national forests in the United States decreased from 12.0 billion board feet in 1989 to 3.5 billion board feet in 1997 as the focus of the U.S. Department of Agriculture Forest Service shifted from timber production toward wilderness preservation, protection of habitat for threatened and endangered species, watershed protection and restoration, and recreation (U.S. Department of Agriculture, Forest Service 1998).

Industry Trends Affecting Remote Sensing

Many forest industry trends will affect the future of remote sensing in forestry. Some of the most important are as follows:

- Smith and others (2003) note that industrial forest landowners have moved from an exclusive emphasis on supplying fiber toward a view of forest land as a biological asset that must be managed financially. If this is true, additional information inputs, such as remote sensing, that increase financial returns might well be justified.
- As noted earlier, industrial forest management is increasing in its intensity, partly because there has been an effective decrease in the amount of public land available for active management. It can make economic sense to spend more for information about the forest resource if the additional expenditure decreases the overall cost of inputs, particularly in the establishment and early growth phases.
- Information available from digital remote sensing can now be combined with other digital geospatial information to provide a complete scheduling picture from site preparation to harvest scheduling within an organization.

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Chapter Overview

Remote sensing has been actively integrated into forest inventory and management systems for more than half a century. The methods used now are still effective, but there is much potential for increased use of remote sensing both for traditional inventory purposes and to provide the information necessary to increase forest productivity. This chapter starts with a retrospective view of photo mensuration, and this is followed by a brief discussion of lidar remote sensing, one of the more promising new technologies for collecting data for forest inventory and monitoring. The discussion of lidar remote sensing is followed by an example that shows how information obtained by remote sensing could increase productivity and, thus, justify increased expenditure for information. The chapter closes with a brief discussion of barriers that must be overcome before remote sensing data are transformed into information directly useful to foresters.

WHERE WE HAVE BEEN: PHOTO MENSURATION

Vertical aerial photographs, while used in forestry since the late 1920s (particularly in Quebec and Ontario, Canada) (Spurr 1960), have been commonly used by foresters in the United States since the 1940s (e.g., Lund and others 1997). Forestry applications of aerial photography have been diverse, covering most aspects of the private and public goods provided by forests. However, a primary driver for forest photogrammetry has been forest mensuration, classically defined as "the determination of dimensions, form, weight, growth, volume, and age of trees, individually or collectively, and of the dimensions of their products" (Helms 1998). Substantial effort has gone into ways of using photographs as a means of determining volume by species accurately, precisely, and at the lowest possible cost. This effort has been reasonably successful, but applications of aerial cruising (e.g., Avery 1978) are becoming significantly less common in the United States, although quite common elsewhere (e.g., Canada).

There are several possible reasons for the decline of photographic mensuration. These can be summarized as follows:

1. The precision of photographically derived volume estimates is not as high as that of field-derived volume estimates.
2. Photographic interpretation and photogrammetry require specialized skills that are increasingly being supplanted by other ones, such as skills in the use of Geographic Information Systems (GIS), in accredited forestry programs (Sader and Vermillion 2000). This is occurring despite results from the most recent survey of desired entry-level competency and skill requirements which show that more entry-level forestry positions require knowledge of aerial photos (68 percent) than GIS (43 percent) (Brown and Lassoie 1998).
3. In much of the United States, forest land parcel size is steadily decreasing and accessibility increasing, thus decreasing the economic justification for (or even the feasibility of) photo mensuration.
4. Research in forestry remote sensing now focuses on actual and potential applications of newer airborne and spaceborne sensors, such as radar, lidar, and high-resolution digital optical sensors.
5. Wide use of medium-resolution spaceborne sensors such as the Landsat Multispectral Scanner and Thematic Mapper that are inherently digital has led to an expectation of ever more automated approaches to information extraction. Most algorithms in operational use are based almost entirely on the use of discriminant functions to categorize the brightness value vector from each pixel, even though this approach makes use only of hue. Hue is just one of the nine commonly identified elements of image interpretation, the others being shape, size, pattern, texture, association, shadows, resolution, and site (Olson 1960).
6. The actual or perceived benefits of using photos for inventory may be less than the costs incurred.

The last of these points is the most important, since we can assume that forest managers and scientists are obtaining the information needed without widespread use of ordinary photography. However, demands on forests are increasing, and the information required to sustainably manage forests in the face of this demand must also increase. Foresters are being asked to increase production of wood and fiber on an ever-decreasing land base while maintaining the important supplies of public goods (viable fish and wildlife populations, clean water, and recreational opportunities) that well-managed forests have always provided. To meet this challenge, forest managers will require new types of information, and remote sensing will help to supply these. If remote sensing fills our requirements, we will need to evaluate previous successes and failures and work to improve the match between information that can be objectively and accurately derived from remotely sensed data and the information needed for forest management (Wynne and others 2000).

Aerial Cruising

Aerial (photo) volume tables have been constructed for both individual trees and stands (Avery 1978). All are based on total tree height and visible crown diameter for individual trees. For stands, volume tables use stand height and percent crown closure at a minimum; many also include visible crown diameter classes. These tables use visible crown diameter as a surrogate for stem diameter and percent crown closure as a surrogate for basal area or stem density.

Tree heights are typically measured by stereoscopic parallax methods that employ a parallax bar or wedge and large-scale photographs. Shadow lengths can be used where terrain is level and stands are relatively open. While the accuracy of these measurements varies, on 1 inch = 20 chains photography, the average difference between ground- and photo-measured tree heights (with well-trained interpreters) is typically about 1 foot (Spurr 1960).

Visible crown diameter is measured with either a micrometer wedge or a dot-type scale. It can be argued that crown diameter is more accurately measured on large-scale photographs than on the ground, but measurements made on photographs are not directly comparable to those made on the ground because in photographs (1) only the dominant overstory trees are visible, and (2) the edges of any particular crown are obscured by the crowns of adjacent trees. For these reasons, photo-derived visible crown diameters are always underestimates of actual crown diameter. Even given these limitations, however, photo-measured visible crown diameter is often better correlated with actual tree and stand volume than field-measured crown diameter, because it is a measure of the tree's functional growing space (Spurr 1960). Measurement consistency varies widely with conditions, but can be expected to be on the order of 3 to 4 feet two times out of three on 1:12,000 photos (Paine 1981), which is why most volume tables are based on 3- to 5-foot diameter classes.

Percent (overstory) crown cover is the most subjective of the three direct forest measurements made from aerial photographs. It can simply be ocularly estimated or (more commonly) ocularly estimated with the aid of crown density scales. It usually is an overestimate of actual crown cover, because small canopy gaps are often not visible and shadows are often treated as trees. When typical forestry photo scales are used, standard errors do not exceed 10 percent, but the bias of an individual interpreter commonly ranges from 5 to 10 percent (Spurr 1960).

However, volume estimates derived by using stand photo volume tables are too imprecise for many uses, as standard errors of the estimate are likely to exceed 25 percent (Spurr 1960). While standard error can be reduced by increasing the number of samples, stand photo volume tables are also biased, requiring double sampling with regression using matched field- and photo-measured plots (e.g., Paine 1981). This casts doubt on the economic feasibility of photo mensuration for the smaller tracts that are increasingly common.

To summarize, timber volume can be estimated from aerial photographs. Bias exists because (1) a vertical aerial photographs image-only portions of the crowns of dominant overstory trees; and (2) subjectivity, particularly in crown closure estimation, leads to interpreter-specific bias. The latter bias also leads to unacceptably high standard errors of the estimate. Substantial training that is increasingly hard to obtain is required to make accurate direct tree and stand measurements based on aerial photographs. All these factors combined make the use of aerial inventory cost-effective primarily for large, relatively inaccessible areas.

Stratification

At this point one might reasonably ask why acquisition of photography is still so routine in many organizations charged with managing forest lands. The answer is, in part, that photos are used for more than just aerial timber cruising. Other uses include forest mapping for management planning, stress detection, forest area estimation, and land navigation, particularly in remote and infrequently mapped areas. These uses, however, are often secondary in comparison to the routine use of photos to stratify timber cruises. Stratification refers to “the subdivision of a population into strata (subpopulations) before sampling, each of which is more homogeneous for the variable being measured than the population as a whole” (Helms 1998).The advantages of stratification include (1) more precise estimation of the population mean (given properly constructed strata), (2) separate estimates for each subpopulation, and (3) reduced costs (Avery 1978, Avery and Burkhart 2002). As Avery and Burkhart note (2002), photographs are commonly used in stratified sampling to measure area, allocate field samples by volume classes, and plan fieldwork. For many organizations, photo acquisition can be justified by stratified sampling alone. This stratified sampling not only improves precision and reduces cost, but also changes the flow of information within an organization, with the result that there is a two-way flow between field personnel and the organization's information systems.

WHERE WE ARE GOING: THE EXAMPLE OF LIDAR

Lidar, or light detecting and ranging, sensors are the optical equivalent of radar. They use a light (laser) beam, rather than a microwave radar beam, to obtain measurements of the speed, altitude, and range of a target (Helms 1998). Most of the current small-footprint (< 1 m) laser altimeters can record the time (and sometimes intensity) of at least two returns, which often correspond to the top of the canopy and the ground. Many times, however, only one return is recorded, and it may correspond to vegetation, the ground, or some cultural feature. Sophisticated processing algorithms utilizing neighborhood approaches can usually identify the bulk of the nonground returns, thus making it possible to create a bare-earth digital elevation model (DEM) with suitable interpolation techniques. Once a DEM has been created, the first returns can be interpolated to produce a canopy height model, a representation of the vertical distance from any arbitrary point on the forest floor to the topmost part of the canopy above that point. Over forested areas, the canopy height model provides canopy height at any point imaged. The canopy height model differs from photogrammetrically derived tree height in one important way—the canopy height model is a continuous representation of the canopy surface, rather than the height at any one point. It should be noted that canopy height models can be derived photogrammetrically, but many automated image-correlation algorithms function comparatively poorly over tree canopies.

From this canopy height model, and sometimes in conjunction with coregistered optical data (Gougeon and others 2001, McCombs and others 2003, Popescu and others 2004) tree, or more typically stand, volume can be determined using direct measurements corresponding to those made from photographs, namely total height, visible crown diameter, and percent crown closure and or stem counts. Some of the same problems associated with direct measurements from photographs also pertain to lidar. These are as follows: (1) lidar sensors measure the distance only to the crowns of overstory vegetation; (2) direct measurements from lidar tend to be biased (e.g., Nilsson 1996); and (3) lidar data are very expensive unless some economy of scale is realized. However, there are two substantial benefits. Firstly, the data seem to be very amenable to processing by automated techniques (at least for conifers), which increases objectivity and thus precision. Secondly, when direct measurements are used in empirical models to estimate either field-measured, e.g., total height, or derived parameters, e.g., volume or basal area, stand-level predictions are unbiased (Means and others 2000, Naesset 2002).

Again, stand volume tables require measures of height, percent crown cover, and sometimes crown diameter. Lidar-based estimates of volume require similar measurements. Determination of individual tree heights using lidar data requires identifying individual overstory stems, usually through a local maximum approach that presumes that the highest point in a local neighborhood corresponds to the top of a tree. Although this technique is effective, errors of omission or commission can occur with improper window size. Popescu and others (2002) used the height of each cell in the canopy height model to set the size of a variable window based on tree height, making possible the successful prediction (R^2 = 90 percent and 85 percent, respectively) of maximum height and mean height of dominant stems (diameter at breast height > 5 inches) even on very small 0.017-ha (0.04-acre) plots of common southeastern conifer species. As plot size increases, the need to measure individual trees decreases, and the percentage of variance explained increases. For example, Means and others (2000) used lidar-derived variables—without identifying individual trees—to explain

93 percent of the variance in height on 0.25-ha (0.6-acre) stands of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco].

Percent crown cover is particularly easy to calculate using lidar data; it is simply the number of vegetation (nonground) returns above a certain height divided by the total number of returns. Crown diameter, however, has been a little more difficult to determine, as it requires accurate stem identification as well as a way of distinguishing one crown from the adjacent one. There is substantial ongoing work in this area, but Popescu (2002) determined crown diameter for each identified tree by (1) fitting a 4-degree polynomial with least squares using singular value decomposition in both the horizontal and vertical dimensions of the canopy height model, (2) identifying critical points for each of the two fitted functions based on the first and second derivatives of a three-point Lagrangian interpolation, and (3) averaging the distance between critical points on the two perpendicular profiles. For southern pines, this technique explained 62 to 63 percent of the variance in crown diameter for the dominant trees on 0.017-ha plots (Popescu and others 2002).

Like photos, then, lidar canopy height models can serve as the base data from which important variables can be measured; namely, visible crown diameter, percent crown closure or stem count, and total height. In addition, variables unique to canopy height models, particularly those relating to the distribution of heights within any one grid cell or plot perimeter, have been successfully used as independent variables in models employed to estimate plot- or stand-level parameters (e.g., Means and others 2000, Popescu and others 2002). Examples of this type of variable include the percent crown cover or height at a specific height percentile.

Volume has been successfully calculated for conifers by use of lidar-derived measures of height, crown closure, stem density, and/or crown diameter, or of variables relating to the distribution of heights within a particular grid cell. Popescu and others (2004) was able to explain > 80 percent of the variance in volume on small (0.017-ha, 0.04-acre), heterogeneous southern pine plots in Virginia's Appomattox-Buckingham State Forest using average (per plot) crown diameter obtained by applying a lidar-derived canopy height model as the only independent variable. Means and others (2000) were able to explain 97 percent of the variance in 0.25-ha (0.6-acre) Douglas-fir plots in the H.J. Andrews Experimental Forest using the 80^{th} and 0^{th} percentile of height (the height greater than the given percentage of lidar first returns) and the 20^{th} percentile of crown cover (proportion of first returns below the given percentage of total height). Many other studies have been similarly successful in estimating volume for coniferous plots or stands on the basis of lidar data.

Lidar-based forest measurements, while based on many of the same principles as photo-based measurements, such as using crown diameter as a surrogate for stem diameter, are typically more accurate and less biased than photo-based measurements. As with aerial photographs, bias exists because laser altimeters see only portions of the crowns of dominant overstory trees. However, increased levels of automation have led to substantial reductions in both interpreter-specific bias and the need for specialized training. Furthermore, lidar canopy height models afford the characterization of the whole population, rather than just a sample, of the dominant overstory trees in a specific area of interest. However, lidar data are still quite expensive for small areas on a per-unit basis, so lidar-based inventory, like photo analog inventory, is cost-effective primarily for large and/or relatively inaccessible areas. This description hardly characterizes the typical southern forest landscape, which is dominated by the holdings of nonindustrial private forest landowners.

THE LIKELY FUTURE NEED FOR ADDITIONAL REMOTELY SENSED DATA

The most commonly used standard for all remotely estimated forest measurements is field inventory, which typically employs remotely sensed data only for stratification. Thus in order to be widely accepted and used, remotely derived estimates of important forest biophysical parameters must have the same level of precision and accuracy as field-derived measurements, and be less expensive than they are. The lack of widespread adoption of these new technologies is de facto proof that this standard has not yet been met. As with all technological innovation, however, the cost per unit of information derived from remotely sensed data will continue to decrease, thus increasing their potential use for traditional inventory needs as a tradeoff with field costs. Another factor to be considered is that increasing forest productivity will require more remotely sensed data. Organizations will be willing to spend more for information if this expenditure results in increased productivity.

JUSTIFYING INCREASED USE OF REMOTELY SENSED DATA: THE EXAMPLE OF INTENSIVE (AND/OR SITE-SPECIFIC) FOREST MANAGEMENT

Most of the preceding discussion has focused on traditional assessment and inventory, an ongoing need whose importance is not likely to diminish in the near future. However, inventories using existing remote sensing technologies suffer, on the whole, from being more expensive and less accurate than field inventory for the small tracts that are coming to dominate the southern forest landscape. Thus they are not widely used in most instances. However, traditional assessment and inventory is only part of a larger picture of forestry information needs—needs that are likely to become urgent as management for increased production intensifies on some private tracts and the demands for multiple uses continue to drive public forest management. The following discussion addresses the potential effect of more intensive management of portions of the private land base on the future of forestry remote sensing.

Partially as a result of increased demand, and partially as a consequence of effective reductions in the land base resulting from (1) permanent land use conversion, (2) changes in public land management priorities, and (3) changes in the motivations and attitudes of nonindustrial private forest landowners, forest managers are increasingly being called upon to produce more wood or fiber from less land with shorter rotations. This challenge is being met with silvicultural tools that have agricultural analogs, such as site preparation, nutrient management, release from competition, and improved genetic stocks. The agricultural model can be pushed even farther as management intensifies; it can be argued that intensive forest management is as suited for precision forestry as intensive farm management is suited for precision agriculture. Mulla's (1997) definition of precision agriculture is as follows:

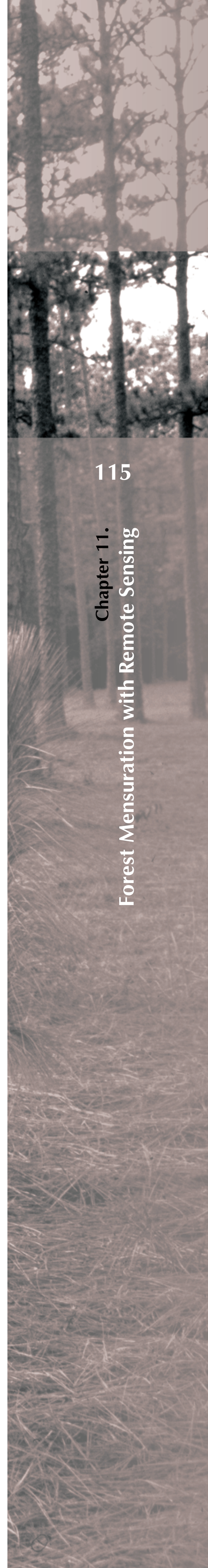
> Precision agriculture is an approach for subdividing fields into small homogeneous management zones where fertilizer, herbicide, seed, irrigation, drainage, or tillage are custom-managed according to the unique mean characteristics of the management zone.

Precision forestry is analogous to precision agriculture in that traditional management units (forest stands are analogous to agricultural fields) must be subdivided for specific prescription of silvicultural treatments; e.g., site preparation, fertilization, and release from competition.

However, there are some important differences between precision agriculture and precision forestry. Forest stands are typified by the (1) important array of public goods provided, such as clean water, wildlife habitat, carbon storage, and recreational opportunities; (2) much longer rotations required; (3) widespread use of helicopters for spraying; (4) species; (5) minimal use of irrigation; and (5) general lack of effective yield monitoring at the time of harvest. This last difference cannot be seen as problematic for precision forestry, as many experts (e.g., Pierce and Nowak 1999) agree that yield-based determination of preharvest spatial variability is a temporary solution, to be replaced by the use of remote sensing technologies. Given the relative importance and degree of development of forestry applications of remote sensing, precision forestry should not need to evolve through the yield-monitoring stage. Furthermore, precision forestry subsumes precision silviculture, precision inventory, precision growth and yield, and precision harvest scheduling, creating a complete information pathway. Remote sensing and related geospatial information technologies provide the inventory information necessary to (1) define the treatment unit for each silvicultural prescription and (2) provide the within-stand measurements of forest biophysical parameters necessary for growth-and-yield models and related harvest scheduling models.

Landowner records usually provide information on stand type, age, initial stocking density, and site preparation. Required parameters suited to remote estimation include leaf area index, current stem density, crown diameter, height, and species or species group. The last is especially helpful for timing and/or locating need for release from competition. Foliar nutrients can also be assessed using airborne hyperspectral, or, potentially, tailored handheld instruments (e.g., Bortolot and Wynne 2003), though such approaches have so far not been cost-effective when compared with lab analysis of foliar samples.

The relative need for and cost:benefit ratio of remotely sensed and precisely located *in situ* data must drive both the research in and the adoption of appropriate technologies. Furthermore within the wide variety of remotely sensed data that are well suited for precision forestry applications, researchers must find the best combination of



spectral resolution, spatial resolution, and canopy height information for estimating each required parameter. Data types include but are not limited to (1) canopy height models derived from lidar or digital photogrammetry, (2) high spatial-resolution optical data, (3) moderate-resolution multispectral data, and (4) hyperspectral data at a variety of spatial resolutions. Research being carried out by Government, industry, nongovernmental organizations, and universities is providing the base for improved integration of remote sensing in forest management. However, the gap between remote sensing research and accessible, useful information is still too large.

FROM DATA TO APPLICATIONS

It has been said that production forestry organizations make or lose money near the bottom rungs of the organizational ladder, not at the top (Smith and others 2003). Most field foresters have substantial experience with aerial photographs but have neither the time for nor the interest in processing images from digital remotely sensed data. In many cases, given the widespread use of and familiarity with aerial photographs in forestry, digital images can be subjectively analyzed for the wide variety of applications mentioned in this chapter. However, it can be argued that this model limits the potential utility of remote sensing to forestry, as it may not provide any net increase in information. The kinds of sensors that will help facilitate a net increase in forestry information derived from remotely sensed data include laser altimeters and hyperspectral scanners. The data these sensors yield will only be suited, in their raw form, for use by image analysts or other experts in the same field. Field foresters generally do not have the experience to qualify as experts in image analysis. They "require information, not images . . . ." (Oderwald and Wynne 2000).

The National Research Council, in their recent study on "Transforming Remotely Sensed Data into Information and Applications" (2001), identified three gaps that must be bridged to develop effective civilian applications of remote sensing:

1. The gap between raw data and the information needed by end users
2. The gap in communication and understanding between end users and those with remote sensing technical experience and training
3. The financial gap between data acquisition and usable applications

While these identified gaps apply across the spectrum of end users, they are particularly relevant for forestry. The report goes on to make the following recommendations, which are also quite pertinent to forestry:

1. Publicly available studies identifying the full range of short-term and long-term costs and benefits of remote sensing applications should be carried out by a full range of public and private stakeholders.
2. Cognate Federal Agencies should help fund and foster a wide variety of remote sensing training materials and courses.
3. Staff exchanges should occur between remote sensing users and producers.
4. Graduate fellowships and research assistantships should be sponsored by land grant, sea grant, and agricultural extension programs to encourage work at agencies that use remote sensing data.
5. Federal agencies need to expand their support for applied remote sensing research.
6. Formal mechanisms should be established to enable applications users to advise private and public sector providers on their requirements.
7. Data preservation is important and should be routinely addressed by all data providers.
8. Internationally recognized formats, standards, and protocols should be used whenever possible to facilitate data exchange and ease of use.

It is evident from the foregoing that forestry is not the only application area where there is a large gap between obtaining remote sensing data and translating the data into useful information. It is evident that concrete recommendations for bridging this gap have been made. As a community of forest scientists and managers, it is our responsibility to identify information needs of the future, and to make sure that adequate methods of meeting these needs can be made available.

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Forest Health

Chapter 12.

Healthy Forests in the South:

Challenges for the 21st Century

Theodor D. Leininger and Gregory A. Reams[1]

The health of forests in the Southeastern United States, as elsewhere in the country, is tied closely to the history of human presence on the land and the use and abuse of its abundant natural resources. In his discussion of the relationship between forest condition and the Native American presence in the Southeast, Rauscher (this book) makes two points. Firstly, the forests of 500 years ago are believed to have been very different from the forests of today. Forests were more open, and their condition was maintained by Native American fires. Secondly, once Native American populations were significantly reduced by disease, the forests began to change, becoming more dense and stratified. It is clear that few, if any, plants, animals, or microbes from other continents were present in North America before it was settled by Europeans. Whereas large segments of Native American populations were wiped out by foreign diseases within 100 years of European settlement on the continent, the effect of this settlement on Native American vegetation was less immediate, beginning in earnest in the middle to late 1800s, and continuing today.

The condition of precolonial southeastern forests and the changes to plant community structure that resulted from harvesting and the introduction of nonnative plants, animals, and microbes have been well summarized (Owen 2002). Owen (2002) lists several nonnative diseases, insects, and plants—including chestnut blight {*Cryphonectria parasitica* (Murrill) Barr [formerly *Endothia parasitica* (Murrill) Anderson & Anderson]}, Dutch elm disease [*Ophiostoma ulmi* (Buisman) Nannf.], butternut canker [*Sirococcus clavigignenti-juglandacearum* (N.B. Nair, Kostichka & Kuntz)], white pine blister rust [*Cronartium ribicola* (J.C. Fisch)], gypsy moth (*Lymantria dispar* L.), balsam woolly adelgid [*Adelges piceae* (Ratzeburg)], Japanese honeysuckle (*Lonicera japonica* Thunb.), and cogon grass [*Imperata cylindrica* (L.) Beauv.]—that have altered southeastern forests considerably and which continue to affect the biology of these forests. Those interested in learning more about these and other introduced pathogens, insects, and plants may start with volumes by Tainter and Baker (1996), Anon. (1985), and Miller (2003).

Much of the research and management effort of foresters, plant pathologists, entomologists, and weed scientists during the 20th century was directed to learning the bionomics of nonnative species, trying to contain their spread, and restoring ecosystems altered by their presence. Unfortunately, there have been few successes in controlling the advance of, and the damage caused by, most introduced species; and so the next generation of scientists and forest land managers will face growing challenges. In addition, forest health concerns in the South have expanded over the last several decades to include native and nonnative invasive insects, pathogens, and plants; disease complexes; urbanization; forest fragmentation; air pollutant effects; and increased risk of wildfire. Recently discovered nonnative insects, such as the Asian longhorned beetle [*Anoplophora glabripennis* (Motschulsky)] and the emerald ash borer [*Agrilus planipennis* (Fairmaire)], as well as the recently discovered nonnative disease sudden oak death (*Phytophthora ramorum* Werres), while not currently known to be in southeastern forests, present a threat to our forests because they are known to damage tree species endemic to the Southeast. Continued novel research and the development of new monitoring techniques offer the best hope for restoring and maintaining the health of southeastern forests.

In the opening years of the 21st century, as in those of the 20th century, concern about the health of the Nation's forests has influenced policy at the highest levels of the Federal Government. The Healthy Forest Initiative, announced in August

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2002 by President George W. Bush, directed Federal agencies to develop administrative and legislative measures that will help reduce the threat of catastrophic wildfire to America's forests and rangelands (Anon. 2003a). The U.S. House of Representatives responded by passing H.R. 1904, the Healthy Forests Restoration Act of 2003. While the Administration's intent was to allow greater flexibility in dealing with emergency situations, especially wildfires, through a reduction in complex procedures and by providing for more rapid decisionmaking, forest preservationists were concerned that revised rules would lead to indiscriminate clearcutting of the national forests.

As was the case 100 years ago, foresters and forest health professionals were thrust into the midst of controversy and given the opportunity to inform intelligent and rational discussion. The Healthy Forests Restoration Act of 2003 was signed into law on December 3, 2003 at which time it fell primarily to Federal scientists and managers, especially within the U.S. Department of Agriculture Forest Service (Forest Service), to develop the means of carrying out the act's requirements. In addition to addressing the reduction of "risks to communities, municipal water supplies, and some at-risk Federal lands from catastrophic wildfires," the act also seeks to "promote systematic information gathering to address the impact of insect infestations on forest and rangeland health" and "to improve the capacity to detect insect and disease infestations at an early stage, particularly with respect to hardwood forests" (Anon. 2003b).

Title IV of the act addresses insect infestations and specifically mentions the need to

> assist land managers in the development of treatments and strategies to improve forest health and reduce the susceptibility of forest ecosystems to severe infestations of bark beetles, including Southern pine beetles, hemlock woolly adelgids, emerald ash borers, red oak borers, and white oak borers on Federal lands and State and private lands; and to disseminate the results of such information gathering, treatments, and strategies.

Ten of the thirteen States served by the Southern Research Station are mentioned in connection with epidemic outbreaks of the southern pine beetle (*Dendroctonus frontalis* Zimmermann), a subject addressed by T. Evan Nebeker in this book, and Arkansas is cited as having an unprecedented outbreak of the red oak borer [*Enaphalodes rufulus* (Haldeman)]. Most interesting in the legislation is language urging the development of a system that will give forest managers early warning of catastrophic environmental threats to forests, thereby increasing the likelihood that such threats can be isolated and treated before they get out of control; and to "prevent epidemics, such as the American chestnut blight in the first half of the twentieth century, that could be environmentally and economically devastating to forests" (Anon. 2003b). Clearly, social and political forces in the United States are keenly interested in forest health issues of stand management, wildfire suppression, and outbreaks of native and nonnative insects, diseases, and invasive weeds; all of which present tremendous challenges and opportunities to forest health professionals in the 21st century.

The development of appropriate research and management responses begins by asking the right questions, so that needs can be determined based on the most important and immediate resource management concerns. Forest Service Research and Development asked the right questions in the report "Great Issues, New Solutions: A Summary of Forest Service Research Addressing the Four Great Issues," which was a response to the Healthy Forests Initiative. In the report, members of the Forest Service Research and Development staff in Washington, DC, enumerated the successes and ongoing research and development of scientists in the Agency's six research stations, Forest Products Laboratory, and Institute of Tropical Forestry (Anon. 2003c). They also asked questions that range from the more general, such as, "How do nonnative species invasions affect community structure, trophic interactions, and disease dynamics?" and "How do microbial organisms affect the environment?" to the quite specific, such as, where changes have been nearly irreversible, e.g., American chestnut [*Castanea dentata* (Marsh.) Borkh.], "How can we reestablish 'native' hybrids to restore forest values?" and "How do insects and pathogens affect fuel dynamics and flammability?" Some questions concern the management of ecosystems. Examples of these are, "How do natural and human disturbance processes and their interactions impact and shape ecosystems?" "How do fire, insects, and disease affect long-term productivity and carbon dynamics of ecosystems?" "How can we restore and maintain the health and productivity of disturbed ecosystems?" and "What is the potential for management intervention?"

Other questions relate to monitoring capabilities. Examples of these are, "Can we develop a quick response capability that provides essential scientific knowledge to help managers isolate new invasive species before they become established?" and "What methods can be developed to monitor and assess noxious weed impacts?" These, and a host of other related questions, will drive much of the work of forestry researchers and managers at the beginning of the 21st century.

Chapters in this section of our book address some of the more pressing issues of forest and ecosystem restoration, nonnative invasive pests, and native insects and diseases in ever-changing climatological, social, and political environments. The second chapter "Restoration of Southern Ecosystems" by John Stanturf, Emile Gardiner, Kenneth Outcalt, William Conner, and James Guldin presents an overview of restoration efforts in four ecologically varied and socially valued southern forest types. The authors observe that methods for restoration are more advanced for bottomland hardwoods and longleaf pine (*Pinus palustris* Mill.) forests than for deepwater swamp and shortleaf pine (*P. echinata* Mill.) forests. Bottomland hardwood restoration occurs mostly on private land; restoration of deepwater swamps and shortleaf pine forests occurs mostly on public land; and both private and public landowners are working to restore longleaf pine. Ownership has implications for the economics of forest land restoration. For example, current Federal programs that provide large easement payments, such as the Wetlands Reserve Program, are expensive and probably justified on poor sites. On better sites, restoration might pay for itself, with only cost sharing needed to establish the forest.

Stanturf, Gardiner, Outcalt, Conner, and Guldin emphasize that forests are resilient and that forest habitats will develop whether or not we intervene. The best we can do is to establish initial conditions that foster development of a forest appropriate to the site and present conditions. Attempts at re-creating ancient forests are likely to fail, because the conditions under which such forests developed cannot be replicated.

The third chapter of this section "Understanding and Controlling Nonnative Forest Pests in the South" by Kerry O. Britton, Donald A. Duerr, II, and James H. Miller discusses nonnative diseases, insects, and plants that have caused drastic changes in southeastern forest ecosystems and have cost a lot of money for management, containment, and research. The authors discuss the biological basis for the invasiveness of nonnative pests and what can be done about these pests. Included at the end of the discussion is a listing of Internet Web sites that are examples of a form of late 20th-century technology transfer that will undoubtedly endure, and be improved upon, in the current century.

The fourth chapter "Advances in the Control and Management of the Southern Pine Bark Beetles" by T. Evan Nebeker addresses recent advances in the control and management of native southern pine bark beetles and the outlook for future management. Nebeker also refers to several Web sites as examples of ways entomologists are distributing critically needed information about bark beetles and methods for controlling them. One of the changes Nebeker forecasts is that forest resource protection of the future will be aimed more at prevention of damage through the development and use of hazard- and risk-rating expert systems.

The fifth chapter "The Impact and Control of Major Southern Forest Diseases" by A. Dan Wilson, Theodor D. Leininger, William J. Otrosina, L. David Dwinell, and Nathan M. Schiff discusses the ongoing work to discover novel control methods for several hardwood and coniferous diseases that continue to beset forests of the Southeast. Tree diseases continue to present challenges for pathologists and forest managers even as we enter the second century after the father of forest pathology, Robert Hartig, wrote the first forest pathology textbook in 1874 (Tainter and Baker 1996). One of the findings of the Southern Forest Resource Assessment (Wear and Greis 2002) was that more forest land in the eastern part of the southeastern region will be converted to pine plantations, while new hardwood forests will be created on former agricultural land in the western portion of the region. Management of these forests that lack diversity of tree species, as well as third- and fourth-growth natural stands, will present many challenges to forest health researchers and forest managers. These challenges will need to be overcome in the midst of changing climatological and sociopolitical environments that will mean understanding and addressing dynamic ecological variables with smaller budgets and fewer people.

The sixth chapter "Monitoring the Sustainability of the Southern Forest" by Gregory A. Reams, Neil Clark, and James Chamberlain discusses how monitoring efforts have been modified and implemented to specifically address the evolving forest health concerns in the South, which now include native and nonnative invasive insects, pathogens, plants, plant-disease complexes, urbanization, fragmentation, air pollutant effects, and wildfire risk. Significant adaptations to the Forest Service's Forest Inventory and Analysis (FIA) sampling design have been made to accommodate monitoring needs of the Forest Health Monitoring (FHM) Program. These needs include the requirement to provide for early detection monitoring to evaluate status and change in forest conditions. To provide this function, FHM detection monitoring is now integrated with the new continuous (annual) forest inventory design currently being implemented by FIA.

The FIA Program has been in place since the 1930s and has reported changes in forested acres, forest type, growth, mortality, and harvest by State on a 6- to 10-year cycle since the program's inception. The current modifications to the FIA and FHM Programs are an outgrowth of the National Acid Precipitation Assessment Program (NAPAP) and the National Vegetation Survey (NVS). Both NAPAP and NVS employed FIA field plots in their surveys of acid rain and ozone impacts on forests. The use of FIA plots to do forest health monitoring under NAPAP led to the formation of FHM.

Initial FHM objectives focused on air pollution impacts on forests. However, since the early 1990s the program has expanded analysis and reporting capabilities to include criteria and indicators of sustainable forest management as identified in the Montreal Process. Specifically, FHM addresses conservation of biodiversity, maintenance of forest ecosystem health, and maintenance of soil and water resources by sampling additional indicators of forest health on an annual subset of FIA ground plots. The forest health indicators include crown condition, ozone injury, lichen communities, down woody debris, vegetation diversity and structure, and soil condition.

Detection monitoring data are used as an early warning system to decide whether implementation of evaluation monitoring is warranted to determine the extent, severity, and causes of undesirable changes. The development of novel and adaptive sampling techniques is also part of the FHM Program. Risk-based sampling is being used for early detection of sudden oak death and emerald ash borer. Eventually, risk-based and adaptive sampling techniques will become universal elements of any large-scale early detection program.

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Chapter 13.

Restoration
of Southern Ecosystems

John A. Stanturf, Emile S. Gardiner, Kenneth Outcalt, William H. Conner, and James M. Guldin[1]

Abstract—*Restoration of the myriad communities of bottomland hardwood and wetland forests and of the diverse communities of fire-dominated pine forests is the subject of intense interest in the Southern United States. Restoration practice is relatively advanced for bottomland hardwoods and longleaf pine (*Pinus palustris* Mill.), and less so for swamps and shortleaf pine (*P. echinata* Mill.). Most bottomland hardwood restoration is taking place on private land, while restoration of swamps and shortleaf pine occurs mostly on public land. Both public and private landowners are involved in the restoration of longleaf pine. Proper matching of species to site is critical to successful restoration of bottomland hardwoods. Techniques for longleaf pine restoration include the reintroduction of growing-season fire and the planting of longleaf pine seedlings and understory species. Safely reintroducing growing-season fire, however, may require initial manipulation of other vegetation by mechanical or chemical means to reduce built-up fuels.*

INTRODUCTION

Forest cover has declined globally, from an estimated 6 billion ha of "original" forest extent (that prevailing during most of the past 10,000 years) to the present 3.87 billion ha (Food and Agriculture Organization of the United Nations 2001, Krishnaswamy and Hanson 1999). Global assessments have identified changing land use, increasing demand for fiber, and exogenous stresses such as global climate change and air pollution as the factors causing loss of forest cover or degradation of forest condition. Many forests in the South are being subjected to similar disturbances and stresses. Restoration of the myriad communities of bottomland hardwood and wetland forests and the diverse communities of fire-dominated pine forests is the subject of intense interest in the Southern United States, as well as in other parts of the world (Parrotta 1992, Stanturf and Madsen 2002).

Our objective is to present an overview of the restoration of four ecologically varied and socially valuable U.S. forest types: bottomland hardwoods, swamps, Coastal Plain longleaf pine (*Pinus palustris* Mill.), and Interior Highland shortleaf pine forests (*P. echinata* Mill.). Restoration practice is relatively advanced for bottomland hardwoods and longleaf pine, and less so for swamps and shortleaf pine. Bottomland hardwood restoration is taking place mostly on private land. Restoration of swamps and shortleaf pine is occurring mostly on public land, while both public and private landowners are attempting to restore longleaf pine.

RESTORATION PRACTICES

Bottomland Hardwood Forests

Restoration of bottomland hardwoods occurs mostly in the Lower Mississippi Alluvial Valley (LMAV), predominantly in three States: Louisiana, Mississippi, and Arkansas (Stanturf and others 2000). The loss of bottomland hardwood forests has been more widespread in the LMAV than elsewhere in the United States. Clearing for agriculture reduced forest cover, and flood control projects drastically changed regional and local hydrologic cycles. Deforestation and

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drainage resulted in a loss of critical wildlife and fish habitat and reduced floodwater retention (MacDonald and others 1979, Sharitz 1992, U.S. Department of the Interior 1988).

The dominant goal of all restoration programs in the LMAV has been to create wildlife habitat and improve or protect the quality of surface water (Haynes and others 1995, King and Keeland 1999, Newling 1990). Afforestation of small areas (usually no more than 100 ha) within a matrix of active agriculture is typical. Although we know how to afforest many sites (Stanturf and others 1998), recent experience with the Wetlands Reserve Program in Mississippi illustrates the difficulty of applying this knowledge broadly (Stanturf and others 2001).

Afforestation is a process in which something can go wrong at any of several steps. Proper matching of species to site is critical to successful restoration (Baker 1977, Baker and Broadfoot 1979, Broadfoot 1976, Dicke and Toliver 1987, Groninger and others 2000, Krinard and Johnson 1985, Stine and others 1995). Availability of planting stock, however, probably has the greatest influence on the assignment of species to sites. Provenance and family within provenance may account for differences in survival and growth of common species (Dicke and Toliver 1987, Greene and others 1991, Jokela and Mohn 1976, Land 1983). Few foresters in the LMAV specify seed source constraints in purchasing agreements. This lack of quality control, or use of uncertified seed, could potentially reduce establishment success, productivity, and forest health.

Bare-root seedlings were used to stock 64 percent of afforestation area to 1997, with direct seeding applied on 29 percent of the afforestation area (King and Keeland 1999). Descriptions of direct seeding techniques are readily available (Allen and others 2001). Suitable techniques for collecting and storing seed of bottomland hardwood species are well documented (Bonner and others 1994).

Site preparation is used to condition the seed or seedling bed; decrease competing or undesirable vegetation, such as nonnative pests; reduce herbivore habitat; improve nutrient availability; and improve access for the planting operation (Baker and Blackmon 1978; Kennedy 1981, 1993). Site preparation can increase survival and improve early growth of hardwood planting stock (Baker and Blackmon 1978, Ezell and Catchot 1998, Russell and others 1998). Contractors use crews of both hand and machine planters, but differences between the operational rates of establishment success of the two methods are unknown (Russell and others 1998). Observations indicate that either method can be effective if properly supervised (Gardiner and others 2002, Michelak and others 2002).

Swamp Forests

Deepwater swamps, primarily baldcypress-water tupelo [*Taxodium distichum* (L.) Rich.-*Nyssa aquatica L.*], pondcypress-swamp tupelo [*T. distichum* var. *nutans* (Ait.) Sweet-*N. sylvatica* var. *biflora* (Walt.) Sarg.], or Atlantic white-cedar [*Chamaecyparis thyoides* (L.) B.S.P.] swamps, are freshwater systems with standing water for most or all of the year (Johnson 1990, Little and Garrett 1990, Wilhite and Toliver 1990). Other deepwater swamp types include cypress domes and depressional swamps such as the Okefenokee and Dismal Swamps. Large-scale commercial logging of swamp forests did not begin until the late 1800s (Davis 1975, Frost 1987, Little 1950). The introduction of the pullboat, and later the overhead-cableway skidder, enabled loggers to penetrate deeper into swamps and increased the amount of timber harvested. Although declining in area (Dahl 2000), there remain about 2 million ha of this forest type, mostly in second-growth timber (Kennedy 1982). There is less experience in the restoration of deepwater swamps than in the restoration of bottomland hardwoods (Mitsch and Gosselink 1993).

Although there has been little success in planting tupelo (DeBell and others 1982), better results have been obtained with Atlantic white-cedar (McCoy and others 1999, Phillips and others 1993) and baldcypress. Planting of cypress began in the 1950s with good success (Peters and Holcombe 1951). Rathborne Lumber Company planted nearly 1 million baldcypress seedlings on cutover land in Louisiana with 80 to 95 percent survival (Rathborne 1951). The Soil Conservation Service, however, experienced severe herbivory, and they recommended suspension of planting cypress until some means of controlling nutria (*Myocastor coypus* Molina) is developed (Blair and Langlinais 1960). Nutria damage to newly planted seedlings remains a serious problem (Brantley and Platt 1992, Conner 1988, Myers and others 1995), and nutria may also damage mature trees (Hesse and others 1996).

Planting of seedlings may be necessary to restore deepwater swamps because natural regeneration is unreliable in such areas (Conner 1988, Conner and others 1986, Hamilton 1984, Hook and others 1967, Kennedy 1982, Smith 1995). Planting 1-year-old baldcypress seedlings at least 1 m tall and larger than 1.25 cm at the root collar improves early survival and growth (Faulkner and others 1986). Planting in the late fall and winter is recommended so that seedlings become established during periods of low water (Mattoon 1915). Even when baldcypress is planted in permanent standing water, its height growth averages 20 to 30 cm/year when there are no herbivory problems (Conner 1988, Conner and Flynn 1989). Tree shelters generally increase the chances of survival of planted seedlings, but they do not prevent all herbivory (McLeod 2000).

A simple technique for planting seedlings in standing water has been tested successfully (Conner 1995, Conner and Flynn 1989, Funderburk 1995, McLeod and others 1996). This technique involves root pruning, or trimming off the lateral roots and cutting the taproot to approximately 20 cm. When this is done, the planter can grasp the seedling at the root collar and push it into the sediment until his or her hand hits the sediment. This method has worked well in trials with baldcypress and water tupelo, but not as well with green ash (*Fraxinus pennsylvanica* Marsh.) and swamp tupelo.

Longleaf Pine Forests

Longleaf pine was once the most prevalent pine type in the South, dominating as much as 25 million ha (Stout and Marion 1993). Burning of understory vegetation by Native Americans augmented the natural understory fire regime of longleaf forests (Abrahamson and Hartnett 1990, Christensen 1981, Robbins and Myers 1992, Ware and others 1993). Longleaf, however, was not well adapted to the forms of disturbance that accompanied European settlement (Frost 1993, Wahlenberg 1946). Logging, wildfires, and conversion to other pines or urban areas reduced longleaf pine to < 5 percent of its original area (Kelly and Bechtold 1990, Outcalt and Sheffield 1996).

Because of past history, an array of potential sites for longleaf restoration is available in various conditions (Outcalt and Sheffield 1996). This includes an estimated 0.5 to 0.8 million ha with intact longleaf overstory and understory (Noss 1989). Other areas with little or no longleaf in the overstory have understories that range from those having most of the native species to those that are devoid of species typical of the longleaf ecosystem (Outcalt 2000). This range of overstory and understory conditions exists across the spectrum of longleaf sites, from dry sandhills to wet savannas. Effective restoration techniques depend on the site type and current condition of the overstory and understory (table 13.1). Generally, techniques include reintroducing growing-season fire and planting longleaf pine seedlings and understory species. Safely reintroducing fire during the growing season, however, may require initial manipulation of other vegetation by mechanical or chemical means to reduce built-up fuels.

Fire suppression has allowed understory shrubs and hardwoods to expand significantly on many longleaf sites. Prescribed burning during the dormant season was introduced on public lands and larger private holdings to reduce fuel buildup, but often had no effect on the well-developed midstory. Reintroducing growing-season fires will adjust structure and relative composition, thereby reestablishing normal function. In the South, growing-season burning of stands with an intact longleaf overstory should be limited to the period from March to July, and late burning (into September) avoided because longleaf pine is then susceptible to fire-caused mortality (Robbins and Myers 1992). Nevertheless, reintroducing growing-season fires into xeric longleaf communities that have not been burned for a long time usually causes some mortality of large trees from 1 to 3 years after the first burn. The exact cause of this is unknown, but mortality seems to be related to smoldering combustion of the excessive litter buildup around the base of larger stems. Several closely spaced dormant season burns should be used to reduce litter buildup prior to any growing-season burning. Caution should be exercised, however, where slopes > 15 percent are burned frequently, because significant erosion can result when mineral soil is exposed in such terrain.

On many sites, supplemental treatments can accelerate restoration of red-cockaded woodpecker (*Picoides borealis* Vieillot) colonies or forest cover at the urban interface zone. Mechanical treatments (chain saw felling, girdling, or chipping onsite) can rid stands of midstory hardwoods (Provencher and others 2001). Such treatments can be followed with a prescribed burn to stimulate grasses and forbs and control hardwood sprouts. Midstory material left onsite should be allowed to decay before the first prescribed burn. Fuel is often sparse in areas dominated by scrub oak, so these areas are often

Table 13.1—Longleaf pine restoration prescription depends upon site type and the condition of the overstory and understory

	Overstory and understory condition		
Site type	Longleaf overstory, woody midstory and understory	Other species in overstory, understory intact	Former longleaf site, no overstory or understory
Xeric and sub-xeric sandhills	Reduce fuel loads with dormant season burns, introduce summer burns[a] to invigorate grasses;[b] consider mechanical[c] or chemical[d] treatments	Chop and burn scrub oak; remove slash pine;[e] plant longleaf;[f] no or minimal site preparation; introduce summer burns	Remove other trees; chop and burn;[g] plant longleaf; plant[h] or direct seed wiregrass;[i] roll in; plant wiregrass plugs under longleaf overstory; introduce summer burns
Flatwoods and wet lowlands	Reduce fuel loads with dormant season burns, introduce summer burns on short intervals[j]	Reduce fuel loads, remove other pines; chop, reduce logging slash; plant longleaf; introduce summer burns	Remove other trees; chop and burn; plant longleaf; plant or direct seed wiregrass; introduce summer burns
Uplands	Reduce fuel loads with dormant season burns, remove other pines; introduce summer burns;[k] consider mechanical or chemical treatments[l]	Reduce fuel loads; remove other overstory pine, plant longleaf; introduce summer burns	Remove other trees; chop and burn; plant longleaf; plant or direct seed wiregrass; introduce summer burns

[a] Glitzenstein and others (1995).
[b] Greenberg and Simons (1999).
[c] Provencher and others (2001).
[d] Brockway and Outcalt (2000).
[e] Outcalt and Lewis (1990).
[f] Barnett and others 1990).
[g] Burns and Hebb (1972).
[h] Outcalt and others (1999).
[i] Hattenbach and others (1998).
[j] Waldrop and others (1987).
[k] Boyer (1990).
[l] Boyer (1991).

difficult to burn. Mechanical treatments with a small single-drum chopper with no offset can be used to knock over and compress the oaks into a ground layer that will carry a prescribed burn after curing.

Restoration is more rapid if burning is supplemented by use of an herbicide such as hexazinone (applied at a rate of 2 kg/ha of active ingredient); desired results can be obtained with one herbicide application and one burn (Brockway and Outcalt 2000). This treatment is effective at topkilling midstory hardwoods with only short-term reductions in understory grasses and forbs on sandhills sites (Brockway and others 1998), although cover of desirable woody species may be reduced for a period. However, herbicide need be applied only once; periodic prescribed burns will maintain the understory condition.

Longleaf seedlings can be bare-root or container, and can be planted by hand or by machine (Barnett and McGilvray 1997, Barnett and others 1990). Site preparation, other than that outlined above, should be avoided to preserve the understory. A planter with a small scalper blade attached can boost bare-root seedling survival if grass cover is > 60 percent (Outcalt 1995). Acceptable survival can be obtained with container seedlings and no site preparation other than burning, although survival may be increased by hexazinone application on areas with heavy scrub oak competition.

The understory is best restored simultaneously with replanting of longleaf seedlings to take advantage of the reduced competition and ease of operability. The critical factor is reestablishment of the grass component because of its important role as a fuel source for ecosystem maintenance.

Most work to date has focused on the eastern portion of the range and reestablishment of wiregrass (*Aristida beyrichiana* Trin. & Rupr.) (Means 1997, Outcalt and others 1999, Seamon 1998). Wiregrass also can be established by planting plugs under an existing longleaf overstory in the spring, in strips spaced about 1 m apart. Fertilizer applied only to the wiregrass in the second- or third-growing season will stimulate growth (Outcalt and others 1999). Wiregrass also can be directly seeded between rows of trees in plantations (Hattenbach and others 1998). Other native grasses can be included in seed mixes. Pineywoods dropseed [*Sporobolus junceus* (P. Beauv.) Kunth.], like wiregrass, will produce seed following burning. In addition to selected common species such as dwarf huckleberry [*Gaylussacia dumosa* (Andrews) A. Gray.] that do not reinvade or survive, some rare species will probably have to be reintroduced (Glitzenstein and others 1998, Walker 1998).

Shortleaf Pine Forests

Shortleaf pine in the Ouachita Mountains also evolved with fire (Foti and Glenn 1991). Fire return intervals before European settlement were from 2 to 40 years, but today fire has been severely suppressed in this forest type (Foti and Glenn 1991). Throughout the 1970s and 1980s, efforts to recover the endangered red-cockaded woodpecker in the Ouachita Mountains had been largely unsuccessful, despite evidence that it once inhabited the region. Managers realized that the decline of the bird was related to decline in suitable habitat, and restoration of the shortleaf-bluestem community became a priority. Roughly 63,000 ha of the Ouachita National Forest were allocated to restoration of pine savanna (U.S. Department of Agriculture, Forest Service 1996).

Restoration of shortleaf pine savanna requires several changes in management. First, sawtimber rotation is lengthened from 70 to 80 to 120 years, which allows longer retention of suitable cavity trees for the woodpecker and results in larger and higher quality pine sawtimber at harvest. Second, the pine component is subjected to a low thinning to reduce overstory basal area. This provides more light and promotes herbaceous growth; a side benefit is a lowered susceptibility to southern pine beetle (*Dendroctonus frontalis* Zimmermann) attack. Third, the hardwood midstory component, which developed in the 60-year period of fire exclusion, must be removed. Fourth, periodic prescribed burns are reintroduced on a 3- to 5-year cycle to reestablish the native prairie flora. Rootstocks and seed for these woodland savanna plants are still viable in the area, and no special effort other than reintroduction of burning is needed for their reestablishment. Finally, artificial cavities are installed in some of the pines for immediate use by the red-cockaded woodpecker.

DISCUSSION

Despite the handicap of incomplete knowledge, attempts to restore native forests abound. Spencer (1995) drew three lessons from efforts to create woodlands in the United Kingdom. These accurately portray the state of the art of restoration ecology applied to forests:

- Forests are amazingly resilient, and functioning forest habitat will develop whether or not we intervene, given sufficient time.
- Attempts at re-creating ancient forests are doomed to fail because the conditions under which they developed cannot be replicated.
- We can at best design and implement the proper initial conditions that will foster development of a forest appropriate to the site and present climate.

The economics of private land restoration will increase in importance. Current Federal programs that provide large easement payments, such as the Wetlands Reserve Program, are expensive and probably justified on poor sites. On better sites, restoration might pay its own way, with only cost sharing needed to establish the forest. Landowners could derive periodic income from timber production and other nontimber products, including ecological services such as carbon sequestration.

Restoration forests could sequester vast amounts of carbon. Baldcypress, for example, can live longer than a thousand years and attain net primary productivity values as great as 20 t/ha/year (Conner and Buford 1998). Biofuels produced from cottonwood (*Populus* spp.) or willow (*Salix* spp.) would not only sequester carbon in soil organic matter but would have the further carbon-offset benefit of replacing fossil fuels (Stanturf and Madsen 2002).

Attention to the effects of restoration at landscape scales is highlighting the need to consider how restored forests will be managed, and raises the question of the degree to which natural disturbance regimes can be incorporated into forest management. In the shortleaf pine restoration program, for example, efforts are concentrated on establishing restored conditions over the full extent of the landscape, primarily for the benefit of the red-cockaded woodpecker. But sustainability of this habitat type in the long term requires that some portion of the landscape should be managed in age classes of 30 years and younger, which are not useful as nesting habitat for the endangered woodpecker.

The forest that results from restoration or rehabilitation may never recover to the original state for all functions (Bradshaw 1997, Harrington 1999). We accept as restoration any endpoint within the natural range of managed forests where self-renewal processes operate (Stanturf and Madsen 2002, Stanturf and others 2001). This approach offers a broader context for restoration on private land, and landowners with management objectives other than preservation are able to contribute to ecosystem restoration (Stanturf and Madsen 2002, Stanturf and others 2001).

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Chapter 14.

Understanding and Controlling
Nonnative Forest Pests in the South

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Abstract—*Invasive nonnative forest pests are multiplying and spreading in every forest type in the Southern United States. The costs of controlling these pests have become extremely high, and the damage they cause to ecosystem composition, structure, and function continues to increase. Plants imported for potential release for forage, crops, soil reclamation, and ornamental purposes are not evaluated for invasiveness. Insect pests and diseases arrive in infested nursery stock, wood products, pallets, and dunnage, in spite of our regulatory system, which has been overburdened by the rapid increase in international trade. The biological basis for the invasiveness of nonnative pests and possible means for dealing with them are discussed.*

INTRODUCTION

Nonnative insects, pathogens, and plants continue to flow into the United States, as they have for the past 500 years (Committee on the Scientific Basis for Predicting the Invasive Potential of Nonindigenous Plants and Plant Pests in the United States 2002). With global trade comes a mixing of once-separated organisms, often with harmful effects on their new natural systems and substantial costs for mitigation. Invasive nonnative pests pose major challenges. We are challenged to (1) detect and minimize entries, (2) detect critical outbreaks and mobilize rapid responses, (3) monitor existing invasive populations and apply integrated pest management (IPM) programs, and (4) disseminate information about the nature of the problem of invasive pests and possible means of its solution. Executive Order 13112, issued in 1999, established the National Invasive Species Council, comprised of the heads of eight Federal Agencies. This Executive order defined an invasive species as a species that is (1) nonnative (or alien) to the ecosystem under consideration, and (2) whose introduction causes or is likely to cause economic or environmental harm or harm to human health. The council finalized in 2001 a "National Management Plan: Meeting the Invasive Species Challenge," which is aimed at coordinating offensive and defensive efforts among the Government Agencies, nongovernmental organizations, and the public. New national initiatives in all elements of an IPM approach to invasive species are planned and specified, with actual regulatory and policy changes anticipated, as appropriations become available. This chapter addresses the biological and social bases for the current predicament, identifies the most damaging invasive pests, gives recommendations for their control, and formulates initiatives required for the defense of our native forests.

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Economic and Ecological Effects

Invasive nonnative pests cost the United States an estimated $137 billion per year (Pimentel and others 2000). This figure does not include the costs of species extinctions. Of the 958 listed threatened and endangered species, 57 percent are at risk primarily because of competition with and predation by invasive nonnatives (Reichard and White 2001). It is difficult or impossible to accurately and objectively determine the cost of species extinctions or of less severe damage to species and habitats. For this reason, natural resource losses are more difficult to estimate than agricultural losses. Forest product industries, although they represent only a small part of total forest value, are easier to evaluate economically. National losses in traditional forest products due to nonnative invasive insects and pathogens were estimated at $4.2 billion per year (Pimentel and others 2000). It has been estimated that 360 nonnative insects have become established in American forests (Liebhold and others 1995).

Data specific to southern forests are scarce, especially for invasive nonnative weeds. Although no comprehensive figures specific to forestry losses due to nonnative weeds are available, the State of Florida has compiled some impressive statistics for invasive nonnative weeds in wetlands. Their control costs for melaleuca (*Melaleuca* spp. L.) alone are $3 to $6 million per year and for purple loosestrife (*Lythrum salicaria* L.) $45 million per year. Florida spends $14.5 million per year to control *Hydrilla* spp. L.C. Rich., and still estimates losses in recreation values for just two lakes at $10 million per year (Pimentel and others 2000).

Since European settlement, nonnative forest pests have changed the composition and function of eastern forests in important ways. For example, as early as 1864, American chestnut [*Castanea dentata* (Marsh.) Borkh.] trees were being eliminated from the Southern Appalachian Mountains, although the cause was not discovered until 1932. Ink disease, caused by the nonnative pathogen *Phytophthora cinnamomi* Rands, virtually eliminated American chestnut in valleys and coves and gradually was extending upslope when chestnut blight [*Cryphonectria parasitica* (Murrill) Barr] arrived and removed the remaining trees, which occupied drier ridges (Crandall and others 1945, Hansen 1999). *P. cinnamomi* continues to impact southern forests, causing littleleaf disease of shortleaf pine (*Pinus echinata* Mill.), root rot on Fraser fir [*Abies fraseri* (Pursh) Poir.] Christmas trees, a decline syndrome in loblolly pine (*P. taeda* L.), and hundreds of other hosts. This same fungus killed 79 percent of the flora in the forests of Western Australia (Weste and Marks 1987) and was recently cited as causing an oak (*Quercus* spp. L.) mortality epicenter in Mexico (Tainter and others 1999).

The oak component in Kentucky, Virginia, and North Carolina is under attack from the advancing front of gypsy moth [*Lymantria dispar* (L.)]. The same forests may soon be threatened by a new species of *Phytophthora* now causing sudden oak death (*Phytophthora ramorum* Werres, de Cock & Man in't Veld) in parts of California. An outbreak of this disease in Oregon is being eradicated, but pathologists are conducting surveys to determine whether other, undetected outbreaks may exist. Beech bark disease (*Neonectria galligena*), dogwood anthracnose (*Discula destructiva* Redlin), and butternut canker (*Sirococcus clavigignenti-juglandacearum*) have reduced host populations as they spread through the understory. Adelgids [*Adelges piceae* (Ratzeburg)] attacking balsam fir [*Abies balsamea* (L.) Mill.] are causing losses of rare and threatened species dependent upon the special habitat associated with the fir (Alsop and Laughlin 1991). Similar losses are anticipated in hemlock forest types (*Tsuga* spp. Carr.) as the hemlock woolly adelgid [*Adelges tsugae* (Annand)] spreads south.

The threats posed by diseases and insect pests have long been recognized by the forestry community. In contrast, invasive nonnative forest plants are more insidious and have received far less attention from foresters. Although weeds cause losses roughly equivalent to those caused by insects and diseases in agricultural systems (Pimentel 1993), the frequent reliance of nonnative plants on disturbance as an entrée to invasion has led to the expectation that such invasions, therefore, are less significant in forests. However, this expectation has proven to be false for two reasons. First, a number of invasive weeds establish successfully without disturbance. Among them are garlic mustard [*Alliaria petiolata* (Bieb.) Cavara & Grande], oriental bittersweet (*Celastrus orbiculatus* Thunb.), and melaleuca. Second, forests are subject to frequent disturbances of various origins. Invasive nonnative plants often proliferate after harvests, fire, windthrow, or hurricanes, which create gaps of disturbed habitat. The increasing occupation of forests by nonnative plants has also been linked to increasing anthropogenic disturbance (Stapanian and others 1998). Such plants inhibit regeneration of native plants and reduce forest growth and yield. Invasive nonnative weeds can alter ecosystems by changing nutrient cycling, geomorphology and physical structure of the site, drainage patterns and water flow, sedimentation rates, and disturbance regimes. They displace native flora by competition, and thus alter wildlife habitat (D'Antonio 2001, Reichard and White 2001).

Pathways

Many invasive forest plants were intentionally introduced as ornamentals or forage crops (table 14.1), often as a result of Government-sponsored plant introduction programs (Mack and Lonsdale 2001). Some of these plants are still being sold as nursery stock. Herbaceous weeds are more likely to have been introduced as seed contaminants or in soil used as ballast (Reichard and White 2001).

In contrast, most nonnative insects and pathogens were introduced unintentionally as contaminants on nursery stock (U.S. Congress Office of Technology Assessment 1993). The sudden oak death pathogen probably arrived on infected rhododendron (*Rhododendron* spp.) nursery stock. Its origin is unknown. The American strains of this pathogen cause only small leafspots and twig blight on rhododendron and many other hosts, but cause lethal cankers on oaks in coastal regions surrounding the San Francisco Bay (Rizzo and others 2002). Species killed by the pathogen include coast live oak (*Q. agrifolia* Nee), tanoak [*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.], and California black oak (*Q. kelloggii* Newb.). Nursery sanitation practices and fungicide applications can sometimes mask infection, particularly in the case of *Phytophthora* species, and may allow infected material to pass inspection. Sometimes an import host is only slightly susceptible to a disease but may harbor the nonnative pathogen, as infected Chinese chestnut (*Castanea mollissima* Blume) probably harbored chestnut blight. The associated pathogen is unnoticed on the resistant host, but under particularly favorable conditions may sporulate and spread to more susceptible native species. Nurseries with overhead irrigation systems often provide this ideal environment.

Table 14.1—Examples of intentionally introduced invasive nonnative weeds

Common name	Scientific name
Melaleuca	*Melaleuca*
Australian pine	*Pinus nigra* Arnold
Japanese climbing fern	*Lygodium japonicum (*Thunb. Ex Murr.) Sw.
Old World climbing fern	*L. microphyllum* (Car.) R. Br.
Kudzu	*Pueraria montana* (Lour.) Merr.
Mile-a-minute weed	*Ipomoea cairica* (L.) Sweet
Tree-of-heaven	*Ailanthus altissima* (P. Mill.) Swingle
Oriental bittersweet	*Celastrus orbiculata* Thunb.
Silktree or mimosa	*Albizia julibrissin* Durazz.
Chinaberrytree	*Melia azedarach* L.
Winged burning bush	*Euonymus alata* (Thunb.) Sieb.
Bush honeysuckle	*Lonicera* spp. L.
Cogongrass	*Imperata cylindrica* (L.) Beauv.
Chinese silvergrass	*Miscanthus sinensis* Anderss.
Chinese privet	*Ligustrum sinense* Lour.
Tallowtree	*Triadica sebifera* (L.) Small
Chinese wisteria	*Wisteria sinensis* (Sims) DC.
Japanese honeysuckle	*Lonicera japonica* Thunb.

Another common source of nonnative insects and pathogens has been the trade in wood and wood products (U.S. Congress Office of Technology Assessment 1993). In the United States, 35 percent of all softwood consumed is imported, and up to 70 percent of all international cargo arrives supported by solid wood packing material. The recent arrival of the Asian longhorned beetle [*Anoplophora glabripennis* (Motschulsky)] in solid wood packing material has focused attention on this previously loosely regulated pathway. In addition to established populations in New York and Chicago, the beetles have been intercepted in 26 warehouse locations in 12 other States. Solid wood packing material is usually constructed of poor-quality wood, often from trees damaged or killed by pests. Bark remnants increase the likelihood of pest association, and boards with bark attached can be hidden in middle layers of products such as wooden spools. One study found 2,500 live insects in 29 short log bolts used to brace granite blocks in metal containers (Allen 2001).

The particularly invasive nature of many nonnative forest pests first became apparent near the close of the 19th century. Over the past 100 years, plant pathologists, entomologists, and weed scientists have developed a broadly applicable concept of IPM. In this chapter, we will describe a few important nonnative forest pathogens, insect pests, and invasive plants, and will discuss their entry pathways, control strategies, and ecological and environmental impacts. We will apply the lessons learned from these examples to develop recommendations for a more proactive IPM approach to preventing future invasions.

INVASIVE NONNATIVE FOREST PATHOGENS

Nonnative pathogens are presumably more disruptive than native pathogens because they have not coevolved with their new host. Therefore, the host lacks resistance genes, unless some generalized response to attack provides adequate protection against the new pest. Chestnut blight, dogwood anthracnose, and Dutch elm disease [*Ophiostoma ulmi* (Buisman) Nannf.] will be used here to provide examples of such "unnatural" interactions.

Chestnut Blight

In 1904, H.W. Merkel, Chief Forester of the New York Zoological Society, noticed that chestnut trees in the Bronx were dying. At first, recent droughts were suspected as the cause, but later a fungus, now called *Cryphonectria parasitica* (Murrill) Barr, was discovered killing the bark and cambial layers of American chestnut. Oriental chestnuts (*Castanea* spp.) were unaffected, and asymptomatic nursery stock is believed to have provided the initial inoculum for this epidemic. Despite every effort to quarantine, remove, and burn infected trees and to protect the uninfected trees with fungicidal sprays, the fungus spread within 40 years throughout the range of American chestnut. Because this is a nonsystemic bark disease, the roots of chestnut survive and produce coppice, but the sprouts eventually become diseased. The fungus is a weaker pathogen but can survive on oak; e.g., live (*Q. virginiana* Mill.), post (*Q. stellata* Wangenh.), scarlet (*Q. coccinea* Munchh.), and white (*Q. alba* L.), as well as oriental chestnut. Thus there is no hope of the disease ever dying out for lack of host material (Anagnostakis 1987, Liebhold and others 1995).

Two separate avenues of research have been taken to reduce the impact of chestnut blight: (1) hypovirulence and (2) resistance breeding. Hypovirulence is a debilitating disease of the fungus, caused by infection by hypoviruses. In the 1950s, researchers in Italy noted that cankers appeared to be callusing over and healing due to hypoviruses. Italian chestnut (*C. sativa* Miller) recovered and remains a viable crop today. In the United States, unfortunately, greater diversity exists in vegetative compatibility (v-c) groups of the fungus than is found in Europe. *Cryphonectria parasitica* strains in the United States are less likely than European strains to fuse mycelium and exchange the virus. Much effort has been directed at getting the virus into the recalcitrant strains. Recently researchers succeeded in getting synthetic DNA coding for viruslike ribonucleic acid particles into the DNA of uninfected strains. It is hoped that the synthetic genes will eventually spread through sexual reproduction into all v-c groups, thus promoting the spread of the hypovirulence.

Early attempts to incorporate Asian resistance genes into American chestnut by crossbreeding gave disappointing results. The hybrids often resembled the Asian species rather than the majestic American parent, because of backcrossing to the Asian parent. The American Chestnut Foundation (ACF's) has selected third-generation backcrosses, containing 94 percent American chestnut genes and possessing varying levels of resistance. Their results indicate that some individuals have resistance genes acquired from the American parents as well. The time and cost required to identify resistant progeny could be reduced greatly by the use of marker-assisted selection for the resistance trait. The ACF hybrids were developed mainly from three Chinese cultivars. The ACF intention now is to broaden their breeding program by incorporating more Chinese sources of resistance and outcrossing to locally adapted American parents (Hebard and others 2000).

Dogwood Anthracnose

The cause of dogwood anthracnose is a fungus named *Discula destructiva* Redlin. The details of introduction and origin are not precisely known, but the lack of genetic diversity in the pathogen points to a recent introduction (Daughtrey and others 1996). The relative resistance of Chinese dogwood (*Cornus kousa* Hatch) suggests that the fungus has Asian origins. In addition, the disease was first detected in North America almost simultaneously near two port cities, on opposite coasts, shortly after trade with China was reopened in 1975. Features of pathogen biology, forest history, and the silvical characteristics of the tree all help explain the severe damage caused by this disease.

The fungus produces only asexual spores, but these grow in great numbers in pustules with a slimy matrix, mostly on the underside of the leaf. They are well adapted to spread in splashing rain. The wet period necessary for infections is unusually long (24 to 48 hours), which partially explains why the disease is more severe in the mountains, at higher elevations, on north-facing slopes, and near streams and waterfalls where moist conditions are common. Wet periods within 2 weeks of each other were needed to maintain epidemic development, whereas dry periods of a month or more greatly reduced the infection rate (Britton 1993). These requirements greatly slowed the spread of the fungus as it reached the southern edge of the Appalachians.

Eastern flowering dogwood (*C. florida* L.), the main host in southern forests, is a rapid colonizer of gaps, and its population probably expanded greatly after the demise of chestnut and as a consequence of logging activity in the early 20th century. This shade-tolerant species persisted after gap closure, surviving under as little as 2 percent ambient light in the photosynthetically active range (Chellemi and Britton 1992). Trees growing in these conditions had few carbohydrate reserves and could not withstand the stress of repeated defoliation when a susceptible population and environmental conditions favorable for epidemic disease development coincided.

Since it was first reported in the southern region in 1986, anthracnose has spread into 277 counties (Anderson and others 1994; U.S. Department of Agriculture, Forest Service 1999). The epidemic is now spreading West more than South or East and is generating much concern in Michigan, Indiana, Ohio, and Missouri. Flowering dogwood impact plots in western North Carolina, where the climate is very favorable for the disease, have incurred 56 percent mortality since 1991 (http://fhpr8.srs.fs.fed.us/2001Conditions/index.html). Disease severity today is much greater at the epidemic front than behind it, for several reasons: (1) the dry weather experienced recently in the South has probably reduced the number of secondary disease cycles occurring each year, (2) the loss of so many dogwoods growing in microsites optimal for fungal development reduced the inoculum load for the surviving trees, (3) survivors are growing on sites less favorable for fungal development, and (4) survivors may possess some genetic resistance.

No economically feasible control measures have been found to protect dogwood in forest environments. A 10-point program for reducing disease severity was developed for landscape trees. The main goal of the program is to improve tree vigor and thus reduce disease impact (Bailey and Brown 1991). The 10 points are:

1. Select healthy trees to plant.
2. Purchase trees from a reputable nursery; do not transplant trees from the wild.
3. Select good planting sites to promote rapid foliage drying.
4. Use proper planting techniques.
5. Prune and destroy deadwood and leaves yearly, and prune trunk sprouts in the fall.
6. Water weekly in the morning during drought; do not wet foliage.
7. Maintain a 4- to 6-inch deep mulch around trees; do not use dogwood chips as mulch.
8. Fertilize according to soil analysis.
9. Use proper insecticides and fungicides where appropriate.
10. Avoid mechanical and chemical injury to trees.

Hybrids of *C. florida* x *C. kousa* resistant to anthracnose were developed at Rutgers University. Selections from resistant *C. florida* survivors at Mt. Catoctin National Park were propagated and tested by the University of Tennessee and entered the market in 2002.

Dutch Elm Disease

The story of Dutch elm disease [*Ophiostoma ulmi* (Buisman) Nannf.] clearly illustrates a weak link in the defensive cordon of our quarantine regulations. Current U.S. regulations prevent entry only of pests that are (1) not present in the United States; or (2) present, but of limited distribution, and subject to an active eradication/control program.

To be effective, inspectors must be able to find and identify new invaders before they enter and become established. Unfortunately, the necessary taxonomic information did not exist in the case of Dutch elm disease. A new invader arrived and was mistakenly assumed to be the original Dutch elm disease fungus, which had become widespread and consequently not subject to regulation.

The new invader was much more aggressive than the first Dutch elm disease species. Thus there have been two separate epidemics of this vascular wilt in North America, Europe, and Asia. The original causal fungus, *Ophiostoma ulmi* (Buisman) Nannf., was probably of Himalayan origin and reached the Netherlands by way of the Dutch East Indies (Brasier 1990). It was introduced from there into North America in the 1930s.

The second, visually similar species, *O. novo-ulmi* Brasier, was not discovered in the American Midwest until after it began killing elms in Britain that had survived the original epidemic. The second epidemic was traced to elm logs shipped from North America in the 1960s.

In Britain alone, *O. novo-ulmi* killed 30 million elm trees. Hundreds of millions of elms (*Ulmus* spp. L.) in the United States were lost to the new fungus (Brasier 2001). Gene flow between the two species has been demonstrated using molecular techniques, and this gene flow brings advantageous *O. ulmi* genes for heterogeneity of v-c groups (and subsequent protection from debilitating viruses) into the more pathogenic *O. novo-ulmi* (Brasier 2001).

All North American elm species, and particularly the historically significant street tree *U. americana* L., are susceptible to Dutch elm disease. The spores are carried from tree to tree by *Hylurgopinus rufipes* (Eichhoff*),* a native elm bark beetle, in the northern tier of the United States and Canada. In the South, *Scolytus multistriatus* (Marsham), the smaller European elm bark beetle, is the more common vector. The beetles become infested with spores as they feed on dying elms, and when they emerge as adults they spread the spores to healthy trees while feeding in twig crotches. The fungus spreads within the tree by spores transported in the xylem, and by mycelial growth through other tissues. Leaves on infected branches wilt, curl, turn yellow, and die. Sometimes the tree dies within a few weeks, its vascular tissue plugged with fungal mycelium, tyloses, and gums. This is particularly true in cases where the fungus has spread through root grafts. In other cases, the tree may die one limb at a time over a period of a year or more (Haugen 2001). The cost of removal of dead elms is estimated at $100 million per year (Pimentel and others 2000). Although *U. americana* was not planted as widely in the South as in the Northern United States, it is gradually losing its place in southern landscapes, as well as in native forests.

Control measures for Dutch elm disease are most successful when adopted communitywide. Rapid sanitation of dead branches and dying trees greatly reduces populations of the beetle vectors. Prunings must be destroyed prior to beetle emergence. Insecticides can also be used to reduce vector populations. Root grafts between diseased and healthy trees should be broken with a vibratory plow or a trenching machine. Trenching should be done prior to the removal of diseased trees to prevent the drawing of inoculum across root grafts from diseased roots to the transpiring healthy tree (Haugen 2001). Santamour and Bentz (1995) list five varieties of Dutch elm disease-resistant *U. americana*: (1) Princeton elm, (2) American Liberty, (3) Independence, (4) Valley Forge, and (5) New Harmony. Other nonnative *Ulmus* species and some hybrids are also resistant to Dutch elm disease.

Injection or infusion of fungicides is used as a preventive measure only for high-value trees. Since the treatment must be repeated every 1 to 3 years, depending on the fungicide used, damage to the tree in creating injection ports is also a significant factor in overall tree health. Stipes and Fraedrich (2001) suggest that injections rise in priority relative to other control options when other factors, such as poor sanitation practices and community objections to insecticidal sprays, contribute to the development of plentiful inoculum. Fungicide injection improves the success of sanitation pruning and has the advantage of localizing control chemicals within the tree, as opposed to insecticidal sprays, which are subject to drift and possible nontarget effects. Again there are no economically feasible control measures suitable for use in the forest environment.

INVASIVE NONNATIVE FOREST INSECTS

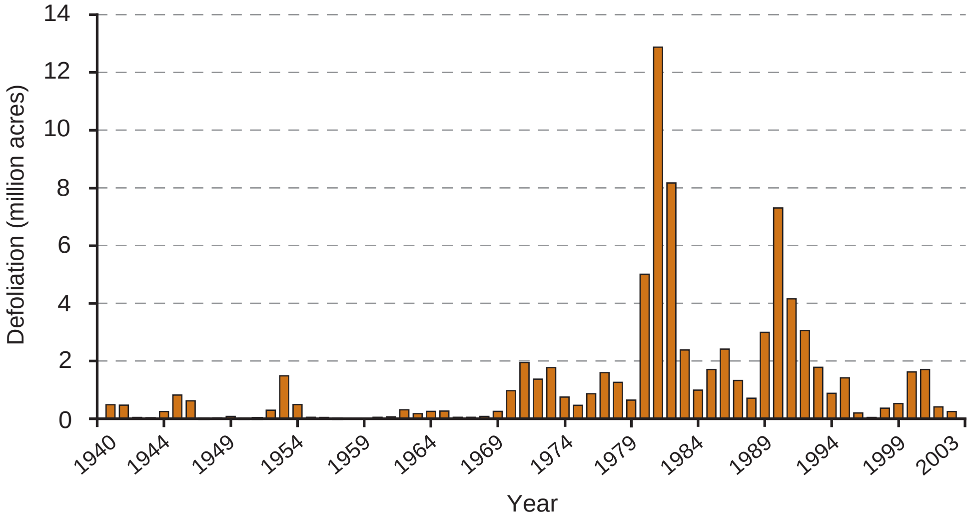
Nonnative insects have had a profound effect on southern forests. Over 70 species of nonnative forest insects are currently established throughout the Southeastern United States. Because these pests have rapid dispersal rates and high reproductive capacities, it is necessary to detect new ones quickly and then apply effective eradication programs based on IPM before they become established and cause further damage. This portion of the present chapter will focus on several of the more destructive nonnative insects which have past, present, or potential future impacts on Southern U.S. forests.

Gypsy Moth

The gypsy moth [*Lymantria dispar* (L.)] is one of the most serious pests of hardwood trees in the Eastern United States. In most years, millions of acres are defoliated by the gypsy moth (fig. 14.1), and the costs of damage and control run into tens of millions of dollars annually. Useful general information about the gypsy moth can be found in the “Forest Insect & Disease Leaflet 162” for gypsy moth (McManus and others 1989) and in the book “Insects of Eastern Forests” (U.S. Department of Agriculture, Forest Service 1985).

The gypsy moth is native to Europe and was introduced into the United States in 1869 by a French scientist living in Boston. The first outbreak occurred in 1889. The gypsy moth has spread to all or parts of 17 States, mostly in the Northeast and the Great Lakes region, as well

Figure 14.1—Amount of defoliation by the European gypsy moth 1940–2003.



as to the District of Columbia. In the Southeast, the current advancing front runs eastwest across northern North Carolina then slants northwest through southwestern Virginia and eastern Kentucky.

The gypsy moth life cycle has four stages: (1) egg, (2) larva, (3) pupa, and (4) adult (moth stage). Only the larvae damage trees and shrubs. Gypsy moth egg masses are most often laid on branches and trunks of trees, but egg masses may be found in any sheltered location. Egg masses are buff-colored when first laid, but may bleach out during the winter months. The hatching of gypsy moth eggs coincides with the budding of most hardwood trees, from early spring through mid-May. Larvae are dispersed naturally by the wind and artificially on cars and recreational vehicles, firewood, household goods, and other personal possessions. The larvae feed until early July before pupating. Adult females do not fly.

Gypsy moth larvae prefer hardwoods, but may feed on several hundred different species of trees and shrubs (for a list of host plants, see http://www.gypsymoth.ento.vt.edu/vagm/index.html). When gypsy moth populations are dense, the larvae feed on almost all vegetation. In the Eastern United States, the gypsy moth's main ecological effect is on oaks and in oak-dominated hardwood forests.

The effects of defoliation depend primarily on the amount of foliage removed, the condition of the tree at the time it is defoliated, the number of consecutive defoliations, available soil moisture, and the species of the host. If < 50 percent of their crown is defoliated, most hardwoods will experience only a slight reduction in radial growth. If > 50 percent of their crown is defoliated, most hardwoods will produce a second flush of foliage by midsummer. Healthy trees can usually withstand one or two consecutive defoliations of > 50 percent. Trees that have been weakened by previous defoliation or that have been subjected to other stresses, such as drought, frequently die after a single defoliation of > 50 percent.

Natural controls, including introduced insect parasites and predators, fungal and virus diseases, and adverse weather conditions, help control the gypsy moth. A number of tactics have the potential to minimize damage by gypsy moth and to contain gypsy moth populations at levels considered tolerable. These tactics include monitoring gypsy moth populations, maintaining the health and vigor of trees, discouraging gypsy moth survival, treating with *Bacillus thuringiensis* var. *kurstaki*, disrupting mating with pheromone flakes containing disparlure, treating with gypsy moth nuclear polyhedrosis virus, treating with diflubenzuron, and mass trapping. The tactic or combination of tactics used depends on the condition of the site and of the tree or stand and the level of the gypsy moth population. Tactics suggested for homeowners, such as removing egg masses, placing burlap bands around boles, or spraying individually affected trees, are usually too labor intensive for managers to use in forest stands.

The gypsy moth infestation spreads at an average rate of 21 km/year along its border to the west and south. In 1999 following a successful pilot project initiated in 1992, the U.S. Department of Agriculture Forest Service (Forest Service), along with State and Federal cooperators, implemented the National Gypsy Moth Slow the Spread (STS) project across the 1,200-mile gypsy moth frontier from North Carolina through northern Michigan. The goal of the STS project is to use novel IPM strategies to reduce the rate of gypsy moth spread into uninfested areas. The STS project significantly decreases the new territory invaded by the gypsy moth each year and protects forests, forest-based industries, urban and rural parks, and private property. Estimated spread rates declined from 20 to 40 km/year to 5 to 14 km/year after STS control and eradication methods were employed in an STS project in the central Appalachians. The average rate of gypsy moth spread was 26.5 km/year before 1990 and 8.6 km/year after 1990 (Sharov and Liebhold 1998). More information on the spread of gypsy moth and the STS project may be found on the STS Web site: http://www.gmsts.org/operations.

Although gypsy moth has been present in the United States for > 100 years, it is difficult to explain and predict the extent of the changes it causes in forest vegetation. A major concern is the potential loss of economically significant and ecologically dominant oak species. Most studies of forest compositional changes after gypsy moth defoliation indicate that less susceptible species will dominate the forest.

Hemlock Woolly Adelgid

The hemlock woolly adelgid [*Adelges tsugae* (Annand)] has been in the United States since 1924 (McClure 1994). This serious pest of eastern hemlock [*T. canadensis* (L.) Carriere] and Carolina hemlock (*T. caroliniana* Engelmann) is a native of Asia. Through 2001, hemlock woolly adelgid infestations have been found in > 150 counties in Connecticut, Delaware, Massachusetts, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, Virginia, and West Virginia. In 2001 alone, 20 additional counties were found to have infestations. At present, hemlock woolly adelgid cannot be controlled in the vast majority of forest settings.

Hemlock woolly adelgid is a sucking insect with an extremely complicated life cycle. Four forms each complete six life stages, some of which develop wings and migrate to feed on spruce. Successful reproduction on spruce has not been observed in North America (Salom 1996b). The forms most damaging to hemlock are wingless and remain on hemlock all year round.

White cottony sacks at the base of the needles are good evidence of hemlock woolly adelgid infestation. These sacks resemble the tips of cotton swabs. They are present throughout the year, but are most prominent in early spring.

When immature nymphs and adults suck sap from their twigs, trees lose vigor and drop needles prematurely. If uncontrolled, the adelgid can kill a tree in a single year. The widespread hemlock mortality that the hemlock woolly adelgid causes is alarming, in view of the importance of hemlock trees to the ecosystems in which they occur.

Application of insecticides is currently recommended for controlling hemlock woolly adelgid in areas where this is feasible (Salom 1996b). Infested trees are drenched with botanical oils and or soaps, or systemic insecticide (imidacloprid) is injected into the trees and or the soil beneath them.

Several native predators feed on the hemlock woolly adelgid, but none of them reduces adelgid populations enough to help the current situation. Two nonnative predators, *Pseudoscymnus tsugae* Sasaji and McClure (a ladybird beetle native to Japan) and *Laricobius nigrinus* (Fender) (a beetle native to the Pacific Northwest), hold promise for biological control of hemlock woolly adelgid infestations. Under certain circumstances, releases of these predators are a feasible and effective control option (McClure and others 2001).

Balsam Woolly Adelgid

Introduced from Central Europe around 1900, the balsam woolly adelgid [*Adelges piceae* (Ratzeburg)] is considered a serious pest of forest, seed production, landscape, and Christmas trees (Salom 1996a). First discovered in Brunswick, ME, in 1908, the balsam woolly adelgid was found in the Southern Appalachian Mountains in the 1950s and has spread to all fir stands in the region since that time. The pest has also found its way into the Pacific Northwest. In the Eastern United States, the adelgid feeds on balsam fir and Fraser fir. Very extensive stands of Fraser and balsam fir have been killed throughout much of these species' range in the East. Because the adelgid does not attack Fraser fir until the trees approach maturity, and because some mature trees escape attack long enough to produce seeds, young Fraser fir trees still exist in their natural range. However, by the mid-1980s, this insect had significantly altered all of the mature Fraser fir-red spruce (*Picea rubens* Sarg.) forest type in the Southern Appalachians.

The balsam woolly adelgid life stages include the egg, three nymphal stages, and female adults. There are no males; females reproduce by parthenogenesis. They are wingless, oval, purplish-black insects about 0.8 mm in length, and are covered with secretions of waxy threads that appear as a dense white wool mass. A female is capable of laying 200 eggs or more in a cluster near her body. The first-instar crawlers, reddish brown and about 0.4 mm in length, are the only stage of the insect capable of moving and dispersing. Once the crawler finds a suitable feeding location, it inserts its tubelike mouth parts into the bark of the host and remains there for the rest of its life. The second and third instars are about 0.5 to 0.65 mm in length, respectively, and closely resemble the adult.

The balsam woolly adelgid generally concentrates either on the outer portions of tree crowns or on the main stem and large branches. Crown infestations are characterized by abnormal drooping of the current shoots and gouting of the outer twigs. The crown becomes increasingly thin, and dieback may occur. Persistent crown infestation can kill a tree over a number of years. Stem infestations usually cause greater damage and mortality. Conspicuous white woolly masses characteristic of stem attack can give the lower bole a whitewashed appearance in the most severe cases. The tree responds to feeding by adelgids in an allergic manner that causes swelling of the sapwood, gouting of the twigs, and increased heartwood formation in the sapwood—a condition called rotholz or redwood. This abnormal growth of sapwood tissue inhibits water flow within the tree.

In forest situations, silvicultural and management techniques can be used to reduce balsam woolly adelgid populations and damage (Salom 1996a). Tree stress may be minimized by thinning overstocked stands, by fertilizing nutrient-poor sites, and by replanting or encouraging more tolerant trees and varieties. There are many different varieties and crosses of Fraser fir, and some varieties are more tolerant of balsam woolly adelgid. A hazard-rating system was developed to aid in management decisions. The main variables used in the system are site elevation, soil moisture regime, percent balsam fir by basal area, total basal area of balsam fir, and stand age. In general, lower elevation dry sites with > 40 percent balsam fir at an older age (45 years of age or more) are most susceptible. Trees between 25 and 45 years of age are moderately susceptible, and trees < 25 years old are least susceptible. In Christmas tree plantations in which only a few trees are infested, it should suffice to rogue and burn those trees. Chemical control can be used effectively on ornamental trees, seed production trees, and Christmas trees (Day and others 2001). Several insecticides are available for use in spraying infested bark and foliage. When feasible, the cutting and removal of infested trees is effective. Cut trees must be wrapped in tarps to ensure that adelgids do not fall off the trees as they are being removed.

Beech Scale and Beech Bark Disease

Beech bark disease (*Neonectria galligena*) is one of the more recent problems to plague Eastern U.S. forests. Beech bark disease refers to a complex consisting of a sap-feeding scale insect and at least two species of *Nectria* fungi (McCullough and others 2001). Beech scale (*Cryptococcus fagisuga* Lind. = *C. fagi* Baer.) was accidentally introduced into Nova Scotia in 1890 on ornamental beech trees from Europe. The scale and associated fungi have spread since that time, and the current range in the United States includes most of New England, northern Pennsylvania, and northeastern West Virginia. Localized infestations of beech scale have been discovered in Virginia, North Carolina, Tennessee, and Ohio (McCullough and others 2001). The overall effect of this insect-disease complex is the mortality of roughly 50 percent of the beech (*Fagus* spp.) trees > 8 inches in diameter (Houston and O'Brien 1983). The resulting forest has a few residual large beech trees and stands of many small trees, often root sprouts from susceptible trees, which are frequently defective.

Beech scale insects are yellow, soft bodied, and 0.5 to 1.0 mm long as adults. They feed on American beech (*F. grandifolia* Ehrh.) and European beech (*F. sylvatica* L.). Adult scales are legless and wingless and have only rudimentary antennae. Reproduction is parthenogenic. This type of reproduction allows for rapid population growth. Beech scale has one generation per year. Immature scales, called crawlers, have functional antennae and are mobile. Crawlers are spread by wind, birds, and people moving infested wood. When a crawler finds a suitable feeding location on a host tree, it inserts its long, tubelike stylet into the bark and begins to suck sap. It then molts to the second crawler stage, which has no legs and is immobile. These produce a white wax that eventually covers their bodies. Thus when trees are heavily infested with beech scale, they appear to be covered by white wool. The small wounds produced by the beech scale's feeding allow the *Nectria* fungi to invade the infested trees (Houston 1994).

Crawlers that fall from trees or are washed off by precipitation usually die. Severely cold weather (-35 °F) that persists for a few days may kill beech scale, but such weather conditions probably never occur in the Southeast. A small ladybird beetle [*Chilocorus stigma* (Say)] feeds on this scale and is common throughout most of the Eastern United States, but this predator does not reduce scale populations enough to control infestations.

Although the scale feeding alone weakens trees, mortality usually does not occur until the trees have been invaded by *Nectria* fungi. This invasion typically occurs after 3 to 6 years of scale feeding. Most large-diameter beech trees in areas where beech bark disease becomes established are killed. Beech is a very important source of food and habitat for many wildlife species and areas with large beech components may change dramatically as a result of beech bark disease. Some trees are partially resistant to beech bark disease, and a very few are completely resistant. Trees with smoother bark appear to be more resistant, probably because the scales prefer to feed where bark is rough (Houston 1997).

The only control is removal of the trees most heavily infested with beech scale or *Nectria* fungi. Resistant trees should be identified and retained. After it is cut, beech often regenerates by prolific root sprouting. This is undesirable because the sprouts form dense thickets, have little value to wildlife, and eventually increase susceptibility to more beech bark disease infestations. Herbicide control of beech root sprouts is, therefore, often necessary. Increasing the diversity of forest stands in which beech is present will reduce the risks and spread rate of the disease. Care should also be taken to avoid transporting infested firewood or logs to uninfested areas.

Asian Longhorned Beetle

The Asian longhorned beetle [*Anoplophora glabripennis* (Motschulsky)] was discovered in New York City in 1996 and in Chicago in 1998. Tunneling by the beetle larvae girdles tree stems and branches, impeding water and nutrient transport within the attacked tree. Repeated attacks lead to dieback of the tree crown and, eventually, death of the tree (U.S. Department of Agriculture, Forest Service and Animal and Plant Health Inspection Service 1999). The Asian longhorned beetle probably traveled to the United States inside solid wood packing material from China. The beetle has been intercepted at ports and found in warehouses throughout the United States, although New York City and Chicago remain the only two areas where infestations of live trees have been found. Since 1996, > 7,000 trees in the two cities have been killed by the beetle, or cut down and destroyed to stop the beetle's spread. Most of the trees lost were highly valued urban trees that provided shade, wildlife habitat, aesthetic value, and benefits for clean water and air. The Asian longhorned beetle has had an economic impact in the tens of millions of dollars.

The Asian longhorned beetle is also a serious pest in China where it kills hardwood trees. In the United States, the beetle prefers maple species (*Acer* spp.), including boxelder (*A. negundo* L.), Norway (*A. platanoides* L.), red (*A. rubrum* L.), silver (*A. saccharinum* L.), sugar (*A. saccharum* Marsh.), and sycamore (*A. pseudoplatanus* L.) maples. A complete list of host trees in the United States has not been determined. An updated list is available at http://www.na.fs.fed.us/spfo/alb/index.htm. Because not all hosts are known and because the beetle has been restricted to urban forests thus far, it is difficult to predict its potential effects on natural forests. It appears, however, that Asian longhorned beetle may have the potential to irrevocably alter many eastern forest ecosystems.

There is usually one generation of Asian longhorned beetle per year, although the life cycle may take as long as 2 years. Adult beetles are usually present from May to October, but they can be found earlier in spring or later in fall if temperatures are warm. Adults typically stay on the trees from which they emerge, but they may disperse short distances to a new host to feed and reproduce. Adult females chew oval to round egg-laying sites in the bark of the tree and place a single egg in each. Each female is capable of laying 30 to 70 eggs. These hatch in 10 to 15 days, and the larvae tunnel under the bark and deep into the wood where they eventually pupate. Emerging adults create a perfectly round exit hole three-eighths inch in diameter. Adult beetles are 1 to 1.4 inches long and have striking white marks against a jet black body. The antennae are longer than the body and have black and white bands.

Currently the only effective means to eliminate Asian longhorned beetle is to remove infested trees and destroy them by chipping or burning. To prevent further spread of the insect, quarantines have been established to avoid the transportation of infested trees, branches, and wood from the area. Early detection of infestations and rapid treatment response are crucial to successful eradication of the beetle. Early detection is difficult, time consuming, and costly, and to be effective, it must involve tree climbers and surveyors in bucket trucks. Since 2000, unattacked potential host trees have been injected with the systemic insecticide imidacloprid as a preventive treatment. Researchers are assessing the biological control potential of a variety of the beetles' natural enemies in Asia.

INVASIVE NONNATIVE FOREST PLANTS

Millions of acres of forest land in the Southeast are being increasingly occupied by nonnative invasive plants, which are also termed exotic weeds. Their range, infestations, and damage are continually expanding. All Federal parks and forest lands in the Southeast have nonnative infestations (Hamel and Shade 1985, Hester 1991). The actual infested acreage, spread rates, and damage estimates are still unknown, although this information is essential for planning containment and eradication strategies and programs (U.S. Congress Office of Technology Assessment 1993). The Forest Service and State partners have initiated a cooperative survey of 42 invasive nonnative plants within the region and another 20 species in Florida; however, it will take several years to collect initial data (for a list, see "Nonnative Invasive Plants of Southern Forests" at http://www.srs.fs.usda.gov/fia/manual/Nonnative_Invasive_Plants_of_Southern_Forests.pdf).

Invasive plants are able to outcompete native species. They reproduce rapidly because of the absence of predators from their native ecosystems, and eventually form dense infestations that exclude most other plants, except certain other nonnatives (Randall and Marinelli 1996). Other reasons for their invasiveness are that they are naturally robust plants or have been made so through plant breeding efforts; that most are perennials with tough roots or rhizomes; that many are still being sold as ornamentals and some are widely planted for wildlife use and soil stabilization; that most produce abundant seeds or spores that are spread widely by birds, wind, and water; and that their seeds or tubers persist in the soil (Randall and Marinelli 1996). It remains unclear what percentage of nonnative plants arriving in the Southeastern United States become invasive. One problem in determining this is the nature of invasive plant spread, which can be characterized by a short-to-lengthy lag phase preceding an exponential spread phase (fig. 14.2). In many species, e.g., kudzu, tallowtree, wisterias, etc., the lag phase can be very protracted and can mask eventual problems. This spread function also explains why eradication is most possible during the early lag phase.

Occupation and infestations by nonnative pest plants decrease forest productivity, threaten forest health and sustainability, and limit biodiversity and wildlife habitat in the Southeast (Wear and Greis 2002). Alterations to ecosystem structure, functions, and processes are occurring, but study of these effects has just begun (Ehrenfeld and others 2001). Some invasives, such as cogongrass [*Imperata cylindrica* (L.) Beauv.], can alter natural fire regimes and increase risk of wildfire occurrence and damage (Lippincott 2000). Nonnative plant "biological pollution" is one of the greatest threats to biodiversity across the southern landscape, attacking our highly valued nature preserves and recreational lands. Adjoining croplands, home sites, pastures, and wetlands contain invasive plant species that will eventually affect forests. These nonnative invaders (often called nonindigenous, alien, or noxious weeds) include trees, shrubs, vines, grasses, and forbs. In all there are about 70 infestation-forming, terrestrial plant species invading forests and their edges in the temperate parts of the Southeast. Thirty of these are discussed briefly here to provide a general sense of identifying characteristics, common pathways of introduction, mechanisms of invasiveness, ecosystem effects, and range of current occupation. Not discussed here are the approximately 70 tropical and subtropical nonnative species currently invading south Florida.

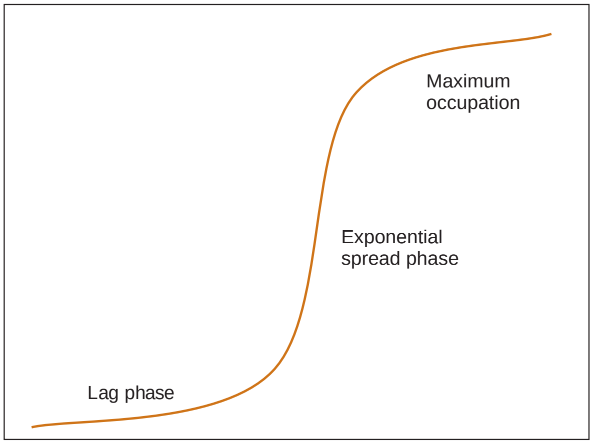


Figure 14.2—Logistic spread model for invasive nonnative plants.

Invasive Nonnative Trees

Nonnative tree species hinder management of forests, rights-of-way, and natural areas by replacing native plants. This dramatically alters habitat and may alter important natural processes. Almost all of the invasive nonnative trees are hardwoods. Some presently occur as scattered trees, while others form dense stands. Most spread widely by prolific seed production and animal dispersal, while existing infestations increase by abundant root sprouting.

Tree-of-heaven or ailanthus [*Ailanthus altissima* (P. Mill.) Swingle] was introduced to North America as an ornamental in 1784 from Europe, although it originates in Eastern China (Miller 1990). A short-lived species with no timber value, ailanthus grows up to 80 feet tall with long, pinnately compound leaves, slightly fissured gray bark, and large terminal clusters of greenish flowers in early summer. Flowers and other parts of the plant have a strong odor. It is a dioecious species and spreads by seeds from female trees. It is shade intolerant, flood intolerant, and allelopathic. Ailanthus establishes after disturbance and increases by root sprouts, often forming dense thickets that displace native vegetation. It occurs throughout the Southeast and is most abundant in Kentucky, Virginia, and Tennessee.

Silktree or mimosa (*Albizia julibrissin* Durazz.) was introduced as an ornamental from Asia in 1745. It is a leguminous tree, 30 to 50 feet tall. It has feathery, pinnately compound, deciduous leaves, smooth light brown bark, and showy pink spring and summer blossoms, yielding abundant dangling seedpods that persist into winter. The seedpods float, which aids in long-distance spread along waterways, and seeds remain viable for many years. Infestations are spreading along rights-of-way, fencerows, and riparian zones, and are encroaching into adjoining forested areas after disturbance, especially into pine plantations. Partially shade tolerant, mimosa invades the forest midstory and replaces native shrubs by root sprouting. It is becoming increasingly common along roadsides throughout the Southeast and is most abundant in Mississippi, Alabama, and Georgia.

Princesstree or paulownia [*Paulownia tomentosa* (Thunb.) Sieb. & Zucc. ex Steud.] was introduced from East Asia in the early 1800s. It is grown as an ornamental and in scattered plantations for speculative production of high-valued wood for export to Japan. It has large heart-shaped leaves with fuzzy hairs on both sides, and in early spring produces showy pale violet flowers that yield clusters of pecan-shaped capsules, each filled with thousands of tiny winged seeds. Paulownia reproduces by abundant seeds and root sprouts, replacing native vegetation, including young trees that might otherwise reach the overstory. It is shade intolerant and invades after disturbance. This deciduous tree grows to 60 feet tall. Because it sprouts rapidly, it often obscures scenic vistas along roadsides. It occurs throughout the Southeast and is presently most abundant in central Tennessee and Virginia.

Chinaberrytree (*Melia azedarach* L.) is another Asian introduction. This traditional ornamental is commonly found around old home sites. It grows to about 50 feet tall and is spread by birds, which disperse its seeds. It has lacy, bipinnately compound dark green leaves and produces pale blue flowers in spring. The flowers yield round yellow fruit that persist during winter. Infestations spread by means of abundant seeding and root sprouting along rights-of-way to adjoining land that has been disturbed. Because it is somewhat shade tolerant, it is increasing in the midstory of pine plantations in parts of the South. The fruit are poisonous to humans and livestock but have potential use as natural pesticides. Chinaberry is common throughout the Southeast and is most abundant in Arkansas, Louisiana, Mississippi, Alabama, and Georgia.

Tallowtree or popcorn tree [*Triadica sebifera* (L.) Small, formerly *Sapium sebiferum* (L.) Roxb.] is a shade-tolerant tree that grows to 50 feet tall. It has light green heart-shaped leaves that turn scarlet in the fall, long drooping flowers in spring, and bundles of white, waxy, popcornlike seeds that remain attached to the tree in fall and winter. The abundant seeds are spread by birds and on water. Tallowtree is a prolific root sprouter and forms monospecific stands (Bruce and others 1997). It was introduced from China to the U.S. gulf coast in the early 1900s, and the U.S. Department of Agriculture encouraged its use as a seed oil crop from 1920 to 1940. Tallowtree is still being sold and planted and is thought to be the most rapidly invading tree species in the region. Tallowtree seedlings are shade tolerant and yet grow rapidly in full sun (Jones and McLeod 1990). Its waxy seeds were traditionally used to make candles, and it has current value as a honey plant for beekeeping and limited pulpwood use. It forms dense stands, and because it tolerates flooding, tallowtree replaces bottomland hardwood reproduction and understory plants in wetland forests throughout the Coastal Plain (Jones and Sharitz 1989). It is also spreading into upland forests from widespread ornamental plantings. It occurs in all the Southern States except Oklahoma, Kentucky, and Virginia, and there are severe infestations in coastal areas of Texas, Louisiana, Mississippi, and Alabama.

Invasive Nonnative Shrubs

Invasive nonnative shrubs often occur with invasive tree species and present similar problems. Herbicide control options are similar to those for trees, but foliar sprays are often more effectively used against shrubs than against trees. All of the most common invasive shrubs are abundant seed producers, and their fruits are often consumed and spread by birds.

Chinese privet (*Ligustrum sinense* Lour.) and European privet (*L. vulgare* L.) are shade-tolerant tall shrubs or small trees growing to about 30 feet in height. These common southern ornamental shrubs were introduced from China and Europe in the early to mid-1800s and have already become some of the most severely invasive species. They form dense stands in the understory of bottomland hardwood forests and exclude most native plants and replacement reproduction. These privets are also increasing in upland forests, fencerows, rights-of-way, and special habitats throughout the region. They drastically alter habitat and critical wetland processes. Both species have leafy stems with opposite leaves < 1 inch long. Chinese privet is semievergreen, and European privet is deciduous, but the two species are nearly identical in all other respects. Both have showy clusters of small white flowers in spring that yield drooping clusters of small, spherical, dark purple berries during fall and winter. Birds spread seed very effectively, but privet stands also increase in density by stem and root sprouts. Both species occur throughout the Southeast.

Multiflora rose (*Rosa multiflora* Thunb. ex Murr.) is an erect-to-arching shrubby rose growing to about 10 feet tall and taller when it climbs into trees. The recurved thorny stems have pinnately compound leaves with 3 to 7 leaflets. White rose flowers are produced in many clusters in spring, and red rose hips, which are spread by birds, appear in fall to winter. Sprouts and runners that root consolidate and expand infestations. The species was introduced from Japan and Korea in the 1860s as an ornamental. Later, Government programs encouraged its planting for use as living fences for livestock containment and as wildlife habitat. Infestations have been confined to pastures but are now extending into forest edges and interior forests, including wetlands. The species occurs throughout the Southern and Eastern United States.

Bush honeysuckles—Amur honeysuckle [*Lonicera maackii* (Rupr.) Herder], Morrow's honeysuckle (*L. morrowii* Gray), tatarian honeysuckle (*L. tatarica* L.), and sweet breath of spring (*L. fragrantissima* Lindl. and Paxton)—are generally deciduous multistemmed shrubs 6 to 16 feet tall with arching branches. The leaves are distinctly opposite, usually oval to oblong in shape, and range in length from 1 to 3 inches. Fragrant, tubular flowers occur in pairs from May to June and are creamy white in most species, but turn yellow or pink to crimson in varieties of tatarian honeysuckle. Red-to-orange berries in pairs are abundant on plants in fall to winter, and seeds are long lived in the soil. All were introduced from Asia in the 1700s and 1800s as ornamentals and wildlife plants. They are widely invading and forming exclusive understory layers in lowland and upland forests, replacing most native plants and preventing regeneration of native trees. Most alarming is the increased occupation of wetlands. These invasive species occur everywhere in the Southeast except Louisiana and Florida and are most abundant in Kentucky and Virginia.

Autumn olive (*Elaeagnus umbellata* Thunb.) is a deciduous, bushy shrub growing to 20 feet tall. It has alternate leaves that are dark green above and silvery beneath. It produces abundant spherical red berries with silvery scales in the fall. Introduced from China and Japan, and still widely planted for wildlife habitat, reclamation of strip mines, and shelterbelts, autumn olive is being spread rapidly and widely by birds and other animals. It is becoming a scattered understory shrub in open forests throughout the Southeast, to the detriment of native trees and shrubs.

Silverthorn or thorny olive (*E. pungens* Thunb.) is a popular ornamental evergreen bushy shrub with long limber shoots projecting to 20 feet when supported by tree limbs. It has alternate leaves, which in spring are silver and scaly on both top and bottom and which by midsummer have become dark green above and silvery beneath. Thorns are widely scattered on its branches and are subtended by brown-scaled red fruit that appear in spring. The fruit are consumed and widely dispersed by wildlife, which results in scattered infestations. This widely planted ornamental shrub was introduced from China and Japan. A shade-tolerant species, it replaces native understory vegetation and prevents natural tree regeneration. It occurs in all Southeastern States except Texas, Oklahoma, and Arkansas.

Winged burning bush [*Euonymus alata* (Thunb.) Sieb.] is a shade-tolerant, deciduous, bushy shrub up to 12 feet tall with opposite leaves along stems with four corky wings. Introduced from Northeast Asia in the 1860s, it is still widely planted as an ornamental. In fall, the leaves turn bright red, while orange fruit appear as stemmed pairs in leaf axils. Birds and animals are attracted to the fruit and spread seed widely. *E. alata* is increasingly invading forests, pastures, and prairies. It forms dense stands that exclude native plants and eventually stop native tree regeneration. This problem is spreading in Oklahoma, Kentucky, Tennessee, Virginia, Georgia, North Carolina, and South Carolina.

Invasive Nonnative Vines

Nonnative vines are among the most troublesome invaders because they often form the densest infestations, making control efforts difficult, especially the application of herbicide. Many of these vines overtop even mature forests and often form mixed infestations with nonnative trees and shrubs.

Japanese honeysuckle (*L. japonica* Thunb.), the most prevalent invasive nonnative vine, is a shade-tolerant, climbing and trailing woody vine with semievergreen, opposite leaves. Paired white to yellow flowers in early summer yield blackish berries in fall and winter. Introduced from Japan in 1806, it is the most widespread and invasive nonnative plant species. It occupies multiple strata in lowland and upland forests, replaces native vines, and alters habitat and ecosystem processes. Japanese honeysuckle is sold as an ornamental and has some value for erosion control. It is also planted and cultured in wildlife food plots and sustains deer herds during winter. It occurs throughout the Southeast and is spread by widely rambling vines that root at nodes, as well as by bird-dispersed fruits.

Kudzu [*Pueraria montana* (Lour.) Merr., formerly *P. lobata* (Willd.) Ohwi] is a woody leguminous vine with lobed trifoliate leaves. It is spread by vines rooting at nodes and by animal- and water-dispersed seeds. Introduced as an ornamental from Japan in 1876, kudzu was planted extensively for erosion control and forage in Government-sponsored programs from 1920 to 1950. It forms dense infestations that exclude native plants, halting forest productivity and changing habitat on millions of acres of land. Kudzu is increasingly invading riparian habitat along rivers and streams by means of floating seedpods. Hydrologic impacts from this mode of spread are anticipated. Kudzu has become a popular southern icon and provides some raw material for folk art. The Forest Service has initiated a biocontrol program for kudzu (Britton and others 2002).

Oriental or Asian bittersweet (*Celastrus orbiculatus* Thunb.) is an attractive but very invasive vine with elliptic to rounded deciduous leaves 2 to 3 inches broad and long, alternating along a woody vine with drooping branches. Clusters of scarlet fruit appear in fall and remain during winter at most leaf axils. The fruits are widely spread by birds. Oriental bittersweet was introduced from Asia in 1736. The showy berries are used as home decorations in winter, and these decorations contribute to spread when discarded. Oriental bittersweet colonizes disturbed forests and along forest edges, spreading into interior forests, forming expanding thickets, and decreasing plant diversity. It is invading from the Northeast and is not yet found in Oklahoma, Texas, Louisiana, or Mississippi. American bittersweet (*C. scandens* L.) has flowers and fruit only in terminal clusters and does not form extensive infestations.

Air yam (*Dioscorea bulbifera* L.) and Chinese yam (*D. oppositifolia* L., formerly *D. batatas* Dcne.) are twining and sprawling vines with heart-shaped leaves and small dangling, yamlike tubers (bulbils) at leaf axils in mid-to-late summer. These tubers drop and form new plants. Although the vines are deciduous, they grow rapidly and can cover small trees in one growing season. Native *Dioscorea* species do not produce "air potatoes," nor do they form infestations that cover trees. Chinese yam is from Asia, and air yam is from Africa. Both were introduced as possible food sources in the 1800s, but are now cultured for ornamental or medicinal use and are often spread by unsuspecting gardeners. Once established, these vines colonize persistently because the prolific bulbils form new plants as they scatter downslope. The vines expand throughout the understory to form exclusive infestations. Their distribution is scattered throughout the Southeast, with air yam occurring mostly in the southern Gulf Coastal Plain and Chinese yam more common in the Appalachians.

Wintercreeper or climbing euonymus [*Euonymus fortunei* (Turcz.) Hand.-Maz.] is a trailing, climbing, or shrubby evergreen plant with opposite, thick, dark green or green-white variegated leaves. It is shade tolerant, spreads to form a dense ground cover, and climbs by aerial roots. Abundant reddish-hulled orange fruit appear in fall and are widely spread by birds. Introduced from Asia as an ornamental ground cover and still widely planted, *E. fortunei* continues to form dense exclusive infestations that decrease diversity, hinder access, and alter habitat. It occurs in Kentucky, Virginia, Tennessee, Mississippi, Alabama, Georgia, North Carolina, and South Carolina.

Japanese climbing fern [*Lygodium japonicum* (Thunb. Ex Murr.) Sw.] is a viney deciduous fern with lacy, finely divided leaves and green-to-orange-to-black wiry stems that climb and twine over shrubs and trees. Native to Asia and tropical Australia, it was introduced to North America from Japan as an ornamental and is often spread by unsuspecting gardeners. It is one of three species of climbing ferns in the Southeast. The American climbing fern [*L. palmatum* (Bernh.) Sw.] and Old World climbing fern [*L. microphyllum* (Cav.) R. Br.], another nonnative which grows in Florida, have once-divided leaves. All are perennial plants that grow from creeping rhizomes and are spread by wind-dispersed spores. Dispersal of spores from nonnative species results in rapid spread and widely scattered dense infestations that cover native herbs, shrubs, and eventually trees. *L. japonicum* is invading from the South to the North and has yet to arrive in Oklahoma, Tennessee, or Kentucky.

Chinese wisteria [*Wisteria sinensis* (Sims) DC.] and Japanese wisteria [*W. floribunda* (Willd.) DC.] are woody, leguminous vines with long pinnately compound leaves and showy spring flowers. They spread by adventitious rooting and are less commonly dispersed by seeds. These traditional southern porch vines were introduced from Asia in the early 1800s. They usually spread slowly, although more rapidly near rivers and streams. They form dense infestations mainly around old home sites, often in mixtures with other nonnative plants. Both hinder reforestation and commonly occur as scattered patches throughout the Southeast. The native or naturalized American wisteria [*W. frutescens* (L.) Poir.] does not form dense infestations.

Nonnative Invasive Grasses

Nonnative grasses spread along highway rights-of-way and then into adjoining forest lands. Most nonnative grasses are highly flammable and increase fire intensity. Intense fires tend to kill plants with which the grasses occur and thus facilitate the spread of the grasses after wildfire or prescribed burns. Wildland firefighters and forest home sites are subjected to increased risks where nonnative grasses form heavy infestations. Repeated applications of herbicides are required for control.

Cogongrass [*Imperata cylindrica* (L.) Beauv.] is a dense, erect perennial grass. Its wide yellowish green leaves have off-center midveins and finely sawtoothed margins. It was introduced from Southeast Asia in the early 1900s, first accidentally and then intentionally for soil stabilization and use as forage. It has been rated as the world's seventh worst weed (Holm and others 1979). It spreads by windblown seeds in early summer and by rhizome movement in fill dirt along highways, often yielding circular infestations. This grass is highly flammable. It is mostly shade tolerant. Dense infestations increasingly occupy forest openings, open forests, and rights-of-way in the Southern Gulf Coast States and eventually exclude most native plants. Forest regeneration is hampered and habitat destroyed. This process is hastened by burning (Lippincott 2000). Cogongrass is spreading northward from the Gulf Coast States and had not reached North Carolina, Tennessee, Virginia, Kentucky, Arkansas, or Oklahoma as of 2001.

Nepalese browntop [*Microstegium vimineum* (Trin.) A. Camus] is an annual grass. Stems are from 1 to 3 feet long with alternate, lanceolate leaves to 4 inches long. It forms dense mats and consolidates occupation and spreads by prolific seed production in late summer. Seed remain viable for 1 to 5 years. This shade-tolerant weed is native to temperate and tropical Asia and was first collected near Knoxville, TN, in 1919. It increasingly occupies creek banks, flood plains, forest roadsides and trails, damp fields, and swamps. It spreads into adjoining forests, where it forms exclusive infestations and displaces most, if not all, native understory plants. It occurs throughout the Southeast except in Oklahoma.

Chinese silvergrass (*Miscanthus sinensis* Anderss.) is a densely clumped perennial grass with upright to arching long, slender leaves with whitish upper midveins. It can grow to a height of 5 to 10 feet. Silvery to pinkish loose plumes appear in fall. Viability of the seed is unpredictable. Native to Eastern Asia, *M. sinensis* has been planted in all States for landscaping, recently using sterile cultivars. It is spreading from older fertile plants in all States except Arkansas, Oklahoma, and Texas. Still widely sold and planted as an ornamental, it is highly flammable. It forms dense infestations along rights-of-way and in disturbed upland forests, excluding native vegetation and altering habitat.

Invasive Nonnative Forbs and Subshrubs

Forbs are broadleaf herbaceous plants, while subshrubs are semiwoody. They are usually treated with foliar herbicide sprays or pulled by hand.

Garlic mustard [*Alliaria petiolata* (Bieb.) Cavara & Grande] is an aptly named biennial herb; all parts of the plant have a garlic odor. It grows in small-to-extensive colonies under forest canopies. In the first year, the plant appears as a basal rosette of leaves that remain green during winter. In the second year, stems emerge and grow, becoming 2 to 4 feet tall. Leaves are broadly arrow-point shaped with wavy margins. The flowers form in terminal clusters, and each flower has four white petals. Introduced originally as a medicinal herb from Europe in the 1800s, garlic mustard is displacing native forest understory plants and drastically altering habitat. This species produces prolific seed that can lie dormant in the soil for 2 to 6 years, building large seed banks. Germination occurs only in spring under favorable conditions. A biocontrol program has been started at Cornell University (Blossey and others 2001). Garlic mustard is invading from the Northeast and has yet to arrive in Florida, Alabama, Mississippi, Louisiana, or Texas.

Shrubby lespedeza *(Lespedeza bicolor* Turcz.) and Chinese lespedeza [*L. cuneata* (Dum.-Cours.) G. Don] were both introduced from Japan. Shrubby lespedeza is a shade-tolerant bushy legume that grows up to 10 feet tall. It has three leaflets and produces small purple-pink peatype flowers with white centers. Chinese lespedeza is a semiwoody plant up to 3 feet tall with many small, three-leaflet leaves feathered along erect, whitish stems. It forms tiny cream-colored flowers during summer. Both species produce abundant single-seeded legumes, but dispersal mechanisms are poorly understood. They have been planted extensively for wildlife food and soil stabilization. They are still planted for quail food, and plants often invade surrounding forests, replacing native plants throughout the Southeast.

Invasive Plant Control

The most effective and efficient strategy for control is early detection and effective early treatment of initial invaders. Any successful effort to combat and contain invasive nonnative plants requires an integrated vegetation management approach (Miller 2003, Tennessee Exotic Pest Plant Council 1996). Integrated programs incorporate all effective control methods, which may include (1) preventive measures, i.e., legal controls such as quarantines, border inspections, and embargoes; (2) biocontrol by means of natural predators and diseases; (3) herbicide technology; (4) prescribed fire; (5) livestock overgrazing; and (6) mechanical and manual removal. Preventive measures and biocontrol programs are best organized on a regional basis. Biocontrol agents are largely unavailable now, and although projects to identify such agents are underway, it will take years to develop them (Simberloff and Stilling 1996). Only through careful and precise research and development can effective biocontrol agents that minimize impacts on nontarget organisms be identified.

Current treatment options for specific areas usually involve herbicides, prescribed fire, grazing, and mechanical or manual removal. Fire, grazing, and mechanical cutting treatments usually control only the aboveground plant parts, reducing their height but suppressing the plants only temporarily. Manual treatment usually involves grubbing or pulling plants. This is very labor intensive and is practical only where plants and infestations are small. Thus manual treatment has limited but effective application in special habitats, such as recreational trails or nature preserves, and as a rapid means of first-sight elimination. Mowers, chain saws, and brush cutters remove aboveground plant parts, while leaving roots and rhizomes. Tree shears, root rakes, and harrows can cut and dislodge woody and rhizomatous plants, but leave soil bare for probable reinvasion and possible erosion if it is not rapidly stabilized with native plants. Nonetheless, these soil-disturbing techniques can start reclamation programs when multispecies infestations of invasive woody plants are encountered.

Herbicide treatments often can be more easily and effectively applied following these other treatments. Herbicide treatments also minimize soil disturbance and leave the soil seed bank in place to reestablish native plants. Carefully planned and executed herbicide applications can specifically target nonnative plants and minimize impacts to native plants

(Miller 2003) (http://www.invasive.org/weeds.cfm and http://www.srs.fs.usda.gov/pubs/gtr/gtr_srs062). Well-developed applicator-directed techniques for selective control of nonnative trees and shrubs are tree injection and girdle treatments, basal sprays and wipes, cut-stem applications, and foliar-directed sprays (U.S. Department of Agriculture, Forest Service 1994). Directed treatments of nonnative vines and forbs usually involve foliar sprays applied with backpack sprayers. For treating extensive inaccessible infestations, broadcast applications of sprays and pellets using helicopter and tractor-mounted systems may be required. Yet even in broadcast treatments, the use of carefully timed selective herbicides can safeguard native plants. If the treatment is to be safe and effective, herbicide applicators must read, understand, and follow the herbicide label and its prohibitions before and during use. Continued surveillance and followup treatments are often required to control nonnative plant infestations.

Site Rehabilitation after Nonnative Plant Control

The rehabilitation phase is the most essential final part of an eradication and reclamation program. Fast-growing native plants that will outcompete any surviving nonnative plants must be planted or released. Native plant seeds and seedlings are becoming increasingly available (http://plant-materials.nrcs.usda.gov/). If the soil seed bank remains intact, native plant communities may naturally reclaim many areas after nonnative plants are controlled. Constant surveillance, treatment of new unwanted arrivals, and rehabilitation of current infestations are the necessary steps in managing nonnative plant invasions.

CONCLUSIONS

We have learned much that can help us control invasive nonnatives in the future. An important point is that the cost of controlling nonnative invasives increases greatly the longer control measures are deferred. This suggests that the best approach might be to find ways to improve our ability to prevent invasions or to control invasions before they become crises.

Prevention

The entry and spread of invasive organisms could be stopped by effective legal and policy barriers. Such barriers could range from Federal, State, and county laws that prohibit importation to sanitation of equipment and vehicles before they leave infested zones.

It is helpful to examine opportunities to prevent intentional and unintentional introductions separately. Most invasive nonnative plants have been imported intentionally, in ignorance of their potential invasiveness. Yet, plant exploration and international seed exchange continues. Present regulations only examine incoming plant material for the presence of insect pests and pathogens or contamination with listed noxious weed seed. A system to test invasiveness of plant introductions was developed in Australia in the 1990s and has been helpful in addressing the problem (Mack and others 2000). Several such systems have been proposed (Reichard 2001).

Prevention of spread also requires examining the Internet sales of nonnative plants and animals. This remote means of mail order shipments of nonnative organisms will only increase the global problem. Retail sales within the United States of even federally listed noxious weeds like *I. cylindrica* persist with unproven sterility of cultivars being sold. Only a rapid phasing out of the sale of known invasive nonnative plants will halt the spread through commercial networks.

Unintentional introductions require a different approach. Inspection processes developed for agricultural products have inherent weaknesses in preventing the importation of forest pests. International trade agreements specify that import regulations will only address pests known to be present on the commodity in the exporting country, and for which a risk assessment has been performed. Provisional regulations can be adopted when insufficient data about the pest exist, but the risk assessment process must be initiated. The mitigation measures must be those that protect our resources with the minimum disruption of trade. Crop plants are similar the world over, and it is generally known which pests pose problems. When pests of natural ecosystems are considered, the major difficulty is in knowing which ones might prove invasive.

Biological and ecological characteristics of the pests themselves may render them particularly effective as nonnative invasives. Among these high-risk characteristics are a cryptic nature, which helps them avoid early detection, and extended diapause or dormant periods, which help them survive transit and quarantine. Other characteristics can also increase the probability of pest establishment. Asexual reproduction, for example, reduces the minimum population size needed to establish the pest in a new land. The presence of related hosts, usually at least in the same genus as the original host, increases the risk that a pest will be successful. Importation in association with host material, such as nursery stock or seed, makes establishment much more likely. Additional factors suggested by Pimentel and others (2000) as contributing to pest invasiveness include a lack of natural enemies, an ability to switch to a new host, an ability to be an effective predator in the new ecosystem, the availability of suitable habitats, and high adaptability to novel conditions.

Unfortunately, the supposition that we will know or should know in advance which pests to study, assess as risks, and quarantine has not been borne out by historical experience with any introduced forest pest. Information about the biology and distribution of known pests could possibly be shared more effectively across international borders. However, only a small percentage of the insects and microbes that inhabit forest ecosystems have even been described to date (Campbell 2001). A different approach may be needed to regulate importation of articles likely to contain forest pests.

The present policy of the United States is that imported articles are "innocent until proven guilty." This has also been called the dirty list approach; it requires study of particular articles to prove that they pose an unacceptable risk. In contrast, the inverse policy of "when in doubt, keep it out," or clean list approach, requires study of particular articles to prove they are safe, prior to importation. This is a more conservative approach, but for all the reasons given above, it may be more appropriate to introduction pathways for forest pests. Studies to develop environmentally friendly and economically feasible standard treatments for major import pathways might prove a better investment than continuing to develop regulations on a country-by-country and pest-by-pest basis.

Detection and Monitoring

Detecting early entry is a main defense against unintentionally introduced harmful organisms. Improved detection technology is needed to reduce risk, as the sheer volume of international trade has overwhelmed the present regulatory system. Advances in molecular technology, such as real-time microarrays, which can test for the presence of up to 30,000 organisms in 15 minutes, need to be adapted for implementation on a broad scale. The expense of installing such systems at all ports of entry may seem exorbitant today because this technology is new. But as this technology becomes more widely used, its application to this critical interface may become economically feasible. Again, such technology is only effective against known pests. Monitoring is the basis for effective control and containment programs, both for targeting efforts where the organisms are located and for judging the effectiveness of control measures.

Control, Containment, or Management

Early detection can make it possible to eradicate invasive pests in specific circumstances. If eradication efforts prove ineffective, the next control efforts should be an attempt to provide containment; i.e., to stop the spread. Containment efforts can protect adjoining forests, counties, and States. At present, individual landowners must defend their properties through their own control activities. Sometimes interagency cooperation could be useful. An example of this is the interagency weed team concept U.S. Department of Agriculture, Animal and Plant Health Inspection Service developed to promote prompt eradication across land ownerships. Control methods include cultural methods, pesticide applications, sanitation, physical and mechanical control, and biological control. When invasive organisms cannot be completely controlled or eradicated, then cost:benefit or similar analyses are used to choose which infestations should be managed to minimize ecological degradation, human hazards, and economic loss.

Restoration

Unless affected forest ecosystems can be made more resistant, they will probably be reinvaded. It may be impossible to restore an affected ecosystem to its prior condition because of the residual influence of the pest infestation and because the ecosystem lacks resiliency. At present, it appears feasible only to establish plant components that are resistant to nonnative invasive organisms and leave it to natural processes, such as plant succession, to complete the process.

Research

The current situation with nonnative invasive organisms shows clearly that inadequate research has been applied and applied too late. The recent discovery that interspecific hybridization can occur when nonnative pathogens or nonnative and native pathogens meet (Spiers and Hopcroft 1994), highlights the urgency of further research.

Sometimes such interactions can result in new host ranges (Brasier and others 1999, Newcomb and others 2000) or increased aggressiveness (Brasier 2001). Only through research and technology development for each of the key elements of IPM and successful implementation of proven strategies may current invasions be halted and future invasions be prevented. Because our resources are limited, and the supply of invasive pests is virtually unlimited, landscape-level analyses should be used to learn which ecosystems are most at risk and to prioritize control efforts. Also, methods for screening plant introductions must be developed (Committee on the Scientific Basis for Predicting the Invasive Potential of Nonindigenous Plants and Plant Pests in the United States 2002).

Education and Extension

Informed individuals are needed to combat the invasive nonnative problem. Much of the problem from invasive organisms is perpetuated and exacerbated by an unaware and poorly informed populace. Our Federal Government was designed to react slowly to broad swells of concern raised by the constituency to the attention of its leaders. Managers can only react when they perceive the threat and have the resources, and the citizen consumer will stop spreading nonnative organisms when they are made aware of the dangers. Public education programs might be more successful if we inform the traveling public, in advance of their foreign travel, of the threat to our natural resources from smuggling forbidden products. Once they have made their purchases and packed them away in their suitcases, the option to ignore this issue is much more tempting.

Similarly, a proactive "plant natives" program (http://plant-materials.nrcs.usda.gov) might be easier to promote than the negative message "Don't buy nonnative pest plants." Beneficial characteristics of native plants, such as better adaptation to local climate, less irrigation requirements, and the joys of restoring natural ecosystems in your own backyard should be stressed in homeowner education programs. In fact, many Government land management agencies could set a good example by making improvements in their own landscape designs in this regard. The problem of fighting invasive nonnative pests seems overwhelming, but the war must be won one battle at a time.

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RELEVANT WEB SITES

Asian Longhorned Beetle

http://www.na.fs.fed.us/spfo/alb/index.htm

http://www.aphis.usda.gov/lpa/issues/alb/alb.htm

http://www.uvm.edu/albeetle/

Balsam Woolly Adelgid

http://fhpr8.srs.fs.fed.us/idotis/insects/bwa.html

http://www.ext.vt.edu/departments/entomology/factsheets/balwoade.html

http://fhpr8.srs.fs.fed.us/hosf/bwa.htm

Beech Bark Disease

http://www.na.fs.fed.us/spfo/pubs/fidls/beechbark/fidl-beech.htm

http://www.invasive.org/symposium/houston.html

Chestnut Blight

www.ppws.vt.edu/griffin/accf.html

http://www.apsnet.org/online/feature/chestnut

http://www.forestpests.org/southern/Diseases/chsntblt.htm

http://www.forestpests.org/southern/

http://www.srs.fs.fed.us/pubs/rpc/1999-03/rpc_99mar_33.htm

Dogwood Anthracnose

http://www.na.fs.fed.us/spfo/pubs/howtos/ht_dogwd/ht_dog.htm

http://fhpr8.srs.fs.fed.us/pubs.html

Dutch Elm Disease

http://www.na.fs.fed.us/spfo/pubs/howtos/ht_ded/ht_ded.htm

http://www.fs.fed.us/na/morgantown/fhp/palerts/ded/elm.htm

http://www.ext.nodak.edu/extnews/askext/treeshr/1423.htm

Nonnative Plants

http://www.se-eppc.org/

http://www.aphis.usda.gov/ppq/weeds/ (Federal Noxious Weed Program)

http://www.nrcs.usda.gov/technical/invasive.html (Natural Resources Conservation Service's Web sites related to invasive plants)

http://tncweeds.ucdavis.edu/handbook.html (The Nature Conservancy's Weed Methods Control Handbook)

General Nonnative Forest Species Information

http://www.pestalert.org/

http://spfnic.fs.fed.us/exfor/

http://www.forestryimages.org/ (for forest health images)

http://www.ceris.purdue.edu/napis/ (National Agricultural Pest Information System Web site)

http://www.invasivespecies.gov/

http://www.invasive.org (photos of invasive nonnative species)

General Web Site

http://www.issg.org/database/welcome/ (Global Invasive Species Database)

Gypsy Moth

http://na.fs.fed.us/wv/gmdigest/

http://www.gmsts.org/operations (Slow-the-Spread Web site)

http://www.gypsymoth.ento.vt.edu/vagm/index.html

http://www.fs.fed.us/ne/morgantown/4557/gmoth/

Hemlock Woolly Adelgid

http://www.fs.fed.us/na/morgantown/fhp/hwa/hwasite.html

http://www.ento.vt.edu/~sharov/hwa/

Sources of Native Plants for Reclamation

http://www.plant-materials.nrcs.usda.gov/

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Chapter 15.

Advances in the Control and Management of the Southern Pine Bark Beetles

T. Evan Nebeker[1]

Abstract—*Management of members of the southern pine bark beetle guild, which consists of five species, is a continually evolving process. A number of management strategies and tactics have remained fairly constant over time as new ones are being added. These basic practices include doing nothing, direct control, and indirect control. This chapter focuses primarily on the latter two. Emphasis is given to recent and possible future management strategies that may become part of our overall programs. The World Wide Web will play a key role in the distribution of information about the management of the southern pine bark beetles.*

INTRODUCTION

Five species make up the guild of insects known as the southern pine bark beetles. They include the southern pine beetle (SPB) (*Dendroctonus frontalis* Zimmermann), black turpentine beetle (BTB) [*D. terebrans* (Olivier)], small southern pine engraver (fourspined engraver) [*Ips avulsus* (Eichhoff)], fivespined engraver [*I. grandicollis* (Eichhoff)], and the sixspined engraver [*I. calligraphus* (Germar)] (fig. 15.1). The SPB was responsible, in presettlement forests, for periodic perturbations that maintained uneven-aged forests and a diversity of plant species. These outbreaks were beneficial events in normally functioning southern pine ecosystems. However, the SPB is now viewed as a pest because an economic value is placed on pine and because intensive management of pine forests has caused beetle populations to interfere with efforts to achieve management objectives (Nebeker 2003).

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Because of its history, aggressive behavior, and reproductive potential, SPB causes more concern than the other bark beetles of the Southeastern United States. Although *Ips* spp. have been associated with tree mortality, they are generally considered a less-aggressive species. *Ips* prefer host material that is stressed due to a moisture deficit, slash from harvesting operations, or windthrown material. It is essential to recognize that not just one species kills our pines. However, during periods of drought, as in 1999 and 2000, *Ips* beetles attacked and killed considerable areas of pine. These events increased public awareness of the impact *Ips* can have. During that same period, SPB populations were low across the region, especially west of the Mississippi River, where they were at record lows with zero or near zero attacks reported. The reason for this apparent anomaly is unknown. One could hypothesize that SPB populations were so low because *Ips* populations displaced them during tree colonization. Another possibility is that the drought altered suitable habitat for SPB population development by limiting or changing resource availability. The question as to why the SPB population has been at such a low level during this period remains unanswered at this point. Further efforts are needed to understand the dynamics of insect biology during suboutbreak periods.

SURVEY AND DETECTION

Foresters and entomologists have long relied on ground observations, aerial surveys, and aerial photography to locate southern pine bark beetle infestations. Some progress has been made in this area over the past decade. For example, SPB spots can now be detected remotely (Carter and others 1998). Carter and others (1998) indicate that individual trees with foliage ranging from yellow to brown and classified as heavily damaged by the SPB were easily located in 675- and 698-nm reflectance images. Statistically, mild chlorosis in recently infested pines was detected by a normalized difference vegetation index (NDVI) derived from 840- and 698-nm imagery. However, this was not easily resolved visually in the NDVI images. Detection of infestations now depends entirely on the capability to detect small decreases in leaf chlorophyll content. Thus, it is expected that the increased reflectance near 700 nm that is characteristic of early, damage-induced chlorosis would be resolved more easily in pine plantations, which are even aged and have low species diversity. Interest in these methods will increase as technology improves and satellites with high-image resolution enter commercial service.

Global positioning systems (GPS) have increased the efficiency with which SPB spots can be located on the ground. Capturing the GPS locations of spots during aerial surveys has made it easier for ground crews to locate and evaluate infestations. The use of GPS also helps workers determine whether they are observing new infestations or infestations that were identified previously. This is helpful when one is trying to determine the total number of spots detected during the year.

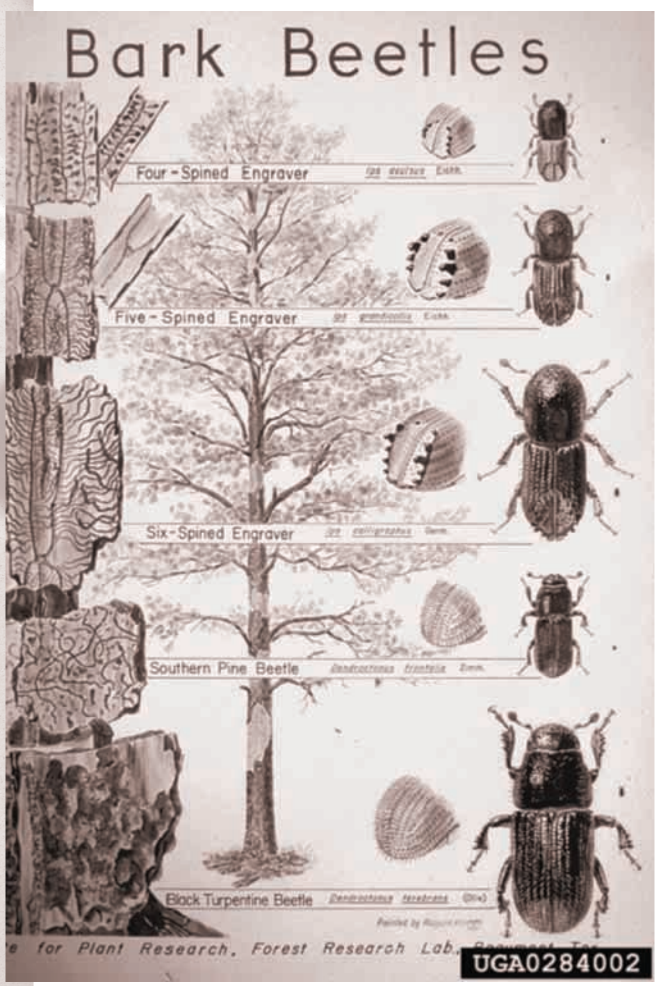

Figure 15.1—Diagram of adults, gallery patterns, and attack sites of the southern pine bark beetle guild (*Ips vulsus*, *I. grandicollis*, *I. calligraphus*, *Dendroctonus frontalis*, and *D. terebrans*). Painting by Richard Kleifoth in 1964, Southern Forest Research Institute, Jasper, TX; photo by Dr. Ronald Billings in 1981, Texas Forest Service, Lufkin, TX.

The use of aerial videography is a relatively new technology. Current uses include aerial surveys to detect SPB spots and the development of hazard ratings for the SPB. Matthews (1998) states that aerial videography at 1,000 feet aboveground level (AGL) proved to be adequate for SPB hazard rating. Because of the resolution limits of video, missions must be flown at about 1,000 feet AGL if individual trees in dense forests are to be detected. There is an added convenience in that the video can be analyzed in an office or laboratory; traditional spotters located spots on sketch maps while flying 500 to 1,000 feet AGL.

Oliveria observed that electronic sketch-mapping has been developed to assist in plotting the locations of infestations during aerial surveys.[2] Selected backdrops (maps or aerial photos) of the survey area can be loaded into a laptop computer. The computer is linked to an onboard GPS system and a touch-sensitive screen. During the survey flight, the computer uses the GPS to display the proper backdrop while indicating the plane's location relative to the ground. The spotter plots observed infestations by touching their locations on the display screen. The data are downloaded into a Geographic Information System (GIS) Program, and maps with spot coordinates are produced.

MANAGEMENT

Integrated pest management (IPM), integrated forest pest management (IFPM), forest health protection (FHP), forest health (FH), and forest resource protection (FRP) have slightly different philosophies, but they all have the goal of protecting and sustaining forest resources (Nebeker 2003). Ecosystem management also has much to offer, but sometimes fails to include consideration of pest problems (Boyce and Haney 1997). Continuing changes in our society and individual views of how forest resources are to be utilized or not utilized directly impact management options. For example, some view certain forest conditions as threatening or unhealthy, while others see the same conditions as healthy or just the natural course of events. The potential for forest fire can be seen in this way. These differing points of view are based on individual

[2] Personal communication. 2001. Forrest Oliveria, Field Office Representative, Forest Health Protection, 2500 Shreveport Highway, Pineville, LA 71360.

or organizational agendas (Allen 1994, Boyce and Haney 1997). Reconciling different points of view is one of the most difficult tasks we face in the protection of our natural resources.

The Expanded Southern Pine Beetle Research and Application Program and the IFPM Program were administered by the U.S. Department of Agriculture Forest Service (Forest Service) out of Pineville, LA, during the 1970s and 1980s. These programs provided an opportunity to gain a great deal of new information concerning the SPB, as well as for *Ips* and BTB. The technology transfer efforts associated with these programs provided a structure for getting pest management information into the hands of users as quickly as possible. Efforts such as these have shown that communication and distribution of information are critical for control and management purposes.

Recently an extremely useful tool for the management of bark beetles has been evolving on the World Wide Web (WWW). Financial resources have become a limiting factor in providing printed material for distribution, and the Web has developed into an outstanding addition to that end. The Web site (http://whizlab.isis.vt.edu/servlet/sf/spbicc/) of the Southern Pine Beetle Internet Control Center (SPBICC) has become a source for SPB information, control strategies, research, and other ongoing activities. This site also supports communication among persons whose work involves southern pine bark beetles. For example, CONTACT _Con-49F8B1C38C Steve Clark (U.S. Department of Agriculture Forest Service, Lufkin, TX) has summarized an IPM Program for the SPB that can be accessed on the SPBICC at http://whizlab.isis.vt.edu/servlet/sf/spbicc/page.html?name=spb_IPM. This program draws together currently available approaches and new investigations. Appropriate links are included to provide additional information about the various control and management options. Information about SPB activity is posted on the SPBICC site as it becomes available. Another site, http://bugwood.org/, contains valuable information about bark beetles and related insects. It also presents a wealth of related information about FH and FHP issues. One can also refer to numerous Web sites at universities, follow the appropriate links, and find needed information. An example of a university site having links to useful sites is http://msstate.edu/~nebekers/. The WWW has become an extremely useful tool for communication and technology transfer. With such information, informed decisions can be made and appropriate strategies can be followed.

We have, for a number of years, recognized various management strategies and tactics that are available when dealing with bark beetles. One option is to do nothing. If we take this approach, we can expect history to be repeated: we can expect periodic outbreaks as a result of population fluctuations, and we can expect that the amount of pine mortality in our forests will reflect past trends. However, with increases in acreage of host type, we might predict proportional increases in bark beetle activity and tree mortality.

Prevention is another management strategy we are beginning to understand. To prevent losses to southern pine bark beetles, we must follow a few guiding principles (Nebeker and Hedden 1984). These principles include (1) matching the tree species to the right site—trees planted on the wrong sites seldom have the vigor necessary to deter or withstand attack; (2) controlling stand density—if a stand's basal area exceeds the site index, then the stand should be thinned to the appropriate level; (3) promptly salvaging all lightning-struck, logging-damaged, diseased, and high-risk trees, and harvesting overmature trees when pest activity is low; (4) planting trees only in their natural range—planting pines outside their range and offsite causes additional stress that increases their susceptibility to attack; (5) minimizing site and stand disturbances—exercising care in use of heavy equipment, road layout, culvert location, and other construction projects since changes in drainage result in tree stress; and (6) harvesting all mature trees at, or shortly after, rotation age. The use of good silvicultural practices reduces the likelihood of insect attack. Good silviculture can reduce losses from SPB (Belanger and Malac 1980).

Hazard rating and thinning have tremendous practical value but have not been fully utilized. Hazard-rating systems have been developed for most subregions of the South (Mason and others 1985). They identify the combinations of site and stand conditions commonly associated with SPB infestations. They also identify the conditions under which SPB is most likely to occur and where the greatest amount of damage would be expected. Hazard ratings do not predict when, or if, an attack will occur, but they do provide information that managers should find useful in identifying and ranking locations or stands that warrant consideration for increased surveillance, preventive treatment, accelerated suppression action, or postdamage appraisal (Hicks and others 1987). Most hazard-rating systems include variables that can be altered silviculturally.

High-hazard stands can be converted to medium-hazard or low-hazard stands through silvicultural treatments that alter parameters such as stand density, basal area, or radial growth.

Thinning, like hazard rating, has often been overlooked as a method of reducing the amount of suitable habitat for the SPB during periods of low populations. Thinning has the potential of affecting the overall population dynamics of the SPB when applied over the landscape. Numerous studies have indicated that thinning is useful in reducing the susceptibility and suitability of stands to SPB attack (Brown and others 1987; Nebeker and Hedden 1984; Nebeker and Hodges 1983, 1985; Nebeker and others 1985). Traugott (2000) indicated that it is important to thin at the appropriate time for the following reasons: (1) to retain high-quality trees, (2) to receive an intermediate income, (3) to enhance wildlife habitat, and (4) to maintain the health and vigor of the stand and, thus, reduce the severity of losses caused by southern pine bark beetles.

In 2001, the Forest Service allocated funds to cooperating State agencies for southern pine bark beetle prevention work. Prior to this, funds had been allocated only for suppression. The move to initiate prevention efforts came as a result of Forest Service efforts to develop nationwide risk maps and to utilize these maps in setting priorities for addressing problems associated with changing FH conditions. FHP (Forest Service) strives to reduce impacts of insects and diseases by implementing pest suppression and prevention projects on national forests and on other Federal, State, and tribal lands. SPB risk can be reduced by early detection and rapid control of spots, which reduces additional mortality caused by spot growth. Thinning helps maintain vigorous, healthy stands resulting in a reduction of habitat for attack and spot growth. It is hoped that practitioners of FRP will welcome this movement toward prevention rather than relying only on suppression strategies and tactics.

Under circumstances in which prevention is not the management strategy of choice, there are other options. They include both direct and indirect methods of control and management that are available or evolving. Direct control measures result in immediate mortality to the bark beetle population. There are four basic direct control tactics: (1) salvage—infested trees and an appropriate buffer strip (uninfested trees) are sold, cut, and removed; (2) cut and leave—infested trees are felled toward the center of the spot to allow for maximum exposure of the infested portion of the bole to the sun; (3) cut, pile, and burn—infested trees are felled, pushed into a pile, and burned; and (4) cut and spray—trees are felled, and their boles are sprayed with an approved insecticide. It appears, however, that it may not be possible to use insecticides to control pine bark beetles in the future. Only lindane and chlorpyrifos are now registered for use in forest operations. Lindane is registered but is not presently available with a label for forestry use. Existing supplies of lindane are disappearing, or have disappeared, and the product will be discontinued within the next few years. However, the manufacturer of a chlorpyrifos-based compound has consented to maintain a forestry registration and is reregistering its product. The manufacturer will not initiate production of the forestry-labeled product until they can determine that there is a demand for it. Also, chlorpyrifos is now a restricted-use pesticide and can be purchased and applied only by certified applicators or persons under their supervision. Other compounds, such as bifenthrin, are being studied as possible alternatives. Direct control tactics other than insecticides will be recommended when immediate mortality to the bark beetle population is the goal. Cut, pile, and burn methods will have limited use because of their cost and the problems associated with smoke.

New approaches to managing bark beetles are always being investigated. For example, verbenone, an antiaggregation compound, has been registered in North Carolina, South Carolina, Mississippi, and Georgia and can be used to suppress SPB. Specialized training is necessary to ensure that the product is used correctly. A Web site, http://everest.ento.vt.edu/~salom/Workshop/workshop.html, has been established for those interested in following this effort. Other strategies and tactics are also being investigated to suppress bark beetle populations by the use of various compounds that have been found to repel or attract bark beetles, but have not yet been registered for use.

BIOLOGICAL CONTROL

Consideration of biological control in relation to the southern pine bark beetles has largely been ignored, especially in relation to intensive pine plantation management systems. Pine trees grown in a monoculture usually create a forest that has less plant and animal diversity than a natural pine forest. In such settings plant diversity is low, and nectar sources for the parasites of bark beetles are limited. Hence, the community of SPB natural enemies is potentially reduced in pine plantations and is therefore less likely to be effective against SPB populations in such settings. In addition, direct control techniques recommended for controlling bark beetles are aimed at killing or disrupting the colonization process, and these techniques also damage natural enemy communities.

Research has discovered that supplemental feeding of SPB parasitoids increases their egg production and longevity (Stephen and Browne 1999). This suggests that providing food for parasitoids can increase parasitism of SPB. A new product has been developed for application to boles and crowns of pines infested with SPB (Stephen and Browne 2000). The use of this new product should conserve and promote parasitoid populations and increase their effectiveness.

It is important to maintain communities of natural enemies. Simple things, such as not cutting trees vacated (used and abandoned) by SPB when implementing direct control tactics is a good strategy. Many of the natural enemies do not complete their life cycle until after the SPB has vacated the tree. Vacated trees also provide nesting habitat for woodpeckers that prey on bark beetles. Our society has emphasized and will continue to emphasize the need for protecting the environment and the need for increasing species diversity whenever possible. Hence, there is a need to expand our efforts in the area of biological control, concentrating on methods that increase biodiversity without harming the environment. It may be possible in the future to plant flowers in or near pine stands to provide nectar that will increase the life span of adult parasites associated with the southern pine bark beetle guild.

As we learn more about the nutritional requirements of the natural enemies of SPB, we must also understand their population dynamics. Progress has been made in this area. For example, it has been hypothesized (Turchin and others 1999) that SPB outbreaks are controlled by a delayed density-dependent response from natural enemies. Augmenting natural populations of predators, parasitoids, and competitors may accelerate the decline of SPB epidemics. In addition, mass-rearing techniques are being developed for one of the key predators of the SPB, the checkered clerid beetle [*Thanasimus dubius* (F.)].[3] Releasing a mass-reared predator would be another option in attempting to manage bark beetle populations.

Recently, new mortality agents have been discovered in association with the SPB. Sikorowski and others (1996) were the first to discover and describe virus and viruslike particles in SPB adults from Mississippi and Georgia. It is believed that this is the first record of viruses associated with SPB and *Dendroctonus* (Coleoptera: Scolytidae) in general. Sikorowski and others (1996) hypothesize that viruses associated with SPB may be an important means of naturally controlling SPB populations and useful in explaining population cycles. Future research will examine this hypothesis.

CONCLUSIONS

It is anticipated that there will be major advances in survey and detection in the future. These advances will involve the use of remotely sensed data obtained from satellites and various other platforms. High-resolution imaging systems are in place or are planned, and accompanying techniques to identify key features on the landscape, such as SPB spots, will become another part of our detection system. Processing imagery of large landscapes will become automated and increase our efficiency in identifying the boundaries of infestations.

FRP of the future will be aimed more and more at prevention. Initial steps have already been taken through the development of hazard- and risk-rating systems. These systems identify areas that are likely to be attacked by bark beetles. This information then becomes part of the decisionmaking process by identifying the areas that should be treated first to reduce the hazard. Hazard-rating information can then be used in connection with other criteria specified in a forest management plan to make a final decision. Hazard-rating systems provide various options for reducing hazard through silvicultural means and become part of a prevention management program. Various decision-support systems that can help us deal with southern pine bark beetles can be accessed through the SPBICC.

We may soon be unable to use any insecticides in our forests. At present, there is effectively only one insecticide labeled for forest uses, and there are no new insecticides on the horizon. Hence we will be dependent on the other direct tactics, such as salvage or cut-and-leave operations, when trying to suppress southern pine bark beetle populations. The practicality of salvage

[3] Personal communication. 2002. John D. Reeve, Assistant Professor, Department of Zoology, Southern Illinois University, Carbondale, IL 62901–6501.

and cut-and-leave tactics is limited by the difficulty or impossibility of finding markets for salvaged trees. Because of these limitations, more and more emphasis will be placed on prevention tactics.

There is hope that new approaches may prove useful. These include the use of antiaggregation compounds that disrupt the bark beetle colonization process. The WWW will be a useful tool for distributing information concerning this approach and other developments in the management of bark beetle populations. New paradigms will influence our decisionmaking process, especially as our understanding of ecological processes improves and helps us to identify and document the key factors regulating bark beetle populations.

We stand at an interesting point in history, one at which we have become much more aware of the environment around us. We have an increased desire to participate in resource management processes that limit adverse environmental change. Such processes include efforts to restore and rehabilitate forests and to conserve our natural resources.

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Chapter 16.

The Impact and Control of Major Southern Forest Diseases

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Abstract—*A variety of forest health issues, concerns, and events have rapidly changed southern forests and plantations in the past two decades. These factors have strongly impacted the ways we manage forest pests in the Southern United States. This trend will no doubt continue to shape forest pest management in the future. The major issues and events of concern include changing forest conditions, urbanization, multiresource issues, increased harvesting, forest fragmentation, expanding human populations, pesticide bans, expansions of native and nonnative pests into new regions, emergence of new damaging insect-disease complexes, and reduced resources to manage these problems. The effects of some of these factors on forest health priorities and specific pest-suppression practices are discussed in relation to some major hardwood and conifer diseases in southern forests. The ways in which these pests are influencing southern forest management priorities and practices and the progress that past and present pest-suppression research has made toward solving some of these pest-suppression problems also are discussed.*

INTRODUCTION

The preceding two decades have brought a barrage of new developments that are shaping the evolution of forest management practices with regard to forest health issues and disease suppression in southern forests. Some of the more important developments impacting forest health management in the South include: (1) legislative bans on the use of many pesticides and chemical controls formerly used to manage forest pests; (2) continued introductions of nonnative pests to which many of our endemic tree species have little resistance; (3) expansion in distributions and outbreaks of important native pests into previously unaffected areas; (4) occurrence of new synergistic forest pest complexes previously unrecognized as important to forest management decisions; (5) nationwide reductions in the research work force (forest pathologists) available to study and develop new pest suppression technologies; (6) drastic reductions in forest management and pest-suppression activities on Federal lands; (7) inadequate approaches to regional pest problems as a result of overemphasis of theoretical research approaches, e.g., modeling systems and disease forecasting, instead of improvements in direct, applied approaches to disease suppression; and (8) the existence of new emerging endemic diseases such as bacterial leaf scorch (*Xylella fastidiosa* Wells and others) that are causing widespread damage previously unrecorded in commercially important fiber- and lumber-producing tree species (Billings 2000, Britton and others 1998). The impact of these issues and events on disease suppression and forest management decisions in general will be treated in the following discussions relevant to individual major hardwood and conifer diseases that occur in the southern region.

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MAJOR HARDWOOD DISEASES

Oak Wilt in Urban Forests

Urban forests are becoming increasingly important components to be considered in the development of forest management objectives as cities and municipalities continue to encroach on natural forest stands. Protection of tree resources in urban areas is becoming more important, not only because urban trees have commercial lumber value or provide habitat and food for wildlife, but because their aesthetic value contributes significantly to property values. A good example of this trend has been demonstrated by the impact of oak wilt, caused by *Ceratocystis fagacearum* (T.W. Bretz) J. Hunt, on urban forestry. Within the last 20 years, oak wilt has caused increasingly devastating losses to valuable urban and suburban trees within and near metropolitan areas of Texas in the South and within major cities in Minnesota, Wisconsin, Iowa, and Illinois in the Midwest (Wilson 2001).

Tree mortality in urban areas causes economic losses in several ways. Reductions in landscape aesthetics resulting from tree mortality can significantly lower property values. The death of a single large urban live oak in Texas can result in a loss of as much as $20,000 in property value (Dewers 1971). It is not uncommon for landowners in Austin, TX, to sell their property once oak wilt has been diagnosed on their land in order to avoid the investment loss associated with the reduction in property value. Losing valuable shade trees can substantially increase utility bills (cooling costs) for homeowners. Tree removal costs also can be significant when they involve large trees. Finally, replacement costs associated with replanting trees adds to the final expense of losing valuable landscape trees. The consequences of increases in oak wilt incidence in valuable urban trees have resulted in accelerated economic losses now estimated to have exceeded $1 billion over an area of at least 61 of 254 counties in Texas alone (Wilson 2001).

Figure 16.1—Live oak injured by heavy tree-clearing equipment at a residential building site in Austin, TX, providing entry points (infection courts) for introduction of the oak wilt fungus into the living sapwood by insect vectors. Photo by A. Dan Wilson.

The rise in oak wilt incidence in urban areas has been attributed in part to increases in home construction and landscape improvement activities associated with urban development. Austin, TX, with over 10,000 live oaks (*Quercus fusiformis* Small and *Q. virginiana* Miller) killed by oak wilt in the last 20 years, may be the most heavily affected city in the United States. Residual trees often sustain considerable damage during initial tree clearing of land prior to home construction. Heavy equipment frequently scrapes and removes bark from trees, creating infection courts for the introduction of oak wilt inoculum by insect vectors (fig. 16.1). Tree wounding also occurs when trees are pruned by landowners during times when insect vector activity is high. When such trees become infected, they initiate infection foci from which new oak wilt infection centers develop and spread by root-graft transmission. The storage of oak wilt and bark beetle-infested firewood in piles near residences provides both inoculum and insect vectors by which wounded trees may become infected. An increase in incidence of oak wilt in natural stands has also contributed to a higher incidence in urban areas. Oak wilt incidence increased in many natural oak stands during the first half of the 20th century in the Eastern United States when Dutch elm disease, caused by *Ophiostoma ulmi* (Buisman) Nannf. and *O. novo-ulmi* Brasier, and chestnut blight {*Cryphonectria parasitica* (Murrill) Barr [formerly *Endothia parasitica* (Murrill) Anderson & Anderson]} caused changes in stand composition by removing dominant species that were largely replaced by red oak species susceptible to oak wilt (Wilson 2001). The increased incidence of oak wilt in natural stands has since been closely linked to changes in forest management practices such as high-grade harvesting, preferential thinning, overgrazing, and fire suppression that favor reduced species diversity and increase the number of susceptible red oaks in stands.

The Texas Forest Service administers the Texas Oak Wilt Suppression Project (TOWSP) with funding and technical assistance provided by a combination of U.S. Department of Agriculture Forest Service (Forest Service) funds and matching funds provided by the State of Texas. This has been among the very few cooperative (State) disease suppression programs in the country that have received Federal assistance since 1995 (Wilson 2001). A recent addition occurred when the sudden oak death pathogen, *Phytophthora ramorum* Werres, was first discovered in the United States (California) in 1995, and Federal funds were appropriated for research and suppression beginning in 2003. TOWSP personnel coordinate the efforts of local governments and private citizens to detect and control oak wilt. The project's goals are to educate the public, locate disease centers, provide technical and cost-sharing assistance in suppressing the fungus, and monitor suppression treatments to control spread.

Recent improvements in oak wilt management have resulted from modifications of existing control strategies, empirical advances arising from experiences gained during implementation of suppression programs, and research developments of new suppression technologies. Trenching, the practice of mechanically cutting root connections between healthy trees in advance of the visible expanding edge of infection centers to control root transmission of the oak wilt fungus, has been recommended for many years (Himelick and Fox 1961) and has long been the cornerstone and primary means of suppressing the spread of oak wilt in the United States (Wilson 2001). In Texas, the fungus spreads primarily through interconnected root systems, creating infection foci with radial expansion rates that sometimes exceed 31 m/year. In attempts to stop the advance of infection, cooperators in the TOWSP began cutting barrier trenches in 1988. The TOWSP installed over 762,000 linear m of trench around almost 4,000 infection centers detected in central Texas by 2000 (Wilson 2001). This represented treatment of about 44 percent of confirmed centers detected, but < 10 percent of infection centers likely to exist statewide. Trenching was about 67 percent successful in stopping the spread of encircled infection centers by 1994 (Billings and others 2001). Since 1994, 76 percent of trenches have had no breakouts. This improvement was attributed to installation of deeper trenches (up to 1.8 m) and improved trench placement. The majority of trench breakouts that occurred within the first 3 years after trench installation were due to improper trench placement or insufficient trench depth that failed to sever preexisting root grafts. Breakouts that occurred 3 or more years after trench installation were more likely to result from the formation of new root grafts across the trench by fusions of new adventitious roots arising in the loose, trench-backfill soil from roots previously severed by trenching (Wilson and Lester 2002). During the first several years following trench installation, an abundance of small adventitious roots commonly formed from roots severed in the loose backfill soil by trenching. These roots provided opportunities for initiation of new root-graft connections across trenches in subsequent years.

A recent oak wilt suppression research study, conducted by a Forest Service scientist, investigated the effectiveness of trench insert materials in preventing trench breakouts initiated by root grafting across the trench. These results indicated that trench inserts did not significantly reduce or stop root transmission during the first 3 years following trench installation, but that the use of water-permeable inserts effectively improved the performance of trenches beyond the third post-trenching year, when trenches are still normally effective, and extended trench longevity indefinitely (Wilson and Lester 2002). Water-impermeable materials, however, sometimes promoted trench breakouts by their tendency to redirect root growth around these barriers, leading to the development of new root-graft connections and associated oak wilt root transmission across the trench. Water-permeable inserts were more effective root barriers because they did not direct root growth from the point of root contact. The additional minimal cost of trench inserts above trenching costs is justified in urban and rural homestead sites where valuable landscape trees require more protection, and additional retrenching costs are avoided. Assuming that trench depth and placement problems are now solved through experiences gained by the TOWSP, this improved method of oak wilt suppression should greatly increase trench effectiveness, and could potentially save Texas landowners (alone) hundreds of millions of dollars in tree removal costs and property value depreciations if this control is vigorously implemented by the TOWSP.

The trenching research also confirmed that applications of the systemic fungicide propiconazole (Alamo©) by high-volume bole injections, used by the TOWSP until 1997, are ineffective in preventing root transmission of the oak wilt pathogen in individual trees, despite the high sensitivity of the fungus to this fungicide (Wilson and Forse 1997). The sporadic and undependable effectiveness of propiconazole was attributed to the predominately upward mobility of the fungicide, which precluded root treatment when the fungicide was injected into the lower bole. As previously applied, only a small fixed proportion of the injected active ingredient moved down into the root system by vapor phase activity. City arborists partially compensated for this by increasing the dosage of the fungicide from 3 to 10 ml/L or higher, thus increasing the amount of active ingredient moving down into the roots by vapor phase activity. However, previous research indicated that soil-drench applications of the fungicide at the tree dripline immediately prior to challenge inoculations provided more effective treatment (better coverage) and more protection of root systems, because the fungicide is applied and taken up at the distal ends of roots near root apices, thus allowing more complete and thorough distribution throughout the entire root system (Wilson and Lester 1995).

The combined effect of using the improved trenching methods (cultural control) with trench inserts to prevent root transmission of oak wilt, together with the increased effectiveness of soil-applied fungicide treatments, should significantly advance efforts to suppress oak wilt disease in semievergreen live oaks in Texas and in deciduous oak species affected by this malady in other States. If these controls are implemented, they could potentially save landowners hundreds of millions of dollars in tree removal costs and property value depreciations in Texas, and substantially greater savings in other areas of the United States affected by this disease.

Hardwood Plantation Diseases

Hardwood tree species have been grown in plantations throughout the Southeastern United States for more than 50 years, although the total acreage in hardwood plantations is much less than that in softwood species. Since the early 1990s, market conditions and new approaches to environmental issues have led to changes in cultural methods for growing hardwoods and the planting of many more acres of hardwoods. Fiber-farming technology has allowed industrial growers to plant bottomland hardwood species on upland sites where rapid growth is fostered by irrigation and liquid fertilization, a method referred to as fertigation. This cultural method allows year-round harvesting, whereas wintertime harvesting in natural bottomland stands is limited by wet soil conditions and associated environmental concerns. In the Lower Mississippi River Alluvial Valley (LMRAV) and other areas in the Southeast, agricultural land is being afforested in response to changing agricultural markets and increasing interest in ecosystem restoration (Stanturf and others 2000). Fiber farming and large-scale afforestation present unique challenges and opportunities to growers and pest management professionals.

American sycamore (*Platanus occidentalis* L.) has good commercial value because of its rapid growth and excellent pulping qualities for the production of paper products. Sycamore is commonly used in afforestation efforts. During the early and mid-1970s, sycamore decline was the main problem of concern to sycamore producers in the Southeastern United States. Surveys conducted in the 1970s, focusing on leaf scorch, dieback, and cankers, found a complex of diseases associated with sycamore decline. These included canker stain, caused by *Ceratocystis fimbriata* (Ellis & Halst.) F. *platani* J. M. Walter; Botryosphaeria canker, caused by *Botryosphaeria rhodina* (Cooke) Arx; and anthracnose, attributed to two conidial stages of *Apiognomonia veneta* (Sacc. & Speg.) Höhn (Filer and others 1975). Leaf scorching occurred in all locations surveyed. Leaves were described as scorched, eventually turning completely brown, but not shedding prematurely. These symptoms are common for bacterial leaf scorch, a disease caused by *Xylella fastidiosa* Wells and others (Leininger and others 1999, Sherald and Kostka 1992), but which was attributed in the 1970s to late-summer symptoms of anthracnose caused by fungi, particularly species of Colletotrichum (McGarity 1976). Tree diseases caused by *X. fastidiosa* were considered hard to diagnose in the past because diagnosticians were unfamiliar with the pathogen and no diagnostic tools were available to detect it. Symptoms were easily confused with those of other biotic and abiotic factors such as moisture stress and herbicide damage. The presence of the bacterium in trees previously was difficult to confirm using routine laboratory techniques because of its fastidious nature (Sherald and Kostka 1992). The advent of enzyme-linked immunosorbent assays (ELISA) has made diagnosis of *X. fastidiosa* infections in plants routine, and has facilitated the detection of bacterial leaf scorch in sycamore throughout the Southeast. Polymerase chain reaction is also being used to detect this bacterium in plants. Recent visual surveys and ELISA testing of sycamore plantations across the Southeast showed that bacterial leaf scorch caused severe dieback, decline, and mortality to sycamore saplings growing on sites with or without irrigation (Britton and others 1998). Initially, necrotic zones appear along the midrib and main veins of leaves by late July of the second growing season. Severe marginal leaf scorching in foliage throughout individual crowns and the entire stand is common by the third year. Branch and top dieback occurs in 50 percent or more of a stand and some mortality may occur by the fifth year. In severe cases, premature salvage harvests are justified because of concerns that stands will not contain sufficient volume at the normal pulpwood rotation age to pay for the additional carrying cost. Research is currently underway to identify sycamore genotypes that are tolerant to bacterial leaf scorch disease (Chang and others 2002).

Many of the same hardwood species used in fiber farming also are used for afforesting former agricultural fields. These include several oak species, eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.), American sycamore, and green ash (*Fraxinus pennsylvanica* Marsh.). Forest restoration through afforestation is just beginning on a large scale in the LMRAV, and many successful planting and cultural methods are in use (Stanturf and others 2000). Development of new management methods for controlling insect and disease pests in these monocultural plantation settings is badly needed. Cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.) seedlings growing in nursery beds are susceptible to leaf injury and stunting from *Cylindrocladium scoparium* Morg. (Smyly and Filer 1977). Newly emerged hardwood seedlings of many species are susceptible to damage from soil-borne fungi such as species of *Fusarium*, *Rhizoctonia*, and *Pythium* that cause damping-off (Filer and Cordell 1983). Insect and disease management guides for oaks (Solomon and others 1997), sycamore (Leininger and others 1999), cottonwood (Morris and others 1975), and ash (Solomon and others 1993) will aid in diagnosing many problems, especially in older stands. However, disease problems in nurseries and on stored and newly planted seedlings will require research and development of new control methods, especially since traditional controls such as methyl bromide have been eliminated. Concern for the surrounding environment is likely to lead to the development of biological and chemical controls that minimize long-term effects on ecosystems adjacent to plantations.

Declines of Oaks and Other Hardwoods

Decline disease syndromes, commonly called declines, have been described by Manion and Lachance (1992) as a progressive interaction of abiotic events and biological factors or agents that eventually can lead to individual tree death and widespread forest mortality, depending on the severity of the decline event. Declining trees typically have been predisposed by abiotic factors such as site index, soil type, and climate change, although biotic factors such as old age or genotype also can be predisposing factors. Actual decline is triggered or incited by biotic or abiotic factors such as drought, flooding, insect defoliation, or air pollution. Trees that are already in a weakened physiological state are weakened further, and in this condition may die. They may recover, perhaps to succumb later to other stresses. Biological agents, for example, wood-boring insects, phytophagous insects, wood decay fungi, and bacteria can quickly colonize a physiologically weakened tree and contribute to its final demise. Declines occur periodically and are often triggered by climatic extremes. For example, a report by Ammon and others (1989) summarized 26 decline events during the previous 140 years, and many of these were brought on by periods of drought.

The most recent Forest Service report of forest insect and disease conditions in the United States (U.S. Department of Agriculture, Forest Service 2002) lists several Southeastern States in which forests are experiencing oak decline as a result of severe summer drought from 1998 to 2000. A drought-induced decline of red oaks in the Ozark and Ouachita Mountains of central Arkansas reportedly covers hundreds of thousands of acres and is associated with extraordinarily high numbers of red oak borers [*Enaphalodes rufulus* (Haldeman)] as a contributing factor in the decline (U.S. Department of Agriculture, Forest Service 2002). The Forest Service report also describes oak declines in the Appalachian Mountains of Virginia, North Carolina, Georgia, and in Tennessee, where white oaks were especially affected. During the summer of 2000, many Nuttall (*Q. nuttallii* Palmer), willow (*Q. phellos* L.), and water (*Q. nigra* L.) oaks began declining in the Dewey-Wills Wildlife Management Area in east-central Louisiana because of the 1998 to 2000 drought. To date, nearly 6,000 acres of red oaks have been affected, and the decline includes attacks by the red oak borer and bacterial wetwood infections. In west-central Mississippi during the late spring of 2001, about 2,000 acres of plantation-grown eastern cottonwood trees were severely defoliated by a notodontid moth [*Gluphisia septentrionis* (Walker)]; again, the 1998 to 2000 drought was believed to be a predisposing factor in this decline. Defoliation by the common *Gluphisia* was followed by cottonwood leaf beetle (*Chrysomela scripta* F.) defoliations on the second flush of leaves in 2001, further weakening the trees. This pest of *Populus* species, which is common in the Northeastern United States and Southeastern Canada, defoliated the same cottonwood trees in late spring 2002; lower boles were also infected with bacterial wetwood.

Decline diseases involving climate may be of particular concern for future southern forests if predictions of extremes in atmospheric temperature and precipitation resulting from increased greenhouse gases hold true. Anthropogenic inputs of gases such as carbon dioxide, methane, and oxides of nitrogen into the atmosphere have been increasing for some time above apparently normal historic levels (Ning and Abdollahi 1999). Some research suggests that these increased gas concentrations are affecting global surface temperatures by altering the amount of solar energy reflected off the Earth's surface, resulting in the greenhouse effect (Ning and Abdollahi 1999). Various hypotheses and process models attempt to explain possible climate changes and the subsequent effects to natural and man-made ecosystems (National Assessment Synthesis Team 2000). If there are major systematic changes occurring in the climate, they will likely give rise to more numerous decline-related insect and disease problems.

Root and Butt Rots

Root and butt rots are the most serious cause of lumber cull and degrade in southern forests. All southern hardwood species are affected, and the loss in terms of hardwood timber volume amounts to millions of board feet annually. The lower bole has always been of most concern to hardwood forest managers because these are the most valuable logs in the tree and the logs most likely to be wounded by harvest equipment, by logs pulled on skidder tracks, and by falling trees. During most of the 20th century, forest managers have tried to suppress root and butt rots in southern hardwood stands by preventing the creation of wound scars by which most decay fungi gain entry into the tree. During the first half of the last century, much effort went into controlling wounds caused by fires. At least 80 percent of lower bole decays in bottomland hardwoods were attributed to fire scars during that period (Toole 1960). Protection of the lower bole is still of prime concern in avoiding wounding. However, because fires are rarely a problem in hardwood forests today, this concern has largely shifted from fire wound management to management of logging wounds in residual trees caused by heavy harvesting equipment during precommercial thinning and partial commercial cuts. As demand for hardwood lumber volume increases in the future, management of root and butt rots in hardwoods will slowly begin to move away from the tolerance approach, or a willingness to live with and allow for a certain amount of cull losses by increasing cut volume, to a more preemptive approach based on detecting these microbes in standing trees and adjusting harvest schedules to reduce losses. This approach will require the capability of detecting incipient decay in standing trees and determining the specific causes of decay. However, new technology and decay models will have to be developed to provide the necessary knowledge and detection capabilities before this approach becomes feasible.

At least 30 fungi are known to contribute to root and butt rots in southern hardwoods, but only a relatively few species cause most of the damage. The root and butt rot fungi most frequently encountered in most southern hardwood stands include *Pleurotus ostreatus* (Jacq.:Fr.); *Ganoderma lucidum* (W. Curt.:Fr.); *Hericium erinaceus* (Bull.:Fr.) P.; *Armillaria tabescens* (Scop.) Den.; *Inonotus dryadeus* (Pers.:Fr.) Mu.; and *Laetiporus sulphureus* (Bull.:Fr.) Mu. Other species that are important to a lesser extent in individual hardwood species include *Inonotus hispidus* (Bull.:Fr.) P. and *Tyromyces fissilis* (Berk. & Curt.) Donk, *Lentinus tigrinus* (Bull.:Fr.) Fr., *Phellinus igniarius* (L.:Fr.) Quél, *Trametes versicolor* (L.:Fr.) Pil., *Rigidoporus lineatus* (Pers.) Ryv., *R. ulmarius* (Sowerby:Fr.) Imazeki in Ito, *Tomentella* spp. (Pat.), and the ascomycete *Kretzschmaria deusta* (Hoffm.:Fr.) P. Martin (= *Hypoxylon deustum* (Hoffm.:Fr.) Grev.). The rate of decay development within hardwoods varies with the specific wood decay fungus present and the host species involved (Toole 1959). Thus, decay volume models must account for host species, decay fungi, and log taper equations of individual hardwood species when predicting future lumber volume losses.[2] This information would be necessary for making stand harvesting decisions. Also, a portable, inexpensive, easily used detection device would be necessary to identify the presence and extent of damage by specific decay fungi in standing trees during routine stand evaluations by timber cruisers for the purpose of planning future harvest schedules.

The development of new technologies and methodologies for mitigating losses by wood decay fungi and other microbes causing defect losses in standing timber has been an active field of interest in recent years (Wilson and Lester 1997). Forest managers and cruisers responsible for monitoring forest stands are primarily interested in methods and criteria for minimizing losses in lumber volume and optimizing production in commercial forests. A major challenge facing forest managers is that of establishing policies and procedures for making management decisions to deal with defect losses including decay, discoloration, and structural alterations in the properties of wood caused by microorganisms in the sapwood and heartwood of standing timber. Most estimates indicate that at least 30 percent of the total lumber volume available in many southern hardwood stands is degraded or rendered unmerchantable by lumber defects caused by these pests. Defects in logs of standing trees can lead to significant economic losses ranging from reduced lumber production volume per acre to reduced lumber value (grade), degrade to pulpwood status with no merchantable lumber, and ultimately total loss with no commercial value available for salvage. The most significant challenges to be addressed in relation to defect volume losses in lumber production are to find ways of detecting defect in logs of standing trees and to determine when to cut individual trees that have log defects in order to optimize production on an individual tree basis. The methods used over the past 50 years to detect the presence of log defects in standing trees by cruisers of most commercial lumber producers have involved "sounding" the wood (butt log) by striking it with a hard object to locate hollows in the lower bole. This archaic method is useful only to detect advanced defect in standing trees because trees with incipient or even intermediate stages of defect usually cannot be distinguished from healthy trees. Unfortunately, detecting advanced defect is of little value, because it only serves to identify unmerchantable trees. Also, it occurs long after the decision should have been made to harvest the tree and avoid the high level of cull losses associated with the development of defect to advanced stages.

Previous strategies for managing defects in southern hardwoods involved simply accepting the defect losses caused by microbes and insects by removing the cull volume as the logs were processed at the mill. With the growing demand for quality lumber volume in the United States, new technologies are now needed with the capability of detecting defects in logs of standing trees at incipient stages before significant damage reduces the resulting lumber value in individual trees. New methods and technologies under development, such as electronic aroma detection by conductive polymer analysis (CPA) of volatile metabolites released from microbial log-degrading pests, will allow preharvest field detection of log defects using a portable detector (Wilson and Lester 1997). This will be much more effective than older methods in optimizing lumber yields because it will prevent cull losses by allowing detection and control of the problem long before significant damage occurs. Early detection of these defect-causing microbes in standing trees is useful for predicting future potential damage because the damage potential is species-specific and thus the future depreciated value of individual trees can be estimated by using decay models coupled with fungi-specific decay expansion constants in different hosts. An integral part of this early detection system is the identification of the specific microbe(s) present, because the rate of development, type of damage, and location of defect volume depends on the particular pest present. Several applications of this technology are being developed. For example, CPA recently was used to distinguish the aroma signatures of sapwood cores (host woods) from southern hardwood species (table 16.1). Technology also has been developed to identify forest pathogens and wood decay fungi *in vitro* and in wood samples, and to distinguish between different *Armillaria* species for disease diagnosis (table 16.2). Host- and fungi-specific decay-volume models based on log-taper equations of individual hardwood species also are under development with the objective of predicting future lumber volume losses for planning and establishing future harvest schedules for individual hardwood stands (see footnote 2).

[2] Wilson, A. Dan. 2002. Wood decay volume models. [Not paged]. Unpublished data. On file with: Southern Research Station, P.O. Box 227, Stoneville, MS 38776.

Table 16.1—Global class membership (identity) of aroma profiles for sapwood cores of selected southern hardwoods based on electrical aroma signatures obtained from the 32-sensor array of the Aromascan A32S

	Global class membership[a]					
Sapwood cores	*A. rubrum*[b]	*C. caroliniana*	*C. laevigata*	*L. styraciflua*	*P. deltoides*	*P. occidentalis*
	percent					
Acer rubrum	98.0	0.0	0.0	0.0	0.0	0.0
Carpinus caroliniana	0.0	99.2	0.0	0.0	0.0	0.0
Celtis laevigata	0.0	0.0	91.3	3.8	0.0	0.0
Liquidambar styraciflua	0.0	0.0	3.7	96.7	0.0	0.0
Populus deltoides	0.0	0.0	0.0	0.0	98.8	0.0
Platanus occidentalis	0.0	0.0	0.0	0.0	1.5	99.3

[a] Percentage global class membership (relatedness) of sapwood core aroma profiles based on comparison against reference database for southern hardwoods. Data only list comparisons between aroma signatures of sapwood cores from these six hardwood species.
[b] Mean global class membership for 10 replications per treatment.

Table 16.2—Determinations of global class memberships (identity) of aroma profiles for four *Armillaria* spp. based on electronic aroma signature comparisons with an *Armillaria* reference library database obtained from the 32-sensor array of the Aromascan A32S

	Global class membership[a]			
Armillaria spp.	*A. gallica*[b]	*A. mellea*	*A. ostoyae*	*A. tabescens*
	percent			
A. gallica	100.0	0.0	0.0	0.0
A. mellea	0.0	99.2	8.7	0.0
A. ostoyae	0.0	0.0	91.3	0.0
A. tabescens	0.0	0.8	0.0	100.0

[a] Percentage global class membership (relatedness) of *Armillaria* aroma profiles based on comparison against reference database for these four *Armillaria* species. Data only list comparisons between aroma signatures of these four *Armillaria* species.
[b] Mean global class membership for 10 replications per treatment.

Insect-Wood Decay Pest Complexes

Of all the pests that reduce hardwood lumber production, none are more important than the wood decay fungi and the hardwood borers. Those capable of acting together in symbiotic complexes are even more damaging. Recent Forest Service research at the Southern Hardwoods Laboratory in Stoneville, MS, has been aimed at identifying and quantifying losses caused by important insect and disease pests that are causing substantial reductions in hardwood lumber production and value. This work has revealed new, previously unknown woodwasp-wood decay fungi complexes capable, in some cases, of causing considerable damage to logs in standing trees, ultimately reducing hardwood lumber value. These wood decay fungi are mycosymbionts of a peculiar group of insects, the woodwasps (Hymenoptera: Siricoidea), with larval stages that bore through the wood of stressed and weakened hardwood trees and cause significant damage by forming galleries and vectoring (transmitting) wood decay fungi in the process (Gilbertson 1984, Smith 1979). Like most wood-feeding insects, woodwasps must live in symbiotic relationships with wood decaying microbes because they are incapable of digesting cellulose. The decay fungi are carried in special glands (mycangia) at the base of the abdomen near the ovipositor in female woodwasps. The adult female woodwasp stores inoculum of the wood decay fungus in these mycangial glands, which are connected directly to the oviduct that passes through the ovipositor. The decay fungus is injected into the wood with the eggs during oviposition. The fungus then grows rapidly and produces extracellular cellulases, which digest the wood for larval consumption (Kukor and Martin 1983). When the eggs hatch, the larvae begin boring through the decayed wood, consuming nutrients both from the decayed wood and the mycelium of the fungus itself. The larvae cannot consume and digest the wood until it is decayed by the enzymes of the fungus. The larvae produce extensive galleries throughout the rotting wood, eventually pupate in the wood, and emerge as adults making round exit holes. The wood is decayed far beyond these borer galleries in all directions. Most of these fungi grow very rapidly through the wood, and the wood is decayed almost completely over several years as both the cellulose (wood fibers) and lignin are digested by extracellular enzymes (Wilson and Schiff 2003). Thus, all of these fungi are physiological white rotters. The actions of these two pests together result in synergistic damage to and economic loss of merchantable hardwood lumber volume. The decay fungi also produce discoloration in the wood (a type of stain called zone lines) that further degrade lumber value. The zone lines, produced within decaying wood in association with these wood decay fungi complexes, are a result of somatic antagonism (SA) between different strains of the wood decay fungi competing for the same wood substrate (Wilson and Schiff 2000a). Zone lines that form in wood as SA interactions between xylariaceous fungi represent areas delimiting their territory around decay zones (fig. 16.2). The wood becomes riddled with all three types of damage (borer galleries, decay, and discoloration of wood) until the entire branch or bole becomes unmerchantable. This is a perennial process in which the damage may be compounded by repeated infestations of branches and boles by subsequent generations of the woodwasp.

Two major groups of woodwasps can affect hardwood lumber production. The large, siricid woodwasps (Siricidae: subfamily Tremicinae) attack predominantly oaks, sugarberry (*Celtis laevigata* Willd.), beech (*Fagus grandifolia* Ehrh.), and other bottomland hardwood species. Smith and Schiff (2002) provide a review and keys to the siricid woodwasps of the Eastern United States. These tremecine woodwasps vector predominantly basidiomycetous wood decay fungi. The two most common species are *Tremex columba* (Linnaeus) and *Eriotremex formosanus* (Matsumura). The smaller xiphydriid woodwasps attack mostly maples, elms, and upland hardwood species. They carry ascomycetous wood decay fungi that form spores in microscopic sacks (asci) inside of perithecia embedded in black stromatic tissues that develop on the surface of the wood. The woodwasp family (Xiphydriidae) has 22 described genera, approximately 100 species, and a worldwide distribution (Smith 1978). The family is represented in the United States by a single genus, *Xiphydria*, with 10 described native species. Hitherto, we have isolated the mycosymbionts from 6 of the 10 native xiphydriid

Figure 16.2—Zone lines observed in decayed wood of sugar maple colonized by *Daldinia concentrica*, mycosymbiont of *Xiphydria maculata* woodwasp larvae. These antagonistic interactions form between the decay zones of xylariaceous wood decay fungi around woodwasp galleries, and represent areas delimiting their territory defended by the production of dark inhibitory compounds. Photo by A. Dan Wilson.

Table 16.3—Symbiotic insect-wood decay fungi pest complexes that cause synergistic defect losses of hardwood lumber volume in southern and eastern hardwood species

Woodwasp	Fungal symbiont	Major tree hosts	Common names	References[a]
Siricidae				
Eriotremex formosanus	Basidiomycete	*Quercus phellos*	Willow oak	Unpublished data
Tremex columba	*Cerrena unicolor*	*Fagus grandifolia*	American beech	Stillwell 1964, 1965
		Celtis laevigata	Sugarberry	Unpublished data
Xiphidriidae				
Xiphydria abdominalis	*Xylaria* sp.	*Tilia americana*	Basswood	Wilson and Schiff 2000b
X. decem[b]	*Xylaria* sp.	*Betula nigra*	River birch	Wilson and Schiff 2000b
X. hicoriae	*Daldinia* sp.[c]	*Carya ovata*	Shagbark hickory	Wilson and Schiff 2000b
X. maculata	*D. concentrica*	*Acer saccharum*	Sugar maple	Wilson and Schiff 2000b
		T. americana	Basswood	Wilson and Schiff 2000b
X. mellipes	*Daldinia* sp.	*B. papyrifera*	Paper birch	Unpublished data
X. scafa	*Xylaria* sp.	*Carpinus caroliniana*	American hornbeam	Wilson and Schiff 2000b
X. tibialis	*Xylaria* sp.	*A. saccharum*	Sugar maple	Wilson and Schiff 2000b
		C. caroliniana	American hornbeam	Wilson and Schiff 2000b

[a] References refer to source(s) that reported the symbiotic association and/or new hosts of the woodwasp-wood decay fungus complex.
[b] A new species (Smith and Schiff 2001).
[c] The mycosymbiont of *Xiphydria hicoriae* was tentatively identified as a *Daldinia* species based on superficial observations of culture morphology of a single mycangial strain isolated from only one female woodwasp.

woodwasps known in North America, including *X. abdominalis* Say, *X. decem* Smith & Schiff, *X. hicoriae* Rohwer, *X. maculata* Say, *X. scafa* Smith, and *X. tibialis* Say (Smith 1976, 1979). The known wood decaying fungal symbionts of tremicine and xiphydriid woodwasps in southern and eastern hardwoods of the United States are summarized in table 16.3. All of these mycosymbionts are xylariaceous fungi (Ascomycotina: Xylariaceae), which are known for their ability to cause white rots in hardwood species. They are closely related to *Hypoxylon* species that commonly attack and rapidly decay weakened hardwood trees. It was recently discovered that most of these mycosymbionts are *Xylaria* species not previously known to be symbionts with woodwasps (Wilson and Schiff 2000b). These fungi do not usually form the sexual stage in culture, which has hindered identification to species.

Xiphydriid woodwasps oviposit primarily into the axils of living hardwood branches, causing extensive decay and galleries in this area. This eventually weakens the limb which may then be broken by wind or ice accumulation. The decay can extend into the sapwood of the bole through the remaining branch stub after the limb falls off. Xiphydriid larvae continue to bore and develop in the fallen limb on the ground. Larvae produce galleries throughout the wood until the following spring, pupate, and emerge as adults (Solomon 1995). Adults mate (optionally) and oviposit their eggs once again into the axils of living branches or into dead limbs on the ground to complete the cycle. Most woodwasp species seem to be fairly host-specific, often attacking only one or two hardwood species, although a few species such as *X. tibialis* have a number of hardwood hosts. There also appears to be high fidelity in the symbiotic association between woodwasp species and their fungal symbiont. All woodwasp species examined hitherto apparently depend only on a single mycosymbiont for food and cellulose decomposition.[3]

Woodwasp-wood decay fungi complexes have been found in every major hardwood species. Thus, these pest complexes are potentially significant sources of log defects in all hardwood stands. The occurrence of a new, nonnative siricid woodwasp [*Eriotremex formosanus* (Matsumura)] in hardwood forests of the Southern United States is of considerable concern because this pest has spread from Georgia to Texas since its introduction into the United States in infested wooden shipping crates brought back by the

[3] Personal communication. 2002. A. Dan Wilson, Principal Research Pathologist, and Nathan Mark Schiff, Research Entomologist, Southern Research Station, P.O. Box 227, Stoneville, MS 38776.

military from Southeast Asia after the Vietnam War in the early 1970s (Smith 1996). Recent decay tests *in vitro* have demonstrated that the wood decay fungus vectored by this woodwasp has the potential to rapidly decay sapwood in many eastern hardwoods (Wilson and Schiff 2003). This fungus does not fruit readily on its oak hosts or *in vitro*. This makes identification difficult because the teleomorph or sexual stage contains key taxonomic characters required for identification. Perhaps these symbiotic fungi do not normally produce sexual fruiting bodies because they are regularly carried to appropriate tree hosts by their woodwasp vector and, therefore, do not have to expend energy to produce a metabolically costly fruiting body for sporulation and wind dispersal in order to survive. This is why the extensive damage caused by these pests often goes unnoticed until the tree is cut. These wood decay fungi are rarely visible on the outer surface of trees, and adult emergence holes of the woodwasps look similar to those of other hardwood borers. Consequently, the extent to which these pests are damaging southern oak forests is not known, although preliminary results with wood decay studies *in vitro* indicate that the mycosymbiont of *E. formosanus* and those of xiphydriid woodwasps can cause substantial white rots in eastern hardwoods after only 1 year (Wilson and Schiff 2003). We do not yet understand the importance of the role woodwasps play in the dispersal of wood decay fungi, the impact they have on forest health, or the effects that nonnative pests such as *E. formosanus* and its symbiont will have on lumber defect losses, hardwood timber salvage, and forest decomposition cycles. Further research is needed to elucidate the roles played by these new pest complexes that are invading our southern forests so that appropriate control strategies can be developed. These insect-disease pest complexes will likely receive increasing attention in the future as forest managers become more aware of their existence, their potential to cause damage, and their long-term impact on lumber production in hardwood forests.

MAJOR CONIFER DISEASES

The total land area in pine plantations now exceeds 25 million acres in the Southern United States (Belanger and others 2000). The area is expected to more than double by the year 2030. This valuable resource continues to expand primarily on private lands, which furnish the vast majority of timber products obtained from southern forests (U.S. Department of Agriculture, Forest Service 1988). The majority of these plantations are more than 10 years of age. Loblolly pine (*Pinus taeda* L.) and slash pine (*P. elliottii* Engelm. var. *elliottii*) are the two most planted and economically important pine species in the South. The importance of southern forests and plantations as the major suppliers of renewable wood products in the United States continues to increase as production in Western States declines because of changing public land management policies which are placing less emphasis on forest commodity production in that region. The South is well suited to take on this role because of the rapid tree growth and production possible in southern forests, the wide diversity of wood products that can be produced, the responsiveness of southern pines to intensive culture and even-aged silvicultural systems, and the abundance of low-relief sites allowing fully mechanized harvesting (Blakeslee 1997).

Although relatively few pathogens have had major impacts on pine production in southern plantations and forests, the diseases caused by these pathogens have caused very significant losses in pulpwood and sawtimber production. Fortunately, there also have been significant advances within the past two decades in the development of management strategies to reduce losses to most major pine diseases. These advances have often taken into consideration changes in pathogen adaptations to suppression strategies, environmental conditions, host genetics, and legislative constraints on management alternatives.

Fusiform Rust

Fusiform rust continues to be recognized as the most damaging disease of southern pine forests and plantations. The causal agent, *Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme* (Hedge. & N. Hunt) Burdsall & G. Snow, occurs in a broad band across the Southern States and is prevalent in the most productive high-quality loblolly and slash pine sites in this region (Anderson and others 1986). Fusiform rust incidence has increased dramatically within the last 30 years, especially in intensively cultured stands and in afforestation areas, where 47.9 million acres of former agricultural lands have been converted into pine stands and plantations (Starkey and others 1997). Annual losses to the disease have been estimated at $35 million in five Southeastern States (Schmidt 1998). Forest managers throughout the South are concerned about this disease because it affects stocking, product quantity, and product quality. Fusiform rust management in many areas is highly integrated into land management activities. For example, pine fertilization is frequently delayed by managers until after the trees are 5 years of age to reduce infection during the most vulnerable years (Blakeslee 1997).

The development of genetic resistance in planting stock has been the major disease management strategy used to reduce the incidence and severity of fusiform rust. The efforts of many forest pathologists over the past 40 years have brought genetic resistance to the forefront as an effective routine tool for managing this disease. The absence of a genetic linkage between rust resistance and tree growth rate has allowed the simultaneous development of genetically superior fast-growing trees with enhanced fusiform rust resistance. The genetic resistance approach generally has reduced pine mortality and disease severity in many sites, but some problems have been encountered as a consequence of the wide geographical variation in the genetics of the fungus, which has apparently given rise to strain-specific resistance, variations in pathogen virulence, and perhaps pathogen adaptations to host-resistance genes (Powers and Matthews 1979). Consequently, fungal strains in some areas eventually overcome resistance. Previously, pine breeders have attempted to stay ahead of the rust fungus by constantly producing and rotating new resistant pine growing stock to avoid genetic changes in the fungus that occur when pine selections are grown for too many rotations in the field. However, a new strategy involves the production of breeding lines that minimize rust damage, not prevent infection entirely, to avoid putting selection pressure on the fungus to produce new virulent strains, but maintain low-virulent strains to which pines are tolerant (Walkinshaw and Barnett 1995). Nevertheless, development of fusiform rust resistance has translated directly to increased economic value because the disease affects both the quantity and quality of timber produced (Cubbage and Wagner 2000).

Alternative approaches to fusiform rust suppression have been helpful in shaping efforts to develop integrated programs to manage this disease. The development of predictive models has been useful for identifying the relative hazard or susceptibility of sites to rust damage based on site and stand characteristics (Anderson and others 1986, Borders and Bailey 1986, Froelich and Snow 1986, Starkey and others 1997); and for predicting preharvest rust-associated mortality (Devine and Clutter 1985, Geron and Hafley 1988). Other models have emphasized the importance of preventing rust during stand establishment (during the first 5 years) when the potential impact of rust infection is the greatest (Nance and others 1985). Triadimefon (Bayleton) seed treatments followed by protective foliar sprays have helped reduce the incidence of rust in the early stages of stand development (Hare and Snow 1983). The selective thinning of trees with moderate-to-severe stem girdling caused by rust galls is an effective means of reducing losses to fusiform rust and greatly improves the quality of trees in residual stands (Belanger and others 2000).

Recent research has utilized molecular techniques to study population structure, cellular, and biological aspects of the pathogen to determine genetic variation, identify the genetic mechanism of fungus-induced gall formation in pine hosts, locate rust-resistance genes in pine host genomes, and define cellular resistance responses (Covert and others 1977, Roberds and others 1997, Wilcox and others 1996). This information will ultimately be useful in developing new genetic engineering strategies for creating more resistant pines by taking advantage of new knowledge of host-pathogen interactions at the molecular level.

Pitch Canker

Pitch canker is a disease of pines caused by *Fusarium circinatum* Nirenberg et O'Donnell [= *F. subglutinans* (Wollenweber & Rienking) P. E. Nelson, Toussoun & Marasas f. sp. *pini* Correll and others]. The disease derives its name from the induction of copious pitch flow associated with cankers of pines. The classic symptom is a bleeding, resinous canker of the main stem or trunk, terminals, large branches, shoots, and exposed roots. The canker is usually sunken and the bark is retained, while the wood beneath the canker is deeply resin-soaked. Dieback in the crown results from cankers forming on the branches or shoots. As the branches or shoots are girdled by the fungus, the needles turn yellow to reddish brown; later they turn grayish brown to dark gray. It may take several years, however, for a canker to girdle the main stem. The pitch-soaked wood is a diagnostic character useful in separating pitch cankers from most other maladies of pines (Dwinell and others 1985). The symptoms of pitch canker frequently vary by pine host and management practices. In southern pines, trunk cankers are common on Virginia (*P. virginiana*

Mill.), longleaf (*P. palustris* Mill.), and eastern white (*P. strobus* L.) pines. Dieback is common on slash, loblolly, shortleaf (*P. echinata* Mill.), sand [*P. clausa* (Chapm. ex Engelm.) Vasey ex Sarg.], and pond (*P. serotina* Michx.) pines. Trunk cankers on slash pine are common in seed orchards and are usually associated with the use of tree shakers for cone removal. Cankers on exposed roots can be found on slash pine in seed orchards and other pines in landscape plantings (Dwinell and others 1985).

Pitch canker is an incomplete descriptive name for the range of damage caused by *F. circinatum*. The pathogen infects a variety of vegetative and reproductive pine tissues at different stages of maturity and produces a diversity of symptoms. Damage to pines by this fungus includes growth suppression, stem deformation, and tree mortality. The pitch canker fungus also causes mortality of female flowers and mature cones, and deteriorates seeds of several pine species. Dwinell and Fraedrich (1997) isolated *F. circinatum* from the surface and interior of immature shortleaf pine cones from a North Carolina seed orchard. They concluded that interior contamination by *F. circinatum* was not correlated with necrotic regions, caused primarily by insects, on the cone surface. The mode of entry of the pitch canker fungus into cones is unknown. Entire slash pine seedlots and entire longleaf pine seed-crops have been lost as a consequence of contamination by *F. circinatum,* which resulted in low seed viability and germination (Dwinell and others 1985). Current research is aimed at determining whether the pathogen is primarily on the seed surface or infects the embryo. Contamination of seed in longleaf and shortleaf pines is mostly on the seed surface (Dwinell and Fraedrich 1997, Fraedrich and Dwinell 1997). The fungus appears to be primarily external (Dwinell 1999). There is little empirical data linking seed contamination by *F. circinatum* with seedling cankers that occur in nursery beds and on outplanted sites. The major result of seed contamination by the pitch canker fungus is preemergence and postemergence damping-off (Dwinell 1999, Dwinell and Fraedrich 2000). In addition, pitch canker occurs in bare-root and container nurseries. Diseased pine seedlings show chlorotic or reddish brown needles and wilting. Pitch-soaked lesions usually occur at or near the soil line, but occasionally are found in the region of the cotyledonary node (Barnard and Blakeslee 1980). The pitch canker fungus has been associated with late-season mortality in longleaf pine nurseries (Carey and Kelley 1994).

Fraedrich and Dwinell (1997) concluded that *F. circinatum* is a wound pathogen of longleaf pine seedlings. Any fresh wound, regardless of cause or location, provides an infection court for the pathogen. Insects can create wounds that can be infected by airborne spores of the pathogen or serve as vectors. In the Southeastern United States, the deodar weevil (*Pissodes nemorensis* Germar) creates wounds that may become infected by airborne spores of the pathogen (Blakeslee and others 1978). Recent unpublished research indicates that the Nantucket pine tip moth [*Rhyacionia frustrana* (Comstock)] may not be associated with pitch canker in loblolly pine.[4] In slash pine seed orchards, main stem cankers often develop after injury caused by mechanical cone harvesters. Also, injuries caused by wind and hail may serve as entry points. Hurricanes and tornadoes, in particular, have contributed to the intensification of the disease in some seed orchards (Dwinell and others 1985). The involvement of insects, interactions with other pine diseases, and numerous biotic and abiotic factors can influence the incidence and severity of infections by *F. circinatum*.

Annual mortality due to pitch canker in the Southeastern United States has been low. Southern pines, particularly loblolly, pond, and shortleaf pines, usually recover from outbreaks of shoot dieback (Barrows-Broaddus and Dwinell 1985, Kuhlman and others 1982). From 1945 to 1973, limited outbreaks of pitch canker were noted in the Southeastern United States, but the disease was not considered to be economically important. In 1974, a shoot dieback identified as pitch canker reached epidemic proportions on slash pine in Florida plantations and seed orchards, and on loblolly pine in North Carolina and Mississippi seed orchards (Dwinell and others 1985). These outbreaks spawned considerable research on pitch canker. Over the last three decades, pitch canker outbreaks in the South have occurred sporadically in time and place. Pitch canker has also evolved from a regional problem to one of national and international importance (Dwinell 1999). Because each outbreak has its own unique history, no specific management strategy has been developed to reduce or eliminate the threat of pitch canker disease. An integrated management approach, including chemical control, biocontrol, genetic selection for resistance, and altered cultural

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practices should be considered for specific hosts and growing conditions (Dwinell and others 1985). External contamination of pine seeds can be reduced or eliminated by appropriate seed treatments (Dwinell 1999, Dwinell and Fraedrich 2000). Because wounds serve as infection courts for *F. circinatum*, understanding the cause or causes of the wounding is tantamount to managing pitch canker (Dwinell and others 1985). In cases where the wounding agent is an insect, chemical control may reduce disease intensification. However, regulations on the use of chemical pesticides have severely limited this option. Biocontrol organisms have been ineffective (Barrows-Broaddus and others 1985). Variation in the incidence of pitch canker is common among clones within seed orchards, suggesting that genetic selection for resistance is possible (Barrows-Broaddus and Dwinell 1985, Dwinell and others 1985).

Annosus Root Disease

The fungal root pathogen *Heterobasidion annosum* (Fr.) Bref. is an economically important pest of temperate conifers worldwide and a powerful ecological force that can affect stand structure and composition. Currently, *H. annosum* S and P biological species in North America are genetically distinct entities, but have not yet been elevated to species status (Niemla and Korhonen 1998). Virtually no gene flow occurs between the North American S and P groups, despite their close proximity and overlapping host niches (Otrosina and others 1992, 1993). At this time, only the P biological species of *H. annosum* is known to occur east of the Mississippi River in the United States.

The most crucial stage in the disease cycle of this pathogen is the entry of the fungus into the stand through freshly cut stump surfaces. These cut surfaces provide a suitable niche in which airborne basidiospores can germinate and subsequently bring about mycelial colonization of the stump and root wood. Direct infection of roots through root wounds or possibly unwounded roots can occur in southern pines such as slash pine (Hendrix and Kuhlman 1964) and in *Abies* species (Garbelotto and others 1999). Once present in a stand, infection spreads from stumps to healthy trees via root contacts or grafts, creating ever-widening mortality centers. The fungus derives its nutrition from the enzymatic decomposition of woody tissues, particularly lignin and to a lesser extent cellulose, resulting in a physiological white rot. Thus, wood rotted by *H. annosum* has a characteristic delaminated appearance, and later becomes lighter to almost white as the lignin is removed from cellulosic wood fibers. Infected trees are subject to windthrow as a result of these structural changes in decayed wood.

Roots infected by the fungus in living trees become highly resinous in advance of the invasion front containing active mycelia. Resin production is a physiological, host-defense response of the tree to invasion and may slow and sometimes contain the advance of the infection. The production of resinous compounds in response to infection is metabolically very costly in terms of expended energy and may result in the weakening of the tree over time. The expense of energy for host defense in response to extensive root infection by *H. annosum* predisposes conifers to attack by bark beetles and other root diseases (Alexander and others 1981, Schowalter and Filip 1993). The fungus can persist saprotrophically in the highly resinous stumps and stump roots in longleaf pine for at least 7 years after thinning, providing inoculum potential to infect healthy residual trees via root grafts and contacts (Otrosina and others 2002). Mortality is a dramatic effect of *H. annosum* root disease, but growth reduction usually results from sublethal infections. Because root disease infection in trees is invisible until very advanced stages, considerable growth increment loss can occur in affected stands without significant mortality (Alexander 1989, Alexander and others 1981). On the other hand, slash and loblolly pines may be able to sustain considerable root infection before growth reduction occurs (Bradford and others 1978, Froelich and others 1977).

Considerable research has been done regarding risk assessment with respect to *H. annosum* root disease in the Southeastern United States. Edaphic factors are important elements associated with occurrence and hazard associated with this disease. Sites classified as high risk have well-drained soils containing sand, low organic matter, and low water table (Alexander 1989). These edaphic risk factors have been used to develop hazard-rating maps (Anon. 1999). While these maps provide correlations between certain soil types and *H. annosum* root disease, there is little information available to explain why or how soil factors affect disease development. Soil type affects factors such as water stress, microbial activity, aeration, and root habit, and root configuration can affect the root-infection processes.

Control of *H. annosum* root disease is achieved primarily through prevention. The most effective means to date is the prophylactic application of powdered borax formulations to freshly cut stump surfaces. Borax is toxic to basidiospores and conidia of *H. annosum* (Hodges 1970). Prevention and control is achieved only if borax applications are timely, ideally within a few hours after tree cutting. Technology that automates application of powdered borax by devices that attach to feller buncher equipment is now under development (Karsky 1999). Another avenue for *H. annosum* root disease control is through silvicultural management. Research by Ross (1973) revealed that thermal inactivation of basidiospores is achieved when stump surfaces reach > 35° C, resulting in no stump colonization. These temperatures are common during the summer months south of 34° N. latitude and form the basis for the recommendation that southern pine stands south of this latitude be thinned in the summer. On the other hand, high temperature may not be the sole factor responsible for lowering rates of stump infection. Some research suggests that microbial synergy at the stump surface may be affected by high temperatures on stump surfaces, since the fungus could be reisolated from surface sterilized and inoculated wood bolts at temperatures up to 40° C (Gooding 1964).

Less emphasis has been given to *H. annosum* root disease control in recent years. Preventive measures such as application of borax after thinning are becoming less common. While some data suggest that mortality of trees planted in severely infested sites is minimal up to 22 years after planting (Kuhlman 1986), multiple stand entries and thinning without the proper preventive measures, combined with longer rotation lengths, will increase the importance of this disease in coniferous forests in the Southern United States. Such a scenario exists in certain longleaf pine stands where *H. annosum* root disease results in significant and steady mortality beginning when trees are about 40 years of age. Longleaf pine has been regarded as highly tolerant to this disease, but various factors such as degraded soils, root damage by equipment, and lengthened prescribed fire regimes have resulted in increased mortality due to *H. annosum* and other root pathogens in these stands. Thus, long-term goals of managing longleaf pine on a 75- to 120-year rotation for red-cockaded woodpecker [*Picoides borealis* (Vieillot)] habitat, stand restoration, and seed production can be thwarted if appropriate caution is not exercised regarding root disease (Otrosina and others 1999, 2002). More comprehensive information on *H. annosum* root disease in North America and Europe is presented in Otrosina and Scharpf (1989) and Woodward and others (1998).

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Chapter 17.

Monitoring the Sustainability of the Southern Forest

Gregory A. Reams, Neil Clark, and James Chamberlain[1]

Abstract—*The ecological and economic sustainability of southern forests is being questioned because there are many competing uses for these forests and because there are large regional shifts in forest land use. To adequately understand the state of our forests and their use with respect to sustainability, several significant changes have been made in programs of the U.S. Department of Agriculture Forest Service's Forest Inventory and Analysis (FIA) and Forest Health Monitoring Research Work Units. These changes are enabling these units to better assess the status of and sustainability of our forests. The FIA Program has replaced the 70-year-old periodic forest survey sampling design with a continuous annual sampling program. The new sampling design provides for continuous monitoring and reporting, with the emphasis on current status and trends in forest resources and many of the criteria and indicators of sustainable forest management as identified by the Montreal Process. The program is a collaborative partnership among the Southern State forestry agencies and the U.S. Department of Agriculture Forest Service, Southern Research Station. The process used to develop the new annual forest inventory program has provided the opportunity to build stronger partnerships with State forestry agencies, universities, nongovernmental organizations, and the forest industry. These new and renewed partnerships are of considerable value in defining, interpreting, and reporting on criteria and indicators related to sustainable forestry. Recent collaborative research has produced methods for estimating forest area and area change from satellite imagery, initiatives on how to quantify and report nontimber forest products, and potential uses of remote sensing instruments for on-plot measurements; e.g., global positioning system units, lasers, and camera systems.*

INTRODUCTION

The ecological and economic sustainability of our Nation's forests is being questioned. The definition of forest sustainability is not fixed. As knowledge of forest processes and uses expands, conceptions and components of sustainability will change. At a minimum, sustainability must include both ecological and human dimensions: underlying ecological integrity of soil, water, atmosphere, biological diversity and productivity must relate to human needs for food, water, health, shelter, fuel, and culture. The U.S. Department of Agriculture Forest Service (Forest Service), Forest Inventory and Analysis (FIA) and Forest Health Monitoring (FHM) Programs have been expanding their roles to include analyses of biological diversity and productivity as influenced by soil, water, and atmospheric composition. For example, in the past decade these two programs have been modified to provide the monitoring data and analyses required for the investigation of environmental concerns about air pollutant impacts and effects of climate change on forests.

Concern over perceived and real trends in forest resource conditions has led to numerous requests for improvement in the quantity, quality, and timeliness of information about forests and enhanced access to this information. To address these concerns, FIA and FHM contribute data and analyses to a variety of national and global assessments. The FIA and FHM data address at least 38 of the 67 criteria and indicators of sustainability for reporting under the Montreal Process. FIA and FHM data are essential to those who produce reports required by the Resources Planning Act (RPA) and are increasingly employed to support regional resource assessments used as a basis for forest planning. In response to these needs, FIA and FHM have implemented an annual forest inventory and monitoring program nationwide.

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THE FIA MISSION

The FIA Program has been in continuous operation since 1930. It is the only consistent, credible program that provides forest data for all public and private land within the United States. The program reports on the current status of and trends in forest area, in species composition, in tree size, volume, growth and mortality, and in harvest removals. The FIA and FHM Programs provide additional information on attributes considered to be indicators of forest health. The FIA Program also collects and reports information on wood production and utilization rates by various products, and on forest land ownership.

The FIA Program provides the most objective and scientifically defensible information available about the extent of forests, change in forest area, change in tree species composition, and rates of tree regeneration, growth, mortality, and harvesting.

This information is used to help formulate State and Federal policy decisions, including international reporting; serve as a starting point for more intensive studies on key ecosystem processes; formulate business plans that are economically and ecologically sustainable; and inform the public about the health and sustainability of the Nation's forests.

Historically, the FIA Program has reinventoried each State's forests at intervals of about 10 years. Prior to the annual inventory, FIA had established that (1) forest land remains the predominant land use in the South, (2) the forest land base in the South has been stable for several decades, (3) the pine component of the South's forest is moving steadily toward more planted and fewer natural stands, (4) fears of a southern pine growth decline related to air pollutants have abated, and (5) growth rates on forest industry lands have continued to increase over the last four decades. The annual inventory program enables FIA to identify changes in trends much more quickly than the previous decadal scale design allowed.

FOREST HEALTH MONITORING MISSION

The purpose of FHM is to make statements about the status of and trends in the health of forest ecosystems in the United States. The FHM Program was established in 1991 to address environmental concerns about how natural factors such as insects, disease, and extreme weather events, and anthropogenic stresses such as air pollutants, climate change, population growth, and nonnative species affect forests.

The National Acid Precipitation Assessment Program (NAPAP) Forest Response Program of the mid-1980s was in many ways a precursor of the FHM Program. During the mid-1980s there was increased concern that many forests in the United States were exposed to acidic deposition and other pollutants and that these regionally distributed pollutants might be damaging forests (Barnard and others 1990). Suspected declines in either the productivity or health of southern pines, red spruce, and sugar maple have been attributed to causes of this kind. Many of the policy and research questions asked by NAPAP are similar to those addressed by the current FHM Program.

The FHM Program covers all forested lands through a partnership involving the Forest Service, State Foresters, and other State and Federal Agencies and academic groups. The FHM Program uses data from ground plots and ground surveys, aerial surveys, and other biotic and abiotic data sources to address forest health and sustainability issues. There is one key difference between FHM as implemented in the United States and similar monitoring efforts for Western Europe. Efforts in Europe have opted for onsite monitoring of pollutants and weather variables, while efforts in the United States have relied on the monitoring of bioindicator plants and other variables to monitor the effects of natural and anthropogenic stresses. A key example is that of monitoring the potential impact of ozone. It is known that high levels of ozone do not injure plants unless their stomata are open. High ozone and temperatures often occur at the same time, and these episodes often occur when stomata are closed. Thus, FHM has opted to monitor bioindicator species that are sufficiently sensitive to specific pollutants. This allows for assignment of injury to specific causes and for more accurate estimation of the spatial distribution of injury.

The FHM Program is implemented through five major activities. (1) Detection monitoring uses nationally standardized ground and aerial surveys to evaluate the status of and change in forest conditions. (2) Evaluation monitoring determines the extent, severity, and causes of undesirable changes in forest health identified through detection monitoring. (3) Research on monitoring techniques creates sampling designs and analytical techniques used to develop bioindicators of forest health, provide early detection of invasive species, and devise methods for monitoring urban and riparian forests. (4) Intensive site monitoring enhances understanding of cause-effect relationships by linking the current status of and trends in surveyed attributes and bioindicators to process-level studies of specific issues such as calcium depletion and carbon cycling. (5) Analysis and reporting produces peer-reviewed publications about analysis and interpretation of sampled populations and reports on forest health at national and regional levels.

Since 1999, the FHM ground plot network used for detection monitoring has been integrated with the more intensively sampled forest inventory network maintained by the FIA Program. Currently, FIA has one plot per 6,000 acres, and FHM has one plot per 96,000 acres. Also, FIA has adopted annual survey methods similar to those used in the FHM Program. The merger of the FIA and FHM plot networks and increased coordination of survey methods enable both programs to produce annual estimates of forest area, forest inventory, and bioindicators of forest health. Moreover, the FHM (phase 3) field plots expand the suite of attributes sampled. The FHM attribute list now includes tree crown conditions, cover and diversity of lower vegetation (shrubs, forbs, grasses, and vines), soils, lichen diversity (as an indicator of air quality), indicator plants for ozone presence, and coarse woody debris. This expanded sampling provides data that can be used to estimate forest carbon and forest fire fuel loads. Readers are encouraged to visit http://fia.fs.fed.us/library.htm#manuals for a thorough explanation of all FHM indicators.

The assessment of forest health should be based on definable criteria. The Forest Service's monitoring programs have adopted the Montreal Process and criteria and indicators for evaluating forest health and conditions to provide information for sustainable forest management.

Some of the challenges and concepts that must be considered in integrating and redesigning inventory and monitoring programs are discussed in the following section.

DESIGNING AN INVENTORY AND MONITORING SYSTEM

In designing an inventory and monitoring system, it is important to recognize that definitions of sustainability change over time and vary according to location and interests. Changes in forest type and condition have accelerated, and the rapid pace of change likely will continue in the South. The combination of real change, introduction of new sampled attributes, and definitional changes over time calls for a resilient and simple sampling frame. This goal is very different from the situation in most inventories, in which the sampling strategy is directly tied to the need to efficiently estimate one or two closely related attributes of interest.

Fortunately for the continuity of FIA inventory work, the types of measurement data that were used to estimate forest resources 30 years ago remain equally useful today. Nevertheless, a dominant consideration in planning a long-term monitoring program is the inevitability that a highly efficient sample design, one that optimizes on one or very few resources of interest, will go out of date. Examples in forest inventory work include the use of overly detailed stratification and variable probability of selection based on volume or value per unit area. Design features that involve complex sample structure create potentially serious difficulties, whereas an equal-probability design permits greater adaptability and flexibility. To minimize sample design obsolescence, structure should be employed sparingly and with awareness of its undesirable effects. Variable probability sampling designs and other complex sampling schemes are less amenable to the multiple and changing objectives that long-term monitoring designs must address, and therefore should be avoided (Overton and Stehman 1996).

Simplicity is desirable for many reasons. It is not only that sample elements will change over time (as when forest plots become parking lots); it is also that overall objectives change. Another reason for simplicity is the growing recognition that data collected by federally funded monitoring programs should be accessible to the public at large (Cowling 1992). With a relatively simple sample design, it is more likely that valid results and conclusions can be reached by various public users of the databases.

The simplicity and resiliency needs of the southern FIA Program have resulted in the use of an equal-probability systematic sample design (Roesch and Reams 1999). The new annualized sample design employs five annual panels, whereby plots measured in year one will be remeasured in year six (fig. 17.1). The southern FIA Program has historically used a completely overlapping single-panel design for periodic inventories and is implementing a similar design in its annual surveys (Reams and Van Deusen 1999). To transition from the single-panel periodic survey measured once every 10 years to an annual survey, FIA subpaneled the periodic plot list into five panels. Panels represent a sample in which the same elements (plots in this case) are measured on

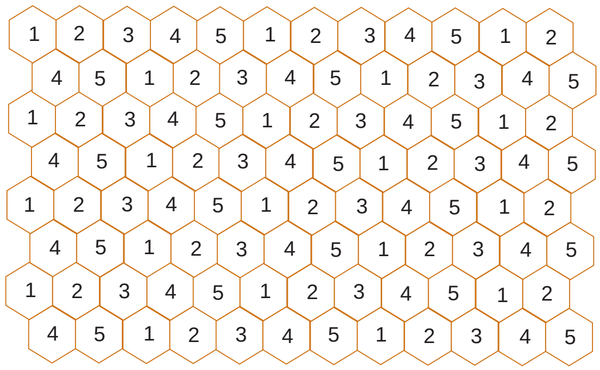

Figure 17.1—An interpenetrating pattern for a five-panel design. No element has another member from the same panel as an immediate neighbor. There is one plot per hexagon (Roesch and Reams 1999).

two or more occasions. Panel designs permit studies of individual change and therefore allow for the accounting of gross change that would be masked in a nonoverlapping design. In southern's FIA Program, the use of a panel design is largely due to the importance of estimating gross changes in growth, mortality, and removals.

Once the new five-panel design is fully implemented, the increased flexibility in inventory estimation techniques will be realized. Annualized estimates like the simple moving average that is very similar to the periodic estimates are providing the foundation of first-generation annual inventory estimates (Roesch and Reams 1999). There are circumstances in which the 5-year moving average will overestimate or underestimate current inventory. These situations are most obvious when there is either an abrupt shift in inventory or a strong trend in the attribute of interest. For example, if a hurricane occurred during the measurement of panel 3, inventory estimates based on a 5-year moving average would overestimate inventory in the affected areas. In such a case, prior panels must be dropped from the estimation process, and only panels measured after the hurricane can be used for inventory estimation (Reams and others 1999).

The time-series nature of the annual survey provides increased flexibility in inventory estimation. Several new approaches have been presented by the scientific community and are being considered for possible implementation. These estimation methods include mixed estimation (Van Deusen 1996), updating using individual tree growth models (McRobert and others 2000), and imputation (Reams and Van Deusen 1999).

SUSTAINABILITY ASSESSMENTS

The past decade has seen increased concern among natural resource managers, the science community, and the public at large over the current status of and emerging trends in forests at international, national, and regional scales. As a result, large-scale assessments of forest sustainability related to one or more major public policy themes or initiatives are becoming increasingly necessary (Reams and others 1999). FIA data, analyses, and interpretations provide the basic information for all types of large-scale forest assessments within the United States. The FIA data also provide the basic inputs used to model future forest distribution and composition, and the availability of forest resources (Wear and Greis 2002).

Sustainability has at least five elements (Floyd and others 2001). These include (1) maintaining resources over time, (2) a concern for future generations, (3) an estimate of future needs, (4) knowledge of current rates of resource use and rates of regeneration, and (5) a widely accepted view of some appropriate level of resource use.

In an effort to monitor forest sustainability as it is defined by the Montreal Process, the Forest Service has identified seven criteria of sustainability with many measurable indicators for each criterion. A criterion is a category of conditions or processes by which sustainable forest management may be assessed. A criterion is characterized by a set of related indicators, which are monitored periodically to assess change. An indicator is a quantitative or qualitative variable that can be measured or described, and which, when observed periodically, demonstrates trends.

The seven criteria of forest sustainability are (1) conservation of biodiversity; (2) maintenance of the productive capacity of forest ecosystems; (3) maintenance of forest ecosystem health and vitality; (4) conservation and maintenance of soil and water resources; (5) maintenance of forest contribution to global carbon cycles; (6) maintenance and enhancement of long-term multiple socioeconomic benefits; and (7) legal, institutional, and economic framework.

The degree to which the FHM and FIA Programs address the ecological criteria and indicators defined in the Montreal Process and agreed upon in the 1995 Santiago Agreement are displayed in table 17.1. The FIA and FHM Programs provide a significant level of information

Table 17.1—The degree to which the FHM and FIA programs are currently addressing the criteria and indicators of the Montreal Process as specified in the 1995 Santiago Agreement[a]

Criterion	Indicator	Measurement	FHM and FIA[b]
Biological diversity			
Ecosystem diversity	Areal extent of forest types	Percent total forest	***
		Percent nonprotected—by forest type and age class	*
		Percent protected—by forest type and age class	*
	Fragmentation of forest types		***
Species diversity	Forest-dependent species	Total number—no. of forest-dependent species	**P
		Status of risk species—no. of breeding populations	*
Genetic diversity	Proportion of former range		?
	Population levels of representative species—species/diverse habitat/total range		*
Productive capacity	Timber production—area and net area available; population estimate is coarser than those provided by FIA		***
	Total growing stock—merchant and nonmerchant available	Plantations—area/growing stock, native and exotic species	***
		Annual removal wood products—compared to sustainable volume	*
Ecosystem health and vitality—based on area and percent forest affected	Insects and disease		***
	Competition from exotics		**P
	Abiotic stressors	Fire	***
		Storms	***
		Flooding	***
		Salination	***
	Management/use	Land clearance	***
		Domestic animals	*
	Air pollutants	S, N, O_3, etc.	**P
		UV-B	?
	Biological indicators of key processes—nutrient cycling, reproduction, etc.	Epiphytes	***
		Insects	*
		Fauna	*
		Vegetation communities	**P
Soil resources—based on area and/or percent	Physical properties	Erosion	***
		Compaction	**
		Other physical properties	***
	Chemical properties	Organic matter	***
		Nutrients	***
		Toxins	**
	Protective functions—watersheds, floods, avalanche, riparian		**

continued

Table 17.1—The degree to which the FHM and FIA programs are currently addressing the criteria and indicators of the Montreal Process as specified in the 1995 Santiago Agreement[a] (continued)

Criterion	Indicator	Measurement	FHM and FIA[b]
Water resources—based on historical patterns	Stream flow and timing		*
	Biological diversity		*
	Physical properties	Temperature	*
		Sediments	*
	Chemical properties	pH	*
		Dissolved oxygen	*
		Electrical conductivity	*
Global carbon cycles—contributed by forests	Total ecosystem biomass/carbon pool—e.g., forest type, age class, etc.		**
	Sequestration/release of carbon	Standing biomass	**
		Coarse woody debris	**P
		Peat	*
		Soils	***
	Forest products		*

FHM = Forest Health Monitoring; FIA = Forest Inventory and Analysis; S = sulfur; N = nitrogen; O_3 = ozone; UV-B = ultraviolet-B.
[a] Criteria six and seven and corresponding indicators are not included because the FIA and FHM Programs are not designed to sample and report these measures.
[b] * = techniques for measurement or estimation developed in other programs; ** = techniques for measurement or estimation under development in FIA/FHM Programs; **P = techniques for measurement or estimation under development and tested in regional FIA/FHM pilot studies; *** = techniques for measurement or estimation developed in FIA/FHM Programs and implemented nationally; ? = unknown whether regional monitoring methods exist.

for the first five criteria, but very little for criteria six and seven. Criteria six and seven are not listed in table 17.1.

FIA and FHM data will continue to provide the basic information at the forest area, plot, and tree level for all types of regional, national, and international forest assessments. The Heinz Center report on the state of the Nation's ecosystems (Heinz Center 2002), national resource assessments such as RPA (Powell and others 1993), the recently completed Southern Appalachian Assessment (Southern Appalachian Man and the Biosphere 1996), and the monitoring of forest carbon stocks (Heath and Birdsey 1997) rely heavily, and in many cases exclusively, on FIA and FHM data to describe and estimate current forest conditions and trends.

Well-planned and executed annual survey systems can provide the basic baseline and monitoring information to address the many scientific questions regarding societal issue-driven assessments of sustainability. Annual inventories that are cost-effective, publicly trusted, and provide unbiased information about forest resource trends, are requisites for the development of sound policy.

PRODUCTS OUTPUT REPORTS

FIA and FHM field-plot systems provide the inventory data used to estimate current volume and volume changes induced by removals and mortality. FIA also conducts canvasses of primary wood-using facilities. This component of the FIA Program complements the field survey by providing independent estimates of removals. Primary mills are those that process roundwood in stem length, log, bolt, or chip form directly from the woods. Examples of industrial roundwood products are saw logs, pulpwood, veneer logs, poles, and logs used to make composite board products. Mills producing products from residues generated at primary and secondary processors are not canvassed. Trees chipped in the woods are included in the estimate of timber drain only if they are delivered to a primary domestic manufacturer (Johnson 1998).

This timber products output (TPO) information is used to track trends in industrial production by mill type and by product mixes across mills. Typical mill types include pulp mills, sawmills, veneer mills, composite panel mills, and other industrial mills; e.g., those that produce charcoal, excelsior, logs for log homes, shavings, and firewood. The TPO information is often used by industry analysts to estimate current rates of demand.

In addition to timber, hundreds of plants, fungi, and microorganisms are being collected and harvested for personal and commercial use. These nontimber forest products (NTFP) are harvested from within and on the edges of forests. They may include fungi, moss, lichen, herbs, vines, shrubs, or trees. Many different parts of plants are harvested, including roots, tubers, leaves, bark, twigs and branches, fruit, sap and resin, and wood. NTFPs can be classified into four major product categories: (1) culinary, (2) wood based, (3) floral and decorative, and (4) medicinal and dietary supplements (Chamberlain and others 1998, 2002).

To date, inventory and monitoring of NTFPs have been limited because there has been no legislative mandate for such activities. However, there is increasing awareness that NTFPs should be recognized as renewable resources, managed scientifically, and collected on a sustainable basis. Forest managers have identified a number of critical problems hindering efforts to improve forest management for NTFPs. These problems include (1) lack of baseline information on the distribution, abundance, condition, and rates of change for NTFP populations of interest; (2) lack of knowledge about the biology and ecology of the flora from which these products originate; (3) diversity of the products and of the collectors; (4) lack of market knowledge; and (5) insufficient personnel and resources to assign to NTFP management.

Emerging policies could significantly change how the Forest Service addresses NTFPs. A new bill would require the Secretary of Agriculture to determine sustainable harvest methods and harvest levels for these products and to establish methods to ensure that revenues are returned to the local units from which they were generated. Implementation of this bill may require tracking the distribution, abundance, condition, removals, and final markets of NTFPs.

In anticipation of these new reporting requirements, a study has been initiated to determine the importance of NTFP industry throughout the South. The lack of knowledge about the role of this industry in rural communities hinders efforts to allocate resources to improve management. This study is an initial effort to define the overall industry, identify obstacles to the collection of data needed to estimate the volume and value of NTFPs, and formulate protocols for regular monitoring of output from the varied segments of this industry.

Assessments of NTFP outputs have never been undertaken in the South. For the most part, lists of enterprises that could be contacted and surveyed do not exist. We are able to utilize some lists, such as those of ginseng dealers in each State. For the most part, we are starting from scratch to develop a framework that will allow for regular contact with NTFP enterprises. On a regional basis, this requires canvassing county agriculture agents to get their estimates of the numbers of enterprises within their geographic areas of responsibility. County agents are asked to estimate the number of firms that deal in four segments of the NTFP industry; i.e., medicinal, edible, floral, and specialty wood. Figure 17.2 presents the perceptions of county agents in 7 of the 13 Southern States.

To undertake assessments of the output by State will require identifying and contacting enterprises in each county. To assess the challenges of undertaking NTFP assessments at this level, the project is carrying out a pilot

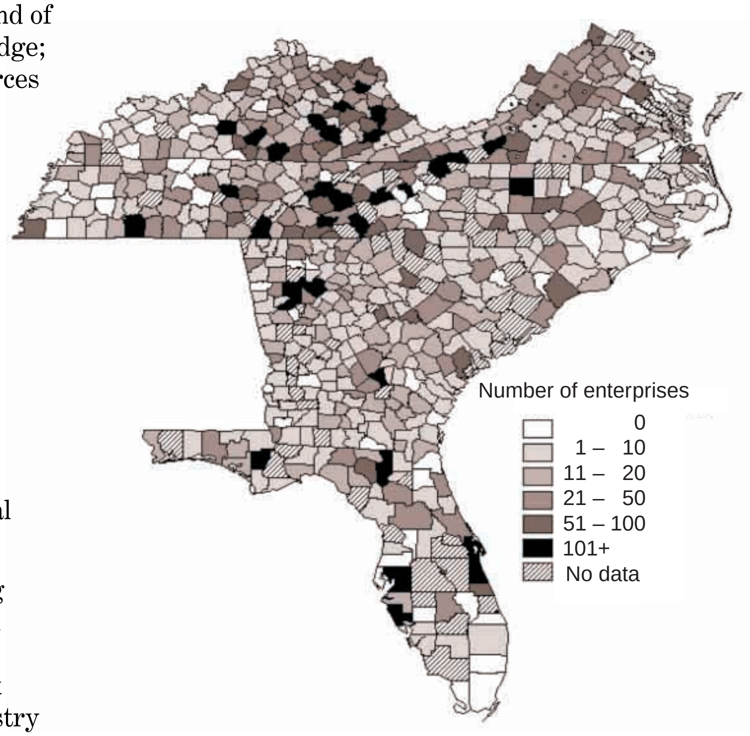

Figure 17.2—Number of nontimber forest products enterprises by county for seven Southern States.

study in western North Carolina. Leads to enterprises are being obtained through initial contacts with local experts. We expect this project to produce a sample frame of NTFP enterprises that will allow for regular monitoring of enterprises in western North Carolina. This work will provide insights that can be used to extend monitoring of NTFPs to other States.

REMOTE SENSING

The 1998 Farm Bill that required the merger of FIA and FHM survey activities into an annual inventory and monitoring program also requested that FIA and FHM make fuller use of remote sensing technology. Nationally, FIA and FHM are transitioning to the use of satellite imagery to estimate and map forest area, and area change. Studies completed in cooperation with the Virginia Department of Forestry and Virginia Polytechnic Institute and State University found that satellite-based methods provide forest area estimates comparable to those produced by the traditional FIA photo-based method (Wayman and others 2001). Wynne and others (2000) cite several reasons for making a transition to greater reliance on satellite-based remote sensing: (1) the long-term viability of the National Aerial Photography Program is in question; (2) satellite imagery provides an opportunity for more frequent updates; (3) certain analyses important for forest inventory, such as spectral change detection to improve removal estimates, can be performed more easily; and (4) a spatially explicit enumeration of the entire landscape can be produced in a more automated fashion. This map can be used to estimate the sizes of strata.

The use of remote sensing technology to collect on-plot measurements is being investigated. Given the intensive data needs mentioned previously, field collection is time consuming and costly. Increasingly on-plot remote sensors are being used and developed to reduce collection time and increase the precision of measurements for some variables.

Active and passive remote sensors are being used to locate forest plots, precisely locate and map objects with geographic coordinates, and collect data on many quantitative variables. FIA uses global positioning systems (GPS) (Hofmann-Wellenhof and others 2001, Kaplan 1996) to locate plot centers.

Other on-plot inventory applications include ultrasonic or laser rangefinders (Fairweather 1994, Liu and others 1995). These tools are used to map locations of objects, e.g., trees, subplots, etc., and determine distances, e.g., plot radii or limiting distances, with much greater accuracy and speed than GPS. These rangefinders can be combined with clinometers or angle gauges to obtain other dimensional information, e.g., diameters, heights, stem form, etc. (Clark 2000, Fairweather 1994, Williams and others 1999).

Other applications of on-plot remote sensors in forestry include using charge-coupled device (CCD) cameras to quantify understory and biomass (Ramachandran and others 2000, Ter-Mikaelian and Parker 2000); using CCD cameras to record stand structure, regeneration, and scenic beauty (Rudis and others 1998); using light meters, densitometers, and digital hemispherical cameras in canopy closure and regeneration studies (Comeau and others 1998); using radio frequency identification for tagging wildlife (Mans and Eradus 1999) and trees (Wilson, in press); and using remote sensors in wildlife monitoring (Demarais and others 2000).

Though these sensors exist and are finding application in forestry, most of them are prototypes and are still in the development process. The following improvements will make these devices standard equipment for inventory foresters:

- Confluence of sensors (GPS, camera, distance, etc.) and processing (numerical methods, models, optimizations) within Geographic Information Systems for rapid solution of problems
- Automated processes allowing the flow of many observation data stream inputs into models, analysis, and onward to the final report
- Advances from hand-held computers to portable data assistants (Kerns and others, in press) to wearable computers (Baber and others 2001)
- Reduced power consumption
- Increased data storage
- Capability for wireless transmission of data from woods to office
- Creation of weatherproof, durable instruments
- Reduced instrument costs
- Improved filters for interference, i.e., light, humidity, sound
- Easier operation

- Improved means of validation
- Revitalization of sampling methods previously underutilized due to previously impractical data needs (Osawa and Kurachi 1997)

The southern FIA Program will continue to take advantage of new technologies where they aid in meeting the objectives of accurate and cost-effective data collection. The exploration, expansion, modification, and development of on-plot remote sensing systems will be required in order to achieve the objectives of FIA in the future.

SUMMARY OF INVENTORY AND MONITORING ENHANCEMENTS

In the 1998 report of the Second Blue Ribbon Panel on FIA and the 1999 Farm Bill, a number of enhancements were suggested to:

- Improve and expand information on ecosystems and noncommodity values
- Recognize and identify ownership, regulatory, and social impacts on forest productivity
- Integrate the FIA and FHM Programs
- Implement the use of satellite imagery for estimation and mapping of forested ecosystems
- Produce the most current resource data possible
- Implement a uniform approach on all ownerships
- Increase consistency and compatibility among FIA units
- Enhance coordination between FIA and public agencies
- Improve service to all groups

In response to these needs, FIA and FHM have introduced improvements in their sampling programs and have designed pilot studies for undersampled populations such as urban and riparian areas and noncommodity values. Since 1999, the FHM ground-plot network used for detection monitoring has been integrated with the more intensively sampled forest inventory network maintained by the FIA Program. A study has been initiated to better understand the importance of NTFP industry throughout the South. The FIA Program has initiated a national ownership survey to identify and quantify the ownership, regulatory, and social impacts on forest productivity. An annual survey is now being implemented consistently across ownerships, with the cooperation of State and Federal partner agencies. Nationally, FIA and FHM are transitioning to the use of satellite imagery to estimate and map forest area and area change. The national compatibility of data collection, database production, estimation, and reporting is ultimately leading to improved service to all of FIA's partner and customer groups.

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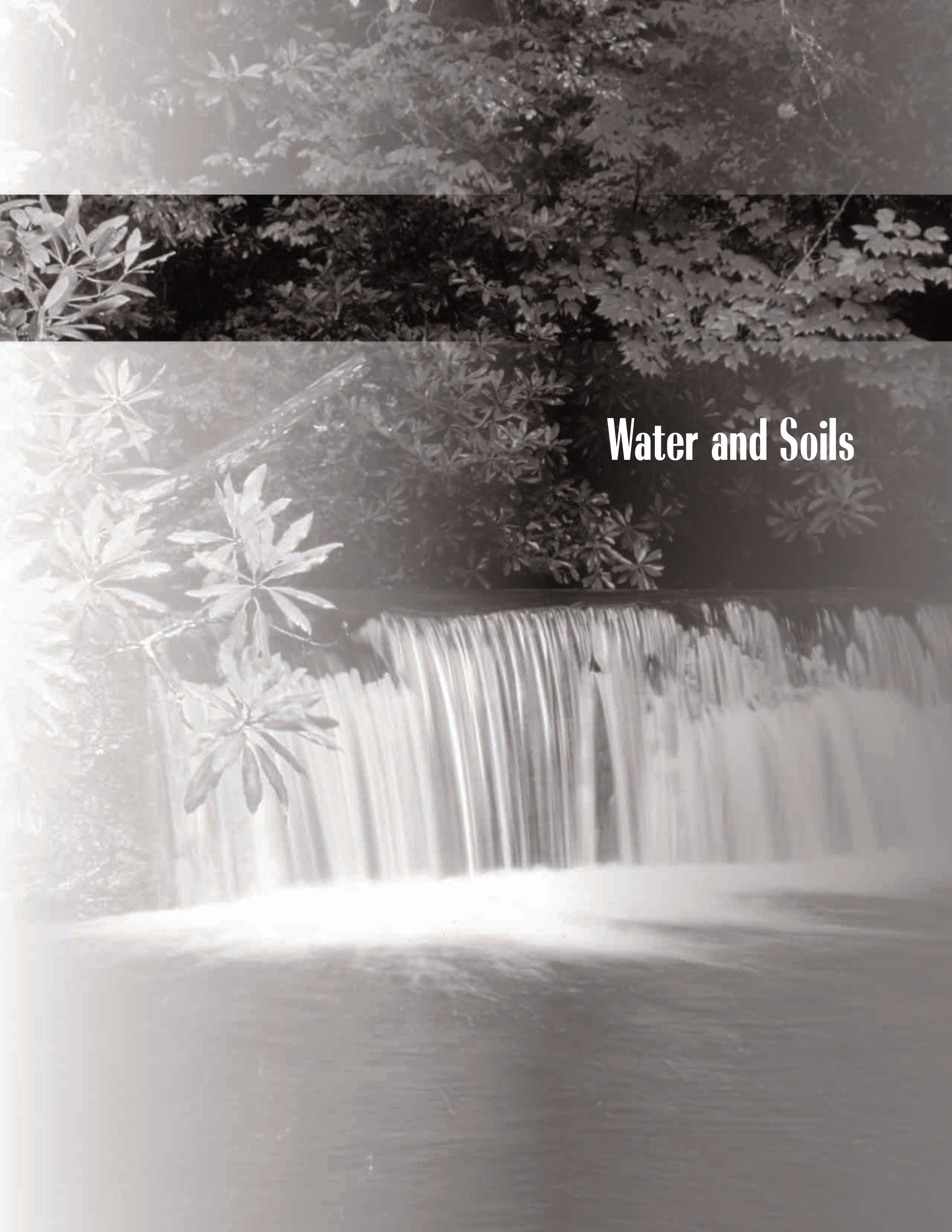
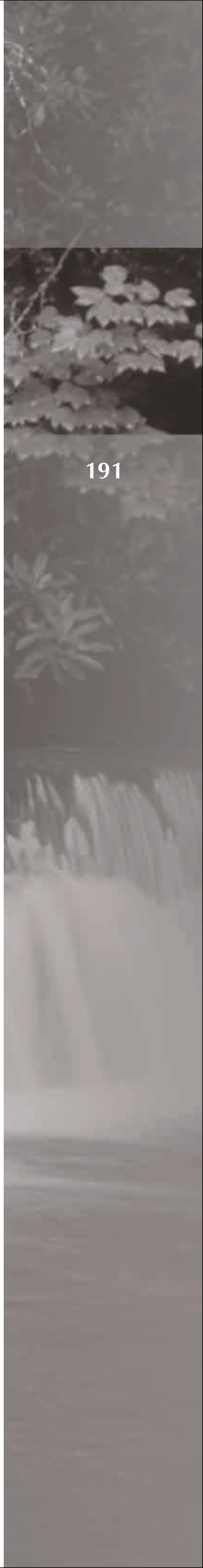


Water and Soils



Chapter 18.

Water and Soils

Carl C. Trettin[1]

In the second chapter, Ge Sun and others discuss the effects of management of southern forests on water quantity and quality. Their thorough review of water quality and quantity research in the South provides valuable insights. This research has shown that the greatest changes in streamwater yield or ground-water table occur immediately following forest land disturbances. The overall water-quantity impact of silvicultural operations is much less on wetlands than in areas having greater relief and shallow soils. Silvicultural practices in the South cause relatively minor water-quality problems. Roads managed without regard to best management practices (BMP) are the major source of sedimentation from forestry operations. Studies of the cumulative effects of land use changes on water quality are lacking. The capability of existing computer modeling tools to describe the forest hydrologic processes and provide practical guidance in designing forest BMPs is limited.

The research discussed by Sun and others is very closely related to the study of forest soils, and I think it appropriate to say a little about work in soil science in the South.

ADVANCES AND CHALLENGES IN FOREST SOIL SCIENCE

It wasn't until the early 1900s that linkages between soils and silviculture were recognized, and the forest soils discipline was established (Wilde 1946). By the late 1930s, the forest was recognized as a system consisting of aboveground and belowground components. In the words of Wilde, "An understanding of the forest lies just as much below as above the ground line." Organic matter was known to be a critical component of the soil, affecting fertility, moisture retention properties, and the rooting environment. Studies of the factors affecting soil organic matter turnover and the role of organisms were well known. The early forest soil scientists established that soil quality could be affected by silvicultural practices, especially harvesting and fire. It was well understood that careless harvesting caused reductions in soil organic matter, increased bulk density to the detriment of rooting, and promoted erosion. Fire was known to effect soil fertility, especially when hot fires followed a harvesting operation. Woodland grazing was very common, and it was recognized that this grazing reduced soil organic matter, altered the nutrient cycle balance within the forest, and increased erosion.

Soil management was a well-established concept by the early 1930s. In the silvicultural context, soil management included the application of practices to conserve soil organic matter, maintain nutrient cycles and organic matter, and enhance fertility. The biggest factor driving the development of soil management practices was the challenge of restoring millions of acres of degraded agricultural lands to forest. Much of this land occurred in the Southeastern United States, and was the basis for many of the national forests that were established during that period. The need to reforest large acreages across a diverse landscape led to the recognition of species suitability, which was an early precursor to the considerable body of soil-site research that was to emerge in the 1960s to 1970s.

The tremendous advances in forest productivity that have been realized in the Southeastern United States are a testament to the effectiveness of the soil management practices that are based on a large body of forest soils research. The relationships of species to site conditions were recognized early on, and eventually led to the development of formal classification systems and the design of forest soil or site surveys. Those systems also facilitated the application of soil management prescriptions across the region. These approaches were embraced by the forest products industry in the Southeast, which used soil and site inventories as a basis for harvest scheduling, site preparation prescriptions, fertilization, and weed control prescriptions.

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Major advances in forest soil science occurred in the areas of fertilization, water management, and site preparation (Bernier and Winget 1975, Stone 1984, Youngberg 1978, Youngberg and Davey 1970). Given that the soils of the Southeastern United States are old, highly weathered, and generally abused, development of fertilization prescriptions was fundamental to the reforestation efforts and for improving site productivity. As a result, prescriptions for nitrogen and phosphorus fertilization are now routine across the region. Similarly, the site preparation techniques developed to ameliorate certain soil conditions and reduce vegetative competition also represent an important advance in soil management. Bedding is perhaps the best example of these techniques. The use of elevated planting beds improves aeration and moisture conditions and tends to concentrate nutrients in the rooting zone. Water management prescriptions evolved when it was recognized that water regimes could be manipulated to reduce potential soil damage during forest operations, improve regeneration, and sustain productivity and water quality.

Research in the Southeastern United States produced major advances made in the fields of soil biology and soil chemistry. A prominent example is Marx's research on mycorrhizae (Marx and Bryan 1975), which has widely influenced nursery practices, stand regeneration, and fertility management. The various "acid rain" research programs also made considerable contributions to the understanding of soil biology and chemical processes. That work provided the basis for detailed investigations on nutrient cycling, soil acidification, and organic matter dynamics. Understanding the different sensitivities among forest types, e.g., high-elevation spruce-fir vs. Piedmont mixed hardwoods, has provided the basis for improved environmental management.

The impacts of silvicultural practices on the soil have been explored extensively. Considerations about the effects of harvesting, site preparation, or water management on soil quality were based on concerns about sustaining the productive capacity of the site. Research usually showed that such operations significantly affected soil characteristics, e.g., soil bulk density and organic matter decomposition rate, during the immediate posttreatment period. However, such short-term effects are rarely linked to changes in site productivity and impact studies are rarely sustained beyond 2 to 3 years. Tools for interpreting short-term effects over the long term, i.e, rotation, have not been developed.

The concept of riparian buffer zones acknowledges the fundamental linkages between soil and hydrologic processes. Effective design and implementation of buffer zones depends on understanding the ameliorative goal (i.e., sediment removal, reduction in nitrate concentration), and biogeochemical and hydrologic processes. This would not be possible without the advances in soil and hydrologic sciences. The application of this information and concept has been extensive, affecting the design of BMPs and the evolution of ecological engineering as a discipline. The ability to manage natural systems or engineer biological systems, e.g., constructed wetlands, to achieve particular outcomes is fundamental to sustaining healthy forests.

Now and in the next few decades, the maintenance of productivity will be the most important challenge. As the acreage of commercially available forest land declines, there will be a need to produce even greater biomass on the remaining land. Therefore, it will be necessary to develop more intensive fertilization and water management prescriptions. Similarly, advances in the production and use of genetically improved stock may necessitate a parallel effort to optimize fertility and moisture regimes. Questions about impacts of land management on the soil remain. For example, fire effects are still under study. Considerable work remains to be done before we understand sufficiently the role of roots in soil biogeochemical processes and the associated interactions with plant productivity.

How will a changing environment affect the region's forest soils? Climate change may involve altered thermal and moisture regimes; How will this affect the sustainability of the resource? The southern forests are being fragmented by suburban development (Wear and Greis 2002). What are the implications for soil and water resources? Clearly, most of the forest soils in the Southeastern United States have been disturbed, and have changed over the past 200 years. If we knew more about the history of that process, it would be easier to anticipate the future. Unfortunately, there is virtually no basis for assessing the long-term changes in forest soils in the Southeastern States. An exception is the work on the Calhoun Experimental Forest over the past 40 years, which highlights the importance of being able to assess long-term change (Richter and Markewitz 2001). It is clear from that work, and the numerous short-term impact studies, that long-term soils studies are needed to provide the basis for sustainable management. The U.S. Department of Agriculture Forest Service's experimental forest network could be used to address soil and water science questions over time and across most of the major forest types in North America.

Perhaps the most difficult challenge will be the development of spatially explicit, process-based forest soil simulation models that will allow the consideration of management alternatives at the landscape scale. As forest resource management moves into the realm of precision agriculture, better information is going to be needed to optimize both economic and noncommodity values. At present, most process-based forest soil simulation models are based on data for uplands and cannot be applied directly to the complex mosaic of upland, wetland, and aquatic resources at the landscape scale. Models provide a means for synthesizing data, providing interpretations, and identifying important knowledge gaps. Improving the quality and applicability of forest soil and hydrology models will enhance our ability to provide interpretations at the spatial and temporal scales that are appropriate to major issues and questions. The models will also provide the basis for quantifying the uncertainties associated with our interpretations.

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Chapter 19.

Influences of Management of Southern Forests on Water Quantity and Quality

***Ge Sun, Mark Riedel, Rhett Jackson, Randy Kolka, Devendra Amatya, and Jim Shepard*[1]**

Abstract—*Water is a key output of southern forests and is critical to other processes, functions, and values of forest ecosystems. This chapter synthesizes published literature about the effects of forest management practices on water quantity and water quality across the Southern United States region. We evaluate the influences of forest management at different temporal and spatial scales, and we recognize the heterogeneity of forest ecosystems; e.g., wetlands and uplands in the South. Hydrologic models that were developed specifically for southeastern forests were reviewed. We conclude that the greatest streamwater yield or ground-water table changes occur immediately following forest land disturbances. The overall water-quantity impact of silvicultural operations on wetlands is much less than in areas having greater relief and shallow soils. Water quality from forested watersheds is the best when compared to that from other land uses. Silvicultural practices in the South caused relatively minor water-quality problems. Roads without best management practices (BMP) are the major source of sedimentation. Studies on the cumulative effects of land use changes on water quality are lacking. Exiting computer modeling tools are useful but limited in describing the forest hydrologic processes and providing practical guidance in designing forest BMPs. Recommendations to future research on forestry BMPs and forest hydrology in general are proposed.*

INTRODUCTION

Water is a key output of southern forests and is critical to other processes, functions, and values of forest ecosystems. Most of the drinking water in the South comes from forested watersheds. Much of our current understanding of the linkages between southern forest management and water quantity and quality is derived from long-term watershed-scale experiments conducted in more than 140 small watersheds in various physiographic regions in the 13 Southern States (Chang 2002). This chapter synthesizes published literature about the effects of forest management on water quantity and water quality across the region. We evaluate the influences of forest management at different temporal and spatial scales. We recognize the heterogeneity of forest ecosystem, e.g., wetlands and uplands, as affected by climate, geology, and topography. We identify sensitive regions and discuss the effects of management activities on the timing of hydrologic responses across the physiographic regions of the South. We scale up information derived from experiments at field and watershed scales to the regional level. Forest management practices examined in this chapter include harvesting, site preparation, bedding, surface drainage, road building, fertilizer and herbicide applications, and fire management. A review of regional hydrologic characteristics across nine physiographic regions is used as a framework to contrast effects of various management practices on key water-quantity and water-quality variables. Hydrologic models that were developed specifically for southeastern forests are reviewed.

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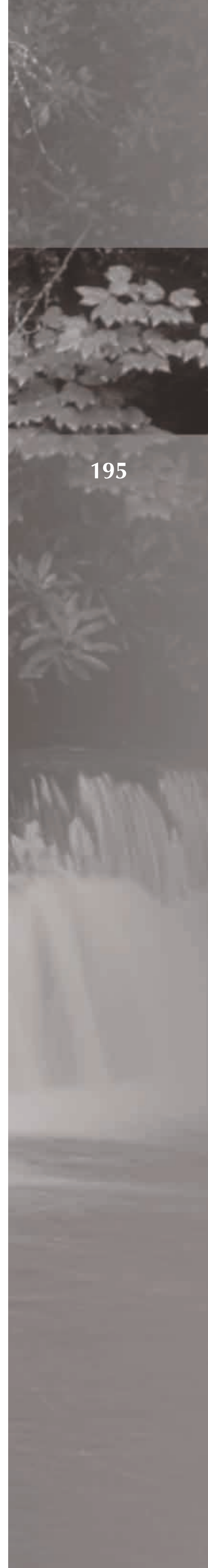

Recommendations for future research on forestry best management practices (BMP) and forest hydrology in general are proposed.

CLIMATE, TOPOGRAPHY, AND HYDROLOGY

Climate, underlying geology, and topography are the major factors that dictate regional hydrologic patterns, soil development, and forest structure and functions. Any attempts to project the impacts of management practices on hydrology must consider these factors as a background. Most southern forests are located in the climate system described as humid forest climate with cool winters and warm-to-hot summers (Muller and Grymes 1998). However, topography and elevation in the Southern United States alter this pattern greatly and result in a variety of hydrologic conditions (Daniels and others 1973).

The South can be described in various ways to facilitate characterization of forest hydrologic conditions in the region and forces that drive them. Bailey's ecoregion classification system is useful in this connection (Bailey 1995) (fig. 19.1). Bailey describes 10 major provinces that intersect with the southern geographic region, and each of these provinces has its unique hydrologic characteristics as affected by climate, topography, soils, and vegetation. We use nine major ecoregion provinces that support forest ecosystems as a spatial framework for describing the general hydrology in the South. We refer to information obtained from regional long-term hydrometeorological databases (Wolock and McCabe 1999) in discussing total annual runoff amount, runoff:precipitation ratio, and seasonal distribution of runoff (table 19.1).

Seasonal dynamics of stream runoff depend on the balances of precipitation input, evapotranspiration (ET) loss, and soil moisture storage capacity. Long-term monthly hydrologic data from four forest sites show that both climate (precipitation and potential ET) and topography (upland vs. flatland) are critical in determining the seasonal distribution of streamflow (figs. 19.2A through 19.2D). Across the Southeastern United States, potential ET is generally higher than precipitation in annual total, and in summer, but lower in other seasons. Therefore, streamflow is highest in winter and lowest in summer. Flatlands have much lower total flow than hilly uplands in summer. Variations of hydrologic characteristics described define all aspects of the water quantity and quality responses to management and design of BMPs (table 19.1).

Figure 19.1—Provinces of the Bailey ecoregion and annual runoff of the Southern United States.

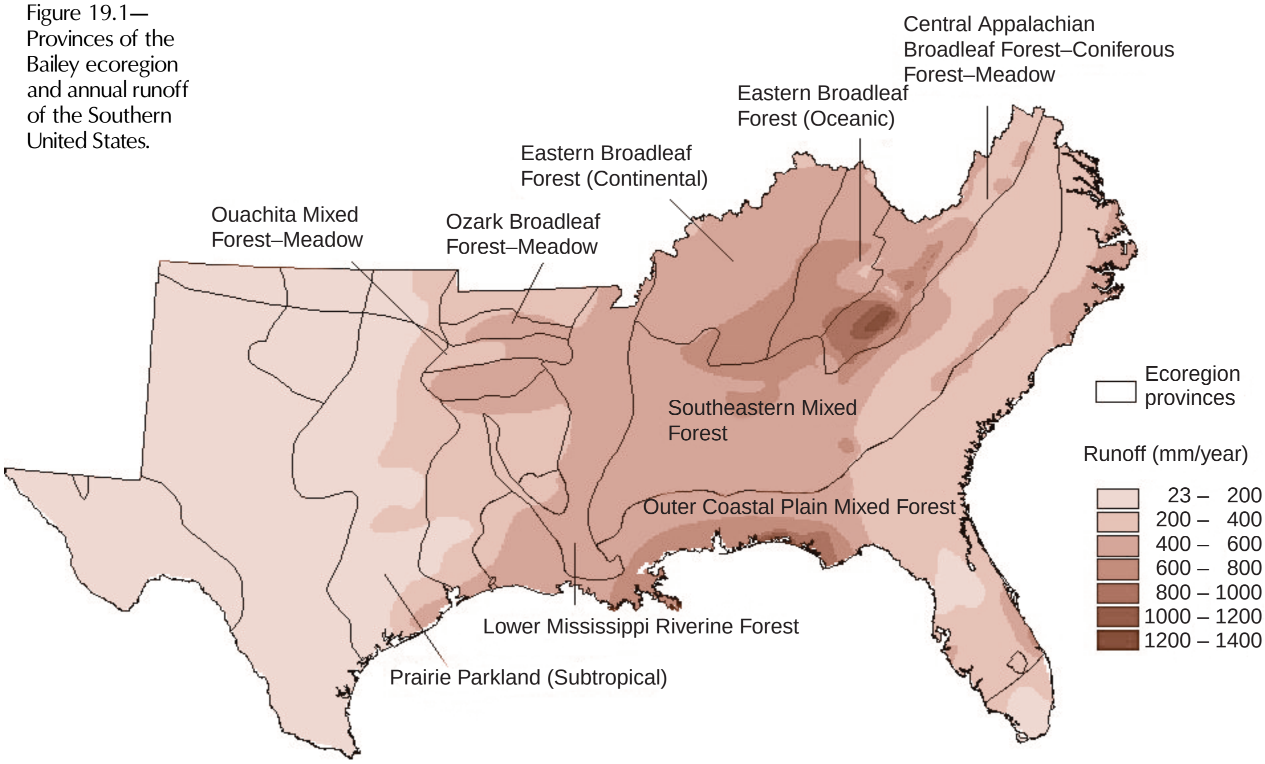

Table 19.1—Hydrologic characteristics of eight major physiographic regions in the Southern United States

Physiographic province	Topography	Climate and hydrology	Forest management concerns
Outer Coastal Plain Mixed Forest	Poorly drained flat lands with elevation < 100 m above sea level	High precipitation (PPT) (> 1200 mm/year) and warm temperatures, high evapotransipration (ET) (> 65 percent of PPT), variable runoff amount (300–800 mm/year), low runoff ratio (< 30 percent in most of area) and slow-moving streams	Impacts on forested wetland hydroperiod and water quality; artificial surface drainage essential
Southern Mixed Forest	Covers upper Coastal Plain and Piedmont, elevation 100–300 m	PPT (1200–1400 mm/year) moderate runoff amount (200–800 mm/year) and runoff ratio (20–60 percent)	Sedimentation caused by new forest disturbance and historical land uses; channel erosion common
Central Appalachian Broadleaf Forest—Coniferous Forest—Meadow (Blue Ridge)	Steep hillslopes at high elevations (300–2000 m)	PPT (1100–2000 mm/year), high runoff (400–1200 mm/year) and runoff ratio (> 50 percent); low ET due to low air temperature	Sedimentation caused by new forest road construction and historical land uses; fish habitat
Eastern Broadleaf Forest (Oceanic)	Rugged topography with elevation 300–800 m; long, narrow valleys and ridges	PPT (1000–1600 mm/year), high runoff ratios > 40 percent	Sedimentation caused by hardwood forest harvesting
Eastern Broadleaf Forest (Continental) (Cumberland Plateau)	Dendritic drainage with winding narrow-crested ridges and deep, narrow valleys; elevation 100–400 m	PPT decreases from 1400 to 1000 mm/year northward, runoff amount (500–700 mm/year) and ratios (35–45 percent) decline westward	Sedimentation caused by road and harvesting operations
Lower Mississippi Riverine Forest	Alluvial plains, elevation < 50 m	PPT (1200–1500 mm/year) with a decreasing south-north gradient; low runoff amount (450–550 mm/year) and runoff ratio (< 35 percent)	Harvesting impacts on wetland water quality and site productivity
Ouachita Mixed Forest—Meadow and Ozark Broadleaf Forest—Meadow	Rugged topography with relief over 300 m and narrow valleys and floodplains	Precipitation decreasing northwestward from1500 to 400 mm/year with runoff (400–550 mm/year) and runoff ratio (> 45 percent)highest at high elevations in the Ouachita and Boston Mountains	Effects of forestry activities on water quality and site productivity
Prairie Parkland (Subtropical)	Flat, with elevation < 5 m in the Coastal Plain to 500 m in the western Great Plains	Low but variable precipitation decreases dramatically westward (700–1100 mm/year); high ET, low runoff (50–300 mm/year) and runoff ratio (5–25 percent)	Water shortage, intensive pine forest management effects on sedimentation

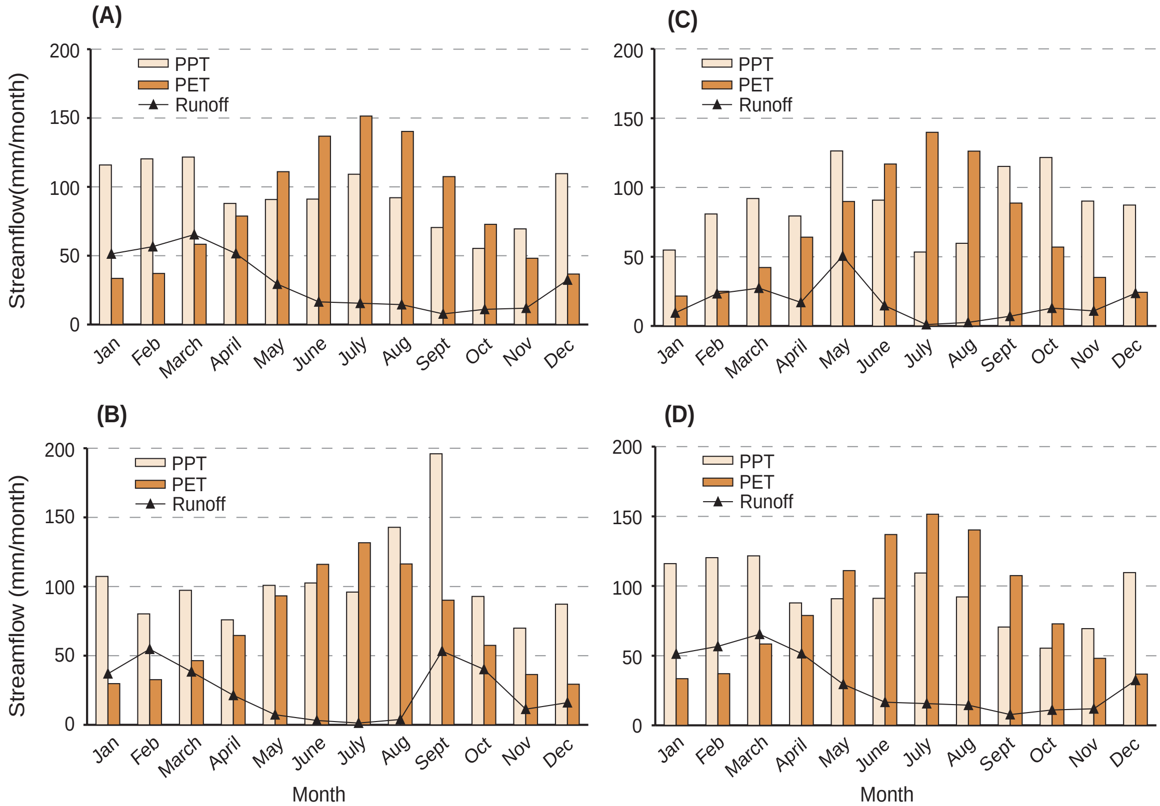

Figure 19.2—Seasonal distribution of streamflow from four representative forested watersheds across the Southern United States: (A) Arkansas mountains, (B) North Carolina Coastal Plain, (C) Texas shrubland, and (D) Georgia Piedmont (PPT= precipitation; PET= potential evapotranspiration).

WATER-QUANTITY IMPACTS

Water quantity or water yield refers not only to total waterflow volume on an annual basis but also to the timing of flow over shorter periods, as in the case of seasonal flow patterns or peak flow rates. For forested wetlands, the most important hydrologic variable is hydroperiod, the number of days when surface water is present per year. Hydroperiod, which is affected both by precipitation and by ET, controls the chemical and biological processes of wetlands. The fluctuation of the water table reflects the change in soil water storage that is roughly the difference between precipitation and ET and runoff. Because the hydrologic characteristics of uplands differ from those of wetlands, and because the forest management practices employed on uplands differ from those employed on wetlands, we discuss the effects of management on water quality for uplands and for wetlands separately.

Water-Quantity Impacts: Uplands

Harvesting—Without exception, experiments at Coweeta Hydrologic Laboratory (Coweeta) showed that forest harvesting in the Appalachian Mountains by clearcuts or partial cuts resulted in increased streamflow (Swank and others 1988). Clearcuts caused water yield to increase by 26 to 41 cm, or 28 to 65 percent of control during the first year after harvest (Douglass and Swank 1972, Swank and others 2001). Harvesting riparian vegetation resulted in a 12-percent increase in daily discharge on average and a nearly complete loss of diurnal variation in discharge (Dunford and Fletcher 1947). Douglass and Swank (1972) quantified the annual response of water yield to harvesting as a function of tree species, aspects and elevations of the watersheds, solar energy received, and basal area removed.

A paired watershed approach similar to the one developed at Coweeta was used to study effects of pine forest management on stormflow and soil loss in the Ouachita Mountains of Oklahoma and Arkansas in the 1980s (Scoles and others 1994). Small-watershed experiments in this region showed that (1) clearcutting increased annual stormflow volume by 100 mm, or 40 percent, and increased the number of stormflow events the first year after harvesting as a result of reduction of ET, however, subsoiling, a practice of breaking down large forest soil pores, reversed this response; (2) stormflow and peak flows under flood-producing conditions (high rainfall, wet soils) were not affected by forest removal; (3) peak flows tended to increase as harvest intensity increased. However, the differences were not large enough to be statistically important. Harvesting had the most influence on peak flows during late summer and early fall, when storms were generally small.

Blackburn and others (1985) reported hydrology and water-quality changes following clearcut timber harvesting in nine small gauged watersheds in eastern Texas. Three watersheds were clearcut, sheared, windrowed, and burned; three were clearcut and drum chopped; and three were left untreated as controls. During the first year following harvesting, stormflow averaged 147 mm for the intensively site-prepared watersheds, 84 mm for the chopped watersheds, and 25 mm for the controls. Stormflow in the second through fourth years following harvesting was less than half that measured in the first year.

With natural regeneration of plants, the increases in water yield declined logarithmically each year after the initial treatment (Swank and Helvey 1970, Swank and others 1988) (fig. 19.3). Depending on the history of forests, water yield recovered 30 to 50 years after harvesting in the Appalachian region (Swift and Swank 1981). At Coweeta, the water-yield increases on the treatment watersheds decreased at a rate of approximately 2 mm per 1-percent increase in regenerative forest cover (Hibbert 1966). Trimble and Weirich (1987) derived similar conclusions from correlations between historic hydrology and reforestation data (1919 to 1967) for large basins (2820 to 19 450 km^2) across the Piedmont regions. They found that reforestation reduced water yield in the Piedmont region, with the most significant reductions in water yield occurring in dry years. Over large heterogeneous basins, 10- to 28-percent increases in forest cover were correlated with reductions in annual water yield of 30 mm (4 percent) to 100 mm (21 percent). Small changes of water yield resulting from modest land use conversion, while not observable on first-order and second-order watersheds, were additive in the downstream direction and resulted in significant water-yield reductions for the encompassing larger basins.

Increases in water yield that result from forest harvesting are not distributed equally over the seasons. It was estimated that approximately 60 percent of the observed increase in water yield resulting from deciduous tree harvesting occurred in the late summer (July) to early winter (November) period. The majority of this increase occurred during the normally low-flow months of August, September, and October (Douglass and Swank 1972).

Conversion from deciduous to coniferous— At Coweeta, conversion of broadleaf deciduous forests to eastern pines reduced streamflow by 20 percent (Swank and Douglas 1974). The magnitude

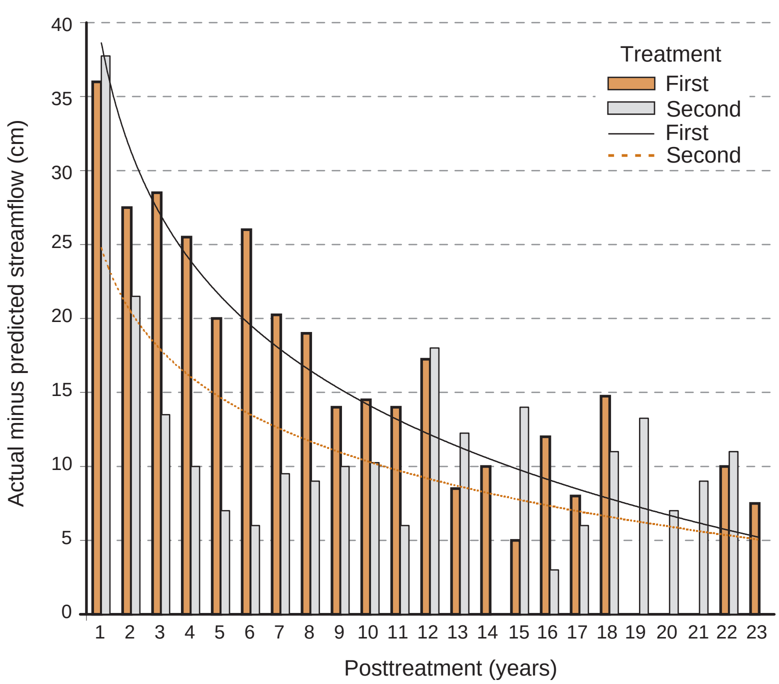

Figure 19.3—Annual streamflow responses to repeated harvesting of mixed hardwood forest (watershed 13 at Coweeta Hydrologic Laboratory) (adapted from Swank and others 1988).

of yield reduction is sensitive to precipitation, with greater reductions occurring during relatively wet years. Two factors are chiefly responsible for the observed reductions in streamflow. First, the interception capacity and subsequent evaporative losses of the white pine (*Pinus strobus* L.) stands can be twice those of the mixed hardwood communities they replaced (Swank and Vose 1994). Second, most of the precipitation occurring at Coweeta falls during low-volume, low-intensity rainfall events. Under these conditions, large amounts of precipitation can be intercepted by the evergreen tree canopy and can evaporate. Thus, conversion from mixed deciduous to coniferous species has a significant impact on water yield.

Although monthly water yield was always reduced after conversion from hardwoods to pines, the reduction was most pronounced during December to April when the differences of ecosystem ET (especially from interception losses) between the two forest types were the largest (Swank and others 1988).

Conversion from forest to grass—Conversion of 80 percent of a forested watershed with low tree density to Kentucky 31 fescue grass (*Festuca* L.) did not cause immediate increase in water yield at Coweeta (Hibbert 1966). A fertilized, highly vigorous, and productive grass system (> 1 m in height) could have used as much water as a forest. However, grass decline resulted in increased total annual water yield and baseflow, especially during the winter seasons. Flow frequency analysis suggested that dense grass or recolonizing forest might use more water than natural mature hardwoods during the summer growing season (Burt and Swank 1992). Stormflow frequency also increased as a result of forest conversion to grass.

Conversion from forest to mountain grazing—Although conversion from forest to grazing increased total water yield, the impacts of grazing on infiltration and ultimately peak flow rates were the most significant effects of the hydrologic changes. Before grazing, 102 mm of effective precipitation produced a maximum peak discharge of approximately 1.15 $m^3/s/km^2$. After grazing, it generated a peak discharge of approximately 28.7 $m^3/s/km^2$ (Johnson 1952). Hydrologic impacts of the mountain grazing were no longer detectable after 4 years of regrowth.

Conversion from forest to farmland—Researchers at Coweeta conducted experiments that combined forest removal practices with land use change. These experiments were designed to investigate the effects of typical land use practices in the Southern Appalachians on water yield and quality. For example, one 9-ha watershed was converted to an operational mountain farm by removing the forest and allowing farmers to utilize local agricultural practices including row cropping and unregulated grazing (Johnson and Kovner 1956). Following the treatment, annual water yield from the watershed increased 22 cm (Bosch and Hewlett 1982).

Water-Quantity Impacts: Wetlands

Wetland hydrology is extremely dynamic, involving complex interactions of surface water and ground water. Wetland hydrology research in the Southern United States is relatively new (Sun and others 2001). Most studies of the hydrologic impacts on southern forested wetlands have been conducted in the last two decades. Wetland hydrologic processes are ground-water driven. This review focuses on water-table responses to forest management practices. We review hydrologic impacts by wetland types because each wetland type has unique hydrologic features and responses.

Bottomlands—Harvesting of bottomland forests usually has little long-term effect on hydroperiod if BMPs are employed (Lockaby and others 1997a) or alternative harvesting methods, e.g., helicopters, are used (Perison 1997, Rapp and others 2001). The most common hydrologic change following harvesting of bottomlands is elevation of the water table (Aust and Lea 1992, Lockaby and others 1997b, Perison 1997, Wang 1996). This "watering-up" is attributed to these: (1) reduction of canopy interception and plant transpiration, (2) reduction of soil saturated hydraulic conductivity and increase of bulk density if harvesting sites are severely disturbed, and (3) increase of surface water storage and blocking of surface and subsurface drainage. However, one exceptional response has been reported: the water table in dark-colored organic soils dropped 20 to 40 cm during the postharvest period (Lockaby and others 1994). The causes of this unique response are not well understood. The water-table effects of forest harvesting on flood plains are most pronounced during the first two growing seasons (Lockaby and others 1997b, Wang 1996).

Depressional wetlands (cypress domes and Carolina bays)—Many depressional wetlands that are seasonally dry and isolated from streams or rivers are present in the Southeastern United States, and especially in Florida and on the

Atlantic Coastal Plain (Tiner and others 2002). Examples are cypress domes (ponds), Carolina bays, and pocosin wetlands of different sizes. They are important habitats for reptiles and amphibians (Russell and others 2002). Many of the small isolated wetlands are imbedded in intensively managed plantations. Isolated wetlands have similar hydrologic characteristics. They receive water and nutrient inputs mainly from precipitation, and lose water through the ET process. Physical and chemical interactions with surrounding uplands and deeper aquifers vary depending on local geology, but usually are minor as a consequence of the generally flat topography and the presence of thick fine-textured layers beneath the shallow surficial aquifer.

A hydrologic impact study at a 42-ha northcentral Florida site consisting of a mosaic of cypress ponds/pine flatwoods (Bliss and Comerford 2002, Crownover and others 1995, Sun and others 2000b) suggests that tree removals from isolated wetlands and surrounding uplands caused the water table to rise and runoff to increase. Harvesting of wetlands and surrounding uplands, and harvesting of wetlands alone, raised the level of the water table by as much as 100 cm. This effect on the water table was greatest during the first dry growing season. It was not significant subsequently; and in fact, the water table was somewhat lower than the control in the subsequent relatively wet years. The hydrologic regime at this site appeared to recover within 5 years. A retrospective 25-year study on a similar landscape in the Coastal Plain of Georgia suggests that the hydrologic impacts of harvesting pine plantations on cypress wetlands are inconclusive (Batzer and others 2000).

Wet flats and pocosins—Wet flats and pocosins occur on broad interstream divides on poorly drained soils. Wet flats occurring on higher elevations are better drained than pocosins, which develop thick organic layers. Most of the wet pine flats and pocosins have been intensively managed for timber production. Forest harvesting practices generally result in short-term water-table rise and an increase in runoff. A long-term watershed-scale (48 to 64 ha) study on a cypress-pine flatwoods landscape at the Bradford Forest in northern Florida showed that "maximum" disturbance caused a 15-cm or 150-percent increase in water yield and the "minimum" disturbance resulted in only an insignificant increase (3 cm) in water yield. Water table rose significantly for both treatments, especially during the drought months (Riekerk 1989b). In the sixth year after treatment, runoff from the maximum disturbance watershed was still significantly 65 percent higher than the predicted value from a regression equation. The ground-water tables in both disturbance sites remained higher than the control. Hydrologic changes (water table and runoff) were most pronounced in dry years. These findings were consistent with those of other experimental and modeling studies (Sun and others 1998a) in the region. Williams and Lipscomb (1981) found a water-table rise of 15 to 35 cm after partial cutting in a coastal pine forest on sandy soils. However, Rodriguez (1981) concluded that clearcutting a wet savanna watershed did not significantly alter the watershed hydrology.

Harvesting under wetland conditions, such as those encountered on wet pine flats, can alter soil hydrologic properties (e.g., hydraulic conductivity, macropores) by soil compaction, rutting, and puddling (Greacen and Sands 1980). The physical property changes affect subsurface flow and water-table depth. Soil compaction, rutting, and puddling become greater with increased soil wetness, clay content, and traffic (Green and others 1983). However, Aust and others (1995) found that skidding altered the hydrology of poorly and very poorly drained soils less than it altered that of moderately well-drained or somewhat poorly drained soils. This suggests that lateral subsurface water movement is an important factor in hydrologic impacts on wet pine flats, especially for fine-textured soils.

A field-scale study on wet pine flats in South Carolina has examined the effects of wet-weather harvesting, dry-weather harvesting, and bedding on hydrology and site productivity (Preston 1996, Xu and others 2002). Two site preparation levels (nonbed and bed) were randomly assigned to both dry-weather and wet-weather harvested plots, and an additional level of preparation (moleplow plus bed) was applied only in the wet-weather harvested plots. Dry-weather harvesting raised the water table 14 cm, and wet-weather harvesting raised it 21 cm. The response differences were largest (> 10 cm) during the growing seasons from May to October. Churning and deep rutting affected the water table significantly in wet-harvesting areas, but not in the dry-harvesting areas. Bedding lowered water tables initially in both areas, but the dry-harvesting site recovered within 2 years after replanting. Bulk density, macroporosity, and hydraulic conductivity were significantly affected by all levels of wet-harvesting disturbance. Dry-weather harvesting also altered those soil physical properties. The degree and extent of impacts were much greater for wet-weather harvesting than dry-weather harvesting (Xu and others 2002). Overall, the study suggests that change in water-table depth resulted from change in vegetation, and not from soil changes caused by harvest traffic. Similar changes in soil physical properties followed harvesting and regeneration in a wet pine-flat site in North Carolina, where soil macroporosity was reduced by half within a 200-cm profile (Blanton and others 1998).

Artificial drainage is used to increase operability and forest productivity on poorly drained soils in the Coastal Plain. Hydrologic effects of ditching vary depending on soil characteristics and the stage of vegetation development. Campbell and Hughes (1991) reported that free drainage in pine plantations on pocosins lowered the water table 30 to 60 cm during wet seasons. Standing water was minimized, but soil saturation was maintained and there was less fluctuation in the water table. Drainage did not change the basic hydrologic cycle or convert wetlands to uplands. A retrospective study in Virginia found that ditching significantly lowered the water table in pine plantations from 0 to 3 years old on wet flats during wet seasons when the water table was close to the soil surface (Andrews 1993). However, the ditching effect was dramatically reduced during the growing season at stand age 23. On Pomona sand in Florida, ditching affected water-table levels up to 45 m from the ditch (2 m deep and 3 m wide) for high and average water-table conditions (80 cm from surface) (Segal and others 1986). Hughes and others (1990) reported that flow volumes and seasonal hydrographs for a 16-year-old plantation, unditched natural timber, fully stocked pine plantations, a mixed plantation and naturally regenerated watershed, and a ditched natural stand did not differ. Simulation by the DRAINMOD hydrologic model suggested that ditch spacing had major effects on the composition of runoff from forest lands but caused limited change in total flow volume (Skaggs and others 1991).

Many field- to watershed-scale experiments and modeling studies have been conducted to determine how artificial drainage affects waterflow quantity and quality on the North Carolina Coastal Plain and to test various controlled drainage methods (Amatya and Skaggs 2001; Amatya and others 1996, 2000, 2002; Chescheir and others 2001; McCarthy and others 1991, 1992). Amatya and others (1997a) describe the 5-year hydrology of a 340-ha drained forested pocosin watershed in eastern North Carolina that had heterogeneous soils and underwent changes in vegetation in different fields during the study period. Total annual outflows from the watershed varied from 29 percent of the rainfall during the driest year, when most of the trees present were mature, to as much as 53 percent during a year of normal rainfall after about a third of the trees were harvested. Average annual ET, estimated as the difference between the gross rainfall and outflow, was 58 percent of the gross rainfall. Flow rates per unit area were consistently higher from a smaller harvested block (82 ha) of the watershed than from the whole watershed, partially as a consequence of routing effects in ditches and canals in the whole watershed. In an ongoing large watershed (2950 ha) study of cumulative impacts of management practices on the North Carolina coast, the runoff:rainfall (R:R) ratio varied from 15 to 32 percent as rainfall varied from 960 to 1410 mm. The forested watershed generally yielded no outflows in summer, when ET demands were high, except during periods when large tropical storms brought the water table to the surface. Annual ET, which was estimated as R:R, averaged 970 mm over 5 years. Heath (1975) gave a similar annual water-budget estimate for pocosins—1300 mm for precipitation, 910 mm for ET, 369 mm for runoff, and 13 mm for seepage. Accumulated data suggest that drainage of forested wet flats and forested pocosin wetlands has rather less impact on runoff than might be surmised. Peak flow rates for free-drained lands are higher than those for nondrained or control-drained areas (Amatya and others 1996).

WATER-QUALITY IMPACTS

In the United States, the best water comes from forested watersheds (Binkley 2001, Binkley and Brown 1993), even when forests are managed primarily for timber production (Binkley and others 1999). Many forest management practices, including timber harvesting, site preparation, prescribed burning, and the application of chemicals (insecticides and fertilizers), have the potential to degrade water quality. The impacts of forest management on water quality in the Southern United States have been summarized in review papers by Riekerk and others (1989a), Shepard (1994), Walbridge and Lockaby (1994), Lockaby and others (1997a), Lockaby and others (1999), and most recently by Fulton and West

(2002). Effects of forest management on the water quality in upland and wetland landscapes are discussed separately.

Water-Quality Impacts: Uplands

Riekerk and others (1989) synthesized findings of studies of silvicultural nonpoint-source pollution in uplands of the South. They noted that sediment production during silvicultural operations was low in the mountains and lower Coastal Plains, but high in the Piedmont and upper Coastal Plains. Nutrient export in the Piedmont and upper Coastal Plains was elevated, and rates of nutrient export were controlled by the degree of soil disturbance and the recovery rate of the vegetation. Nutrient exports in the lower Coastal Plains were not much affected by silvicultural operations.

Harvesting Impacts on Streamwater Chemistry—Change of streamwater chemistry is one important signature of ecosystem response to watershed disturbance. The impacts of forest harvesting on water chemistry and nutrient export were reported in a number of papers based on studies conducted at Coweeta (Douglass and Swank 1975, Johnson and Swank 1973, Swank and Swank 1981, Swank and Vose 1994, Swank and others 2001).

Johnson and Swank (1973) analyzed long-term water-chemistry responses for calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na). They found that clearcutting treatments did not cause substantial losses of Ca, Mg, K, and Na over the duration of experimental record.

Converting hardwoods to white pine at Coweeta not only reduced water yield but also altered streamwater quality (Swank and Vose 1994). During the 20 years following initial treatment, streamwater solutes in the pine watersheds and the mixed hardwood control watersheds were generally similar. However, flow weighted mean nitrate-N (NO_3-N) concentrations increased slightly, 0.1 mg/L, while sulphate ion (SO_4^{2-}) concentrations increased nearly threefold. Johnson and Swank (1973) reported that reductions in the losses of Ca, Mg, K, and Na were 2.3, 1.7, 4.4, and 1.2 kg/ha/year, averaged over both watersheds; and Swank and Vose (1994) reported that the rates of reduction were unchanged 20 years later.

Swank and others (2001) contrasted the long-term water-chemistry records of a grazing and clearcut watershed with those of a control watershed. Increases in nutrient export occurred following harvesting with the largest, though relatively small, losses—1.3 kg/ha NO_3-N, 2.4 kg/ha K, 2.7 kg/ha Na, 3.2 kg/ha Ca, 1.4 kg/ha Mg, 0.4 kg/ha sulphur and 2.1 kg/ha chlorine—occurring during the third year following treatment. Export increases were frequently lower than background rates of atmospheric deposition. As in other studies, the nutrient losses returned to baseline levels within a few years after treatment. However, a second phase of increased NO_3-N losses started 14 years after treatment, and this effect had not been observed in other studies. It was hypothesized that mortality and shifts in species composition, nutrient releases from decomposition, elevated soil nitrogen (N) transformation, and reductions in soil carbon (C):N ratio could have contributed to the elevated NO_3-N export.

Harvesting Impacts on Sediment—Long-term effects of forest road construction and harvesting on watershed sediment loading were studied at Coweeta (Swank and others 2001). Prior to construction of a forest access road (~3 km) and cutting, sediment yield averaged 0.23 metric ton/ha/year while that from a control watershed averaged 0.1 metric ton/ha/year. Most of the logging was completed with a cable yarding system; tractor skidding was restricted to a 9-ha area where slopes were under 20 percent. Road construction and harvesting resulted in significant increases in water yield and soil loss. Over the period of monitoring, the rate of soil loss increased by a factor of 3.5. The majority of the measured sediment resulted from road erosion. The average sediment yield was about 340 metric tons/ha/year or 50 percent above the pretreatment level at the end of this 15-year experiment (fig. 19.4).

Harvesting trees without disturbing the soil generally did not increase sediment levels in runoff in the South, but mechanical site preparation with shearing and windrowing of debris generated significant sediment pollution (Ursic 1986). However, this was not the case in a study that compared the hydrologic responses to clearcutting with skidders and logging with a cable yard on a hilly upland site in the southern Coastal Plain in north Mississippi (Ursic 1991b). In the latter study, skidder harvesting increased sediment slightly (by 0.12 metric ton/ha/year), while cable harvesting increased sediment sixfold (3.3 metric tons/ha/year) over the first 5 years. Subsurface flow was critical in elevated channel erosion and deposition in forested landscapes on unconsolidated formations in the Coastal Plain

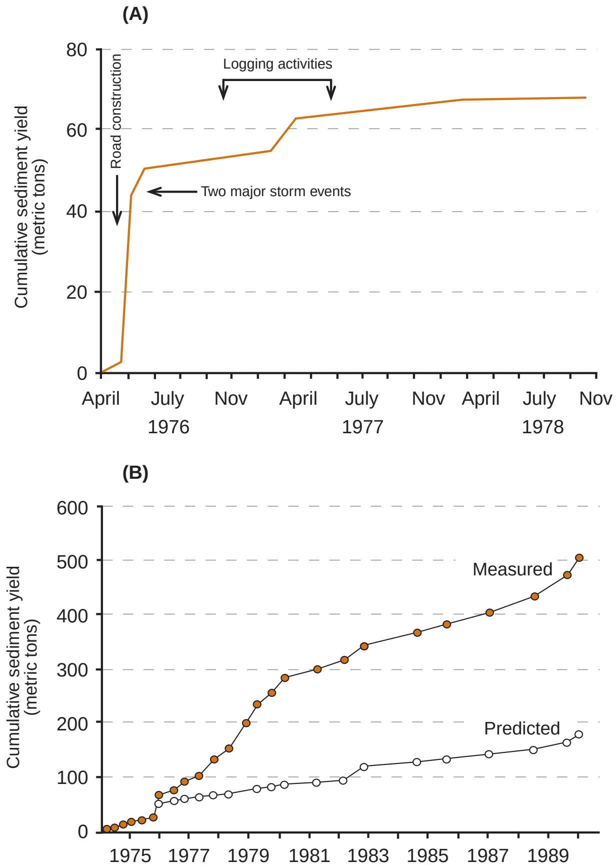

Figure 19.4—Cumulative sediment yield measured at one Appalachian watershed at Coweeta Hydrologic Laboratory (A) in one of the first-order streams below a logging road during the first 32 months after treatment, and (B) in the ponding basin of the second-order stream (Swank and others 2001).

(Ursic 1991b). Another study, which employed 16 small mature loblolly pine (*P. taeda* L.) plantation watersheds on the upper Coastal Plain in Tennessee, also indicated the importance of channel erosion on sediment loading (Ursic 1991a). This study suggested that harvesting of trees growing on previously degraded lands had limited effects (< 0.093-metric ton/ha/year increase) on sediment loading, usually within 4 years.

Mechanical disturbance of the forest floor during harvesting and site preparation is generally supposed to reduce soil productivity and increase soil erosion. One might expect that soil structure and site hydrology would be affected by increased disturbance intensity. However, a recent study at a Piedmont site in Alabama found that surface runoff was lower at a clearcut and bedded site than it was at a site that was clearcut but not bedded (Grace and Carter 2001). Bedding produced additional surface roughness and storage. Although this was a small-scale study, it demonstrated the uncertainty of hydrologic responses to current silvicultural practices.

Scoles and others (1994) described a 15-year study of hydrology and water quality on gauged watersheds in the Ouachita Mountains of Arkansas and Oklahoma. They noted threefold-to-twentyfold increases in soil erosion following selection harvesting and clearcutting. However, the amount was still low, about one-thirtieth of the loss from cropland, and recovery to baseline conditions occurred in the first 5 years of the 35-year rotation. Most erosion occurred during a few large storms each year, and 90 percent of annual stream sediment came from roads. Projected sediment delivery to streams in the Ouachitas as a result of harvesting, site preparation, and erosion from roads was about 0.16 metric ton/ha/year.

Lawson (1985) reported that sediment losses in undisturbed pine forests in the Ouachita Mountains, Ozark Plateaus, and Boston Mountains averaged < 0.02 metric ton/ha/year. Maximum sediment losses of 0.13 metric ton/ha/year were observed during the first year following clearcut timber harvesting. Recovery to preharvest levels of sediment production occurred within 3 years.

Harvesting Impacts on Stream Temperatures— Forest harvesting along streams usually results in increased stream temperatures (Swift 1973, 1982; Wooldridge and Stern 1979). Swift and Messer (1971) monitored stream temperatures in treatment and control watersheds. On the watersheds that were harvested completely, summer stream temperatures increased from an average of 19 °C to more than 23 °C. The most intensive treatments raised temperatures by more than 7 °C. Water temperatures in streams with uncut streamside or riparian vegetation did not increase. Also, temperatures in the impacted streams returned to pretreatment levels when regeneration of riparian vegetation provided shading. The temperature increases significantly altered streamwater quality, in that water temperatures were raised above levels suitable for the native trout populations (Swift and Messer 1971).

Swift (1973) investigated the effectiveness of preserving a 12-m buffer of streamside vegetation in mitigating potential streamwater temperature impacts of forest harvesting on a small, mountain watershed. The stream flowed through alternating cut and uncut riparian zones. Water temperature rapidly increased by up to 6 °C as the stream flowed through a 900-m cut area. It then decreased by approximately 1 °C as the stream flowed through an 800-m uncut riparian area, and increased again as it passed through a 200-m cut area. The stream's temperature eventually stabilized to normal (12.8 °C) when the stream passed through two forested sections of a total of 2100 m. The alternating network of cut and uncut riparian areas limited maximum water temperatures to < 20 °C, a temperature above which trout habitat is impaired.

Swift (1982) reported long-term impacts of cable logging on streamwater temperatures. In the first 2 years following cable logging, average summer streamwater (38 percent shaded) temperatures increased 3.3 °C. Regeneration of streamside trees by stump and root sprouting increased streamside leaf biomass to 78 percent of the pretreatment condition within 3 years following treatment. Subsequent temperature increases averaged 1.2 °C. Minimum temperatures were elevated only in the first year of treatment, whereas daily temperature range (maximum – minimum) was elevated during the 5 years of the study. Swift (1982) predicted that the increase in streamwater temperature would decrease at a rate of 0.3 °C per year, and that streamwater temperature would ultimately return to pretreatment levels.

Harvesting Impacts on Biota—Williams and others (2002) investigated the effects of timber harvesting on physical stream features and regional fish and macroinvertebrate assemblages during a 3-year period in six hydrologically variable streams (basin area 1517 to 3428 ha) in the Ouachita Mountains, AR. Most of the variations in fish assemblages were explained by drainage basin differences, and both basin and year-of-sampling influenced macroinvertebrate assemblages. Williams and others (2002) argue that the lack of logging effects on biota may be due to the scale of the study, timing of the sampling, and high levels of natural variability in the streams.

Forest conversions—The conversion of cove hardwood to mountain grazing at Coweeta resulted in decreased water quality. Peak concentrations of sediment during stormflow events were up to three times higher than expected as the clay fraction of the suspended load significantly increased beyond pretreatment conditions (Johnson 1952).

Converting hardwoods to blue fescue grass at Coweeta (see water-quantity sections also) required spot applications of herbicides to suppress competition. Erosion of the stream channel margin occurred after the first herbicide application. When herbicides were applied a second time, a 10-foot buffer of grass along the channel was left unsprayed. Atrazine was detected in the streamwater following storm events for 4 months after the herbicide treatments. The largest concentration of atrazine, ranging from 24 to 34 parts per billion, occurred immediately after application. Following the second treatment, a sustained, background concentration (4 parts per billion) of atrazine existed in the streamwater for 3 months. No detectable atrazine was found 3 months after the last application (Douglass and others 1969).

Forest road construction—Much of the road research at Coweeta was conducted in conjunction with forest harvesting experiments and was designed to identify methods that would reduce sedimentation from access roads for timber harvesting operations. A comprehensive summary of these experiments and their results is given by Swift (1988) and Swift and Burns (1999).

Hursh (1935, 1939, 1942) reported that soil loss from forest roads could be reduced significantly by mulching or vegetating the adjacent cut-and-fill slopes. Several best construction methods employing bioengineering techniques to stabilize slopes were identified. Use of these methods significantly reduced sedimentation following road construction.

As a part of research on exploitive logging at Coweeta, loggers were allowed to construct roads in a typical fashion. This included the construction of skid trails directly upslope, from roads, and adjacent to and within streams (Swift 1985). These practices resulted in the loss of 408 m^3 of soil/km of road constructed (Lieberman and Hoover 1948b). Sediment delivery to streams was high, and turbidity peaked at 5700 parts per million (Lieberman and Hoover 1948a), significantly reducing downstream aquatic fauna (Tebo 1955). Road erosion became so severe that the roads had to be closed and stabilized. It was concluded that the sedimentation observed in the stream resulted almost exclusively from road erosion and not from other forest harvesting activities (Swift 1988).

Swift (1988) found that soil loss potentials were highest immediately after road construction at Coweeta. The pulses of soil loss after road construction were triggered by intense rainfall events. Soil losses from bare roadbeds were eight times those from graveled roadways. The erosion rates declined in the ensuing 6 months; however, losses from the bare soil were still six times greater than those from the gravel treatments. The largest losses were from roads that received frequent traffic. When logging trucks were present, losses of soil from roads surfaced with thin layers of rock were similar to those from bare-soil roads. Surfacing with large (20 cm) crushed stones afforded the most protection against erosion; however, this stone was deemed too coarse for many vehicular operations. Medium (15 cm) crushed rock provided roadbed protection similar to that obtained with the 20-cm stone but at a significantly reduced cost. Rates of erosion from roadbeds of fine (5 cm) crushed rock were similar to those for bare-soil roads. Seeding of the roadbeds and cut-and-fill slopes of lightly traveled roads reduced erosion rates to 50 percent of those for bare-soil conditions (Swift 1984a).

Swift (1984b) monitored rates of erosion from roadbeds, cut slopes, and fill slopes along a series of road treatments (Swift 1984a). Although soil losses from all surfaces were high during heavy rains, rates of erosion from bare cut-and-fill slopes that made up half of the road prism accounted for 70 to 80 percent of the total soil losses from the sites. Graveling of the roadbed reduced soil losses to < 20 percent of those for the bare-soil condition. A combined treatment that consisted of vegetating the cut-and-fill slopes and graveling the roadbeds reduced total erosion rates to < 10 percent of those for the pretreatment condition. Despite these improvements, the net loss of soil from the entire roadway was 20 times greater than that estimated for undisturbed forest (Swift 1984b).

Fertilization—Binkley and others (1999) and National Council for Air and Stream Improvement (1999d) reviewed world literature about response of streamwater chemistry to forest fertilization in upland and wetland forest ecosystems. They found that forest fertilization usually results in elevated N and phosphorus (P) concentrations, especially if pellets are deposited directly into streams and ditches. However, maximum concentrations of N were rarely above drinking water-quality standards, and elevated concentrations were short-lived (weeks to months). Elevated concentrations were typically one-tenth of those observed in agriculture. Highest N concentrations were observed with repeated applications, and when ammonium nitrate rather than urea was used. No evidence of effects on aquatic organisms was found, but few studies included such an assessment.

In the South, it is common to fertilize with N and P to increase tree growth. In a study on the North Carolina Coastal Plain, fertilization resulted in elevated concentrations of ammonium as much as 3.8 mg/L, total N as much as 9.3 mg/L, total phosphate (PO_4-P) as much as 0.18 mg/L, orthophosphate as much as 0.1 mg/L, and urea as much as 1.2 mg/L measured at the field (27 ha) edges (Campbell 1989). After 3 weeks of treatment, concentrations of all ions returned to pretreatment levels. Concentration of NO_3-N ranged from 0 to 1.2 mg/L during the 60-day monitoring period. Segal and others (1986) and Riekerk (1989b) reported similar findings for studies in the Coastal Plain. Information about effects of fertilization on water quality in other physiographic regions can be found in National Council for Air and Stream Improvement (1999d). Fertilization of forest lands has rarely caused NO_3-N concentration in streams to exceed the U.S. Environmental Protection Agency (EPA) drinking water standard of 10 mg/L, especially when care has been taken in applying the fertilizer.

Prescribed Fires—In the Southern United States, about 1 million ha of forest land is subjected to prescribed burning annually to reduce fuel loads, enhance stand health, and release preferred forest species from competition (Clinton and others 2000, Richter and others 1982, Vose and Swank 1993). The negative impacts of this practice on forest communities include reduction of total ecosystem N as a result of volatilization and leaching (Knoepp and Swank 1993) and a potential increase of sediment loading (Knoepp and Swank 1993, Vose and others 1999). The magnitude of effects of this practice varies greatly and depends on fuels, soil properties, topography, climate, weather, and fire frequency and intensity (Richter and others 1982).

Ursic (1969) described effects of prescribed burning on hydrology and water quality in two abandoned fields in Mississippi. Stormflow during the first year increased 48 percent in one catchment, and stormflow increased in the second and third years also. Treatment of the second catchment, which had a fragipan, did not change the volume of stormflow but significantly increased peak discharges and overland flow. During the first year, sediment production increased from 0.11 to 1.9 metric tons/ha in the first catchment and 7.5 metric tons/ha in the other. Sediment production dropped to < 0.56 metric ton/ha the third year.

Douglas and Van Lear (1983) reported responses of nutrient and sediment export to prescribed burning at a Piedmont site in the Clemson Experimental Forest, SC. Four loblolly pine watersheds were burned twice at 18-month intervals. The first burn took place in March and the second in September. The prescribed burns did not change water quality of the streams.

Clinton and others (2000) summarized the results of four experiments that examined stream nitrate (NO_3-N) responses to forest fires in the Nantahala National Forest in western North Carolina. A fell-and-burn fire (Jacob's Branch) and two stand-replacement fires (Wine Spring Creek and Hickory Branch) were implemented to improve degraded xeric oak (*Quercus* spp.)-pine forests. The fourth (Joyce Kilmer) fire was an arson-related wildfire, burning the understory in an old-growth mesic and xeric forest. The Jacob's Branch and Joyce Kilmer fires occurred in the fall, and the fires on Wine Spring Creek and Hickory Branch were spring burns. Stream nitrate was elevated by 0.03 mg/L for 8 months following the burn on Jacob's Branch and by 0.06 mg/L for 6 weeks following the Joyce Kilmer fire. There was no stream NO_3-N response at the two spring burn sites. Clinton and others surmised that N released during the spring burns was immobilized by vegetation uptake, but that N released during the fall burns was not.

Neary and Currier (1982) monitored stream chemistry [NO_3-N, ammonium nitrogen (NH_4-N), PO_4-P, Na, K, Ca, and Mg] and total suspended solids for five streams burned by wildfire in the Blue Ridge Mountains of South Carolina. Increases in streamwater nitrate, NO_3-N, were attributed to fertilizer applications. Elevated concentrations of NO_3-N and PO_4-P in streamwater occurred mostly during stormflow events, and mean concentrations were not significantly higher than those observed on undisturbed watersheds. Concentrations of anions Na, K, Ca, and Mg ranged from 12 to 82 percent above background levels during the monitoring period.

Forest fires can burn significant amounts of the understory canopy, litter, and duff layers of forests, leaving forest soils unprotected against raindrop impact. The combustion of forest litter and plants in high-intensity forest fires can create and concentrate petroleum-based compounds that induce water repellency in forest soils. This reduces infiltration and increases runoff and soil erosion, especially in the forests of the Western United States (Tiedemann and others 1979, Wolgemuth 2001, Wright and Bailey 1982). However, Wolgemuth (2001) found that forests treated with prescribed fires had erosion rates lower than unburned forests had during subsequent fire events on chaparral watersheds in southern California.

The literature suggests that fire generally has less effect on sediment loading in the Southern United States than it has in the Western United States (Goebell and others 1967, Marion and Ursic 1992, Shahlee and others 1991, Swift and others 1993, Van Lear and Danielovich 1988, Van Lear and Waldrop 1986). Increased soil erosion following fires is frequently associated with forest floor disturbances caused by mechanical site preparation during fire controlling activities. Similarly, operationally disturbed sites and especially skid trails have been found to be more susceptible to erosion following fires (Ursic 1970, Van Lear and others 1985). However, it must be noted that most fire research in the Southern Appalachians has involved fires of low-to-moderate intensity (Swift and others 1993, Van Lear and Waldrop 1989).

Pesticides—Pesticides have been increasingly used in the South to control insects and unwanted vegetation. These organic substances have the potential to pollute water by aerial drift, decomposition, leaching and adsorption, and transport by subsurface flows. Substantial effort has been made to discover the fate of applied forestry pesticides (Michael and Neary 1990; Neary 1983; Neary and Michael 1996; Neary and others 1985, 1993; U.S. Department of Agriculture, Forest Service 1994). The literature suggests that the risk of long-term contamination from pesticide application is low when care is taken. Residues are not persistent and do not bioaccumulate. When herbicides are not applied directly to streams or when buffer strips are used, peak residue concentrations are generally low (< 500 parts per billion), and residue levels in surface runoff are < 36 parts per billion for ground application and < 130 parts per billion for aerial applications (Riekerk and others 1989). Most herbicides used in modern silviculture are of low toxicity to aquatic and terrestrial organisms, and thus pose little hazard to wildlife.

Insect outbreaks—Insect defoliation was responsible for the increased stream nitrate concentration in several watersheds at Coweeta (Swank and others 1981). For example, a sudden rise of nitrate concentrations from 0.5 to 0.75 mg/L in one watershed was caused by a widespread outbreak of the locust stem borer (*Ecdytolopha insiticiana* Zeller) in black locust (*Robinia pseudoacacia* L.) (Swank and Crossley 1988).

Cumulative effects—Multiple forest operations that may or may not be separated in space and time can have cumulative effects on water quality. Bolstad and Swank (1997) analyzed the cumulative effects of land use practices separated in both space and time along the Coweeta Creek in the Appalachians. They found that water quality degraded from the creek's headwaters to the watershed mouth. The water quality at the confluence of two forested subwatersheds was very good. However, averaged stormflow turbidity, conductance, NO_3-N, NH_4-N, temperature, total coliform, fecal coliform, and streptococci counts increased by factors ranging from three (turbidity) to eight (total coliform) as the stream flowed through the residential and agricultural lands to its mouth. The increases in these water-quality parameters were strongly and positively correlated with numerous measures of human impacts including percent nonforest land, paved road density, paved road length, building frequency, and building density.

Water-Quality Impacts: Wetlands

Studies of the effects of forest management on wetland forest water quality and geochemical balances in the Southern United States are summarized in Shepard (1994), Walbridge and Lockaby (1994), Lockaby and others (1997a), and Lockaby and others (1999). Major findings from these papers and other recent publications are discussed below by type of management practices.

Drainage—Drainage usually does not alter water quality greatly. Williams and Askew (1988) reported a small increase in suspended sediments from newly built ditches at a pocosin site in South Carolina and concluded that establishment of pine plantations did not have to harm water quality. Lebo and Herrmann (1998) found that harvesting of loblolly pine plantations increased outflow and slightly increased nutrient concentrations. For a 3-year period after harvesting, increases in annual outflow, N export, and P export were 111 to 164 mm, 2.1 to 2.2 kg N/ha/year, and 0.12 to 0.36 kg P/ha/year, respectively, compared with baseline levels. The baseline values for total N and P loading ranged from 2.7 to 3.4 kg N/ha/year and 0.09 to 0.29 kg P/ha/year, respectively. Outflow and nutrient concentrations returned to baseline levels within 2 to 3 years. These relatively small temporary increases in annual nutrient exports associated with harvesting and site preparation can be considered in the context of 30- to 50-year rotations for loblolly pine in coastal North Carolina. On that basis, they represent an increase of 4 to 7 percent above baseline levels.

In a large drained watershed (2950 ha) with mixed land uses in eastern North Carolina, ranges of measured total N concentrations at the field edges were 0.5 to 15 mg/L for the organic soils and 0.3 to 5.0 mg/L for the mineral soils. The annual total N loading varied from about 4.8 kg/ha to as much as 26.6 kg/ha, with an average of 14 kg/ha. Most of the total N was in organic form. It appears that the variation in nutrient loading attributable only to soil can be as great as that caused by forest harvesting.

Harvesting—In wetands, forest harvesting followed by site preparation activities has the potential to disturb the surface soils, alter surface and subsurface flow paths, increase water yield, and accelerate nutrient cycling rates, and thus affect onsite and offsite water quality. Riekerk (1985) found that clearcutting a pine-cypress flatwoods resulted in significant increases in pH, suspended sediment, and total N, K, and Ca during the first year after harvest. Fisher (1981) described the effects of clearcutting and site preparation on the hydrology and water quality of a pine flatwoods site in western Florida. Runoff volume was increased during the first year, but by the second year most water-quality parameters had returned to near background levels. The impact of silvicultural operations was less on the level, sandy site than in areas having more relief and shallow soils (Fisher 1981).

There are over 12 million ha of bottomland hardwoods forest in the Southern United States. A series of harvesting experiments have been conducted to examine their ecological responses to timber harvesting (Aust and others 1991, 1997; Lockby and others 1994, 1997b; Messina and others 1997; Wang 1996). These experiments indicate that onsite effects of harvesting flood plain forests are minor because the site disturbance is not great, because water movement is slow and because harvesting causes an increase in surface roughness for sediment and nutrient retention (Aust and others 1991, Rapp and others 2001). The treatment effects in these studies were often overwritten by seasonal flooding events (Perison 1997).

Prescribed fires—Controlled burning in the Atlantic and Gulf Coastal Plain reduces the risk of wildfire, controls certain tree pathogens, improves wildlife habitat, and restores desired ecosystems. For these reasons, the use of controlled burning is very common. However, few data are available on the effects of this management tool on the hydrology and water quality of wetlands. One exception is a 3-year paired watershed study conducted at the Santee Experimental Forest in eastern South Carolina (Richter and others 1982, 1983). The treatment and control watersheds were about 160 and 200 ha in area, respectively, and had first-order perennial streams. Dominant soils were Aquults (high water table), and the watersheds were covered by natural stands of loblolly pine. Burns prescribed for twenty 7.1-ha compartments were administered during winters and summers. It was concluded that periodic prescribed fires in these southeastern Coastal Plain pine forests are not likely to have great impacts on onsite or offsite water quality (Richter and others 1982).

WATER QUALITY REGULATIONS, AND DESIGN AND EFFECTIVENESS OF FORESTRY BMPS

Federal and State Water-Quality Programs

There are many Federal and State programs designed to protect water quality. The first Federal water-quality regulation applicable to forestry was included in the 1972 amendments to the Federal Water Pollution Control Act (commonly known as the Clean Water Act). This statute introduced two new concepts in Federal water-quality protection. First, its Section 208 required States to prepare area-wide (watershed or regional) waste treatment management plans; and second, it separated water pollution into two categories: pollution for point and nonpoint sources (Ice and others 1997).

Initially, the Clean Water Act was interpreted as requiring States to prepare water-quality management plans only for waters the States identified as impaired. However, the successful lawsuit NRCD vs. Train (1975) resulted in EPA requiring area-wide programs statewide, not just for areas with water pollution problems. In the regulations developed following NRCD vs. Train, EPA specified that States may develop nonpoint-source control programs that prescribe "Best Management Practices" (Rey 1977). The EPA defined BMPs as

> . . . a practice or combination of practices, that are determined by a state, or designated area-wide planning agency, after problem assessment, examination of alternative practices, and appropriate public participation, to be the most effective, practicable (including technological, economic, and institutional considerations) means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals . . . (Ice and others 1997).

Oregon was the only State that had a silvicultural nonpoint-source control program prior to 1972 (National Council for Air and Stream Improvement 1999c). Florida and South Carolina were among the first States to develop BMPs; South Carolina published its first water-quality guidelines in 1976, and Florida began developing its BMPs in 1976 (Greis 1979). The 1987 amendments to the Clean Water Act created Section 319, which required States to develop and implement programs to control nonpoint-source pollution. This amendment stimulated States to accelerate their efforts to develop silvicultural BMPs, and many State programs began shortly after 1987.

Total Maximum Daily Loads

Section 303(d) of the Clean Water Act requires that States list waters that do not meet water-quality standards or that do not meet their designated uses because of a particular pollutant such as sediment, pathogens, nutrients, or temperature. States must then develop a total maximum daily load (TMDL) for each pollutant causing impairment, specifically for each water body. A TMDL is the maximum amount of a pollutant that a water body can receive and still meet water-quality standards and an allocation of that amount among the pollutant's sources. It can be expressed as follows:

$$\text{TMDL} = \Sigma \text{ waste load allocation} + \Sigma \text{ load allocation} + \text{margin of safety}$$

Waste load allocations are point sources of the pollutant, and load allocations are nonpoint sources, including natural background levels of pollutants such as sediment, nutrients, and temperature. Although TMDLs were included in the 1972 Clean Water Act, it was not until the late 1980s that lawsuits forced the EPA and States to begin implementing the program. Hundreds and sometimes thousands of water bodies were listed in States. The total number listed in 2001 was over 40,000 (National Research Council 2001). States are being required by court orders or by EPA guidance to develop these TMDLs within 8 to 13 years, but the amount of effort required dwarfs the budgets of State water-quality agencies. Meeting these deadlines has become ". . . the most pressing and significant regulatory water quality challenge for the states since passage of the Clean Water Act . . ." (National Research Council 2001).

Routine forest management has not yet been affected by TMDL regulations. The EPA is currently operating under regulations promulgated in 1992, but revision of those regulations is pending. Current EPA policy recommends that States with approved forestry BMP programs grant exemptions to enforceable water-quality standards to forestry operators who implement BMPs (Anon. 2000).

Federal Wetlands Regulations

Section 404 of the Clean Water Act regulates the discharge of dredged and fill material into "waters of the United States," which include wetlands adjacent to navigable waters, interstate wetlands, and isolated intrastate wetlands that could affect interstate or foreign commerce (Guzy and Anderson 2001). The U.S. Army Corps of Engineers (Corps) administers the Section 404 program, and the EPA is responsible for policymaking and oversight of the Corps' management of the program. Those who conduct activities that will result in the deposition of more than a *de minimis* (threshold) amount of dredge and fill material in wetlands must apply for a permit from the Corps. Normal farming, silvicultural and ranching activities such as plowing, seeding, cultivating, minor drainage, and harvesting for the production of food, fiber, and forest products are exempted from this regulation when they are part of established operations (33 CFR 323.4). Other activities exempt from the permit program are minor drainage (that does not convert the site to upland), maintenance of existing ditches, and building of forest roads (subject to 15 BMPs).

In 1995, the EPA and Corps released to the field a memorandum about "Application of Best Management Practices to Mechanical Silvicultural Site Preparation Activities for the Establishment of Pine Plantations in the Southeast." This memorandum specified that a permit would be required for mechanical site preparation to establish pine on wetlands supporting riverine bottomland hardwoods, white-cedar [*Chamaecyparis thyoides* (L.) B.S.P.] swamps, Carolina bays, low pocosins, and wet marl forests. It also specified that other wetlands would continue to be exempt from permitting as long as six new BMPs were employed (Anon. 1996). A more comprehensive description of wetlands forestry regulations is found in Gaddis and Cubbage (1998). A comprehensive treatment of the entire Federal wetlands regulatory program, and a discussion of litigation history, is provided by Want (1998).

Design of BMPs

Generally, BMPs designed to protect water quality fall into four categories: (1) those related to riparian areas, (2) those related to disturbed areas such as roads and landings, (3) those related to wetlands, and (4) those related to harvesting practices. In most Southeastern States, BMPs are voluntary. In Virginia, however, loggers or landowners must notify the State Forester at the start of an activity, and the State Forester can mandate corrective actions when a threat to water quality is identified.

High BMP compliance rates are in the interest of the forest industry because the EPA currently accepts BMPs as appropriate and sufficient mitigation to meet the requirements of the TMDL program. If rates of BMP compliance are not high, water-quality regulations may be imposed. Another reason for employing BMPs is the threat and reality of citizen lawsuits. If runoff from a forestry operation causes water-quality problems for a downstream landowner, the downstream landowner can sue for damages. In such cases, the operator's compliance with BMPs is always a major issue.

Most nonpoint-source pollution caused by silvicultural activities starts with exposure of bare soil and soil disturbance. When raindrops strike the ground, they detach and disperse soil particles. Raindrops also compact surface soil, and this compaction promotes overland flow that mobilizes sediment and transports it to the stream system. If fertilizers or pesticides have been applied to the ground surface recently, then overland flow also transports these chemicals to streams. Therefore, most BMPs are designed to minimize the amount and duration of bare soil and the hydraulic connectivity of runoff from bare-soil areas to streams.

The development of silvicultural BMPs over the last 20 years has been based on forestry research and basic principles of stream ecology. Logger and forester experience, common sense, and political negotiation have also factored into the development of BMPs. Because soils, topography, climate, and political environments vary from State to State, the States have issued different BMP prescriptions.

Riparian Areas

The term riparian area refers to a channel-adjacent terrestrial area in which the presence of the stream and high water tables are primary influences on vegetation and soil development. In turn, the vegetation affects channel conditions by altering the microclimate and providing organic inputs to the stream system. Most BMP guidelines call for maintaining natural conditions in a portion of the riparian areas adjacent to channel systems to protect streamwater quality from potential effects of upland management practices. These riparian protection areas are described as riparian zones, riparian management zones, buffers, filter strips, and streamside management zones (SMZs) in the BMP guidelines defined by different States (Stringer and Thompson 2000). Riparian buffers protect water quality by (a) stabilization of stream banks, (b) filtration of overland flow and adsorption of chemicals transported in overland flow, (c) denitrification of shallow ground water, and (d) maintenance of shade and organic debris recruitment for channels.

Stringer and Thompson have published a review of State guidelines on riparian zones. Their findings are summarized: Most States in the Southeast now specify (a) minimum allowable distance between water bodies and the nearest severe disturbance, e.g., roads or landings; and (b) the allowable harvest within the riparian area (Stringer and Thompson 2000). In most States, the allowable distance between severe disturbance and perennial water bodies (perennial streams and lakes) increases as upland slope increases. This is because the potential for surface runoff impacts is greater with higher upland grades (Trimble and Sartz 1957). Most States allow 25 to 50 percent removal of the overstory within the perennial riparian area (Stringer and Thompson 2000). Generally, BMPs for intermittent streams are less restrictive as they are considered to have less potential nonpoint-source pollution impact than perennial streams. In the Southeast, about one-half of the States set a specific minimum distance to the nearest disturbance, and about one-half relate the distance to upland grade; however, these allowable distances are generally narrower than those for perennial water bodies. Allowable harvest generally ranges from 75 to 100 percent canopy removal. The effects of headwater area forestry operations on water quality are poorly understood. Most State BMPs do not explicitly recommend SMZs for ephemeral streams. Most States in the northern part of the Southeast also have guidelines for forestry practices in areas near coldwater streams that support trout. Generally, BMPs for areas adjacent to coldwater streams are more restrictive than those for areas adjacent to perennial streams in terms of buffer width and overstory removal within buffers.

Roads

Because logging roads create permanent areas of bare and compacted soil, they are the principal contributor of sediment from forestry activities (Swank and others 2001). Road and landing position in the landscape, the soil type and geology present, and method of retirement ultimately determine the magnitude of sediment flux to the stream (Ketcheson and others 1999, Swift 1988).

Impacts of road runoff and sediment can be reduced greatly by reducing or eliminating the hydraulic connectivity of roads to streams. This is done by routing water off roads at regular intervals onto hillslope locations where flow can be dispersed and reinfiltrated. Water bars, broad-based dips, and cross-drains are typical methods by which road runoff is routed from roads onto hillslopes (Cook and Hewlett 1979, Swift 1988). Depending on slopes and native soils, surfacing roads with gravel or rock can also reduce surface erosion. A review of specific State guidelines for BMPs related to roads and skid trails can be found in Stringer and Thompson (2001).

The use of filter strips along roads also mitigates the propagation of road sediment through drainage networks and into streams. While filter strips normally include natural vegetation, their performance may be augmented by using trees and woody slash material to form brush barriers. Use of such materials reduced distance of sediment movement by approximately 40 to 50 percent (Swift 1986). Natural forest litter was also instrumental in inhibiting transport at burned sites. Grass-covered sites on which runoff was diverted through forest litter and brush barriers provided the most resistance to flow. Swift (1986) observed the distances traveled by sediment from forest roads. He recommends that the width of forest road buffers be designed on the basis of land slope and the use or nonuse of brush barriers.

Grace (2000) studied the effectiveness of three common treatments for controlling erosion from cut-and-fill slopes of roads in the Talladega National Forest, AL. The three treatments were (1) native species vegetation mix, (2) nonnative species vegetation mix, and (3) nonnative species vegetation mix anchored with an erosion-control mat. Surface runoff and sediment yield were significantly reduced on both the cut-and-fill slopes. The three control measures reduced sediment production by 60 to 90 percent. The erosion-control mat treatment was the most effective of the three.

Clinton and Vose (2002) evaluated the effectiveness of road paving in reducing the delivery and transport of sediment from mountain forest roads. Delivery and transport of sediment were measured for four surface types: (1) 2-year-old pavement, (2) improved gravel, (3) improved gravel with sediment control, and (4) unimproved gravel. The paved road system generated the least sediment while the unimproved road generated the most. The distance of sediment transport away from the roadbed was greater for the paved road surface and decreased progressively for improved gravel, improved gravel with sediment control, and unimproved surfaces.

Appelboom and others (2002) evaluated the effectiveness of four road management practices (continuous roadside berms, noncontinuous roadside berms, a graveled road surface, and a nongraveled road surface) in reducing sediment loading to ditches within a drained forested watershed on the lower Coastal Plain of North Carolina. They found the presence of access roads under the four practices had little impact on sediment loading at the watershed outlet when comparing the sedimentation of drainage from similar watersheds without access roads.

Wetlands

The Clean Water Act allows minor drainage for forestry without a permit. However, such drainage cannot connect wetlands to uplands. Thinning or harvesting of overstory trees is allowed in most wetlands. However, mechanical site preparation to establish pine stands in certain wetland types is prohibited by the Corps and EPA (Anon. 1996). Most State BMP manuals do not provide much guidance about ditches or drainage. However, many individual forest management companies have developed their own wetland BMPs, and these often stipulate basal area or canopy requirements for wetlands. Silvicultural practices in and around wetlands, therefore, vary greatly from landowner to landowner.

Harvesting and Site Preparation Practices

During harvesting, log decks and skid trails become temporary areas of bare soils. As with roads, the water-quality goal for managing these areas is to limit their hydraulic connectivity to streams. On any site, the number of log decks should be minimized and their distance to streams should be maximized. BMPs call for minimizing the number of temporary stream crossings and for using water bars to disperse runoff from skid trails. Soil rutting should be avoided and minimized. Equipment that exerts low ground pressure is recommended for wet sites. Skid trails on wet sites should be matted with a layer of limbs and branches over which equipment will operate.

BMPs require that mechanical site preparation (plowing, bedding, ripping) be done along contours to impede overland flow and minimize erosion. If debris is piled, it should be piled on contour to act as an organic silt fence. Most BMP recommendations preclude site preparation fires on steep slopes and call for cool fires that do not eliminate the duff layer, which is crucial in the prevention of surface erosion.

Effectiveness of BMPs

The National Association of State Foresters (NASF) tracks State BMP program performance. In its fourth survey, NASF (2001) reported that all 50 States have developed forestry BMPs. This is an improvement since NASF's 1990 survey, when only 38 States had BMPs. The national rate of BMP implementation is 86 percent. Half of the 22 States that monitor BMP implementation had overall BMP implementation rates of more than 90 percent (average 94 percent). A few States reported implementation rates below 80 percent. In addition to monitoring implementation, many States have also conducted assessments of BMP effectiveness. These investigations have found that BMPs are highly effective in protecting water quality during forestry operations (Adams and others 1995, Keim and Schoenholtz 1999, Kochenderfer and others 1997, Vowell 2001, Williams and others 1999). However, different States use different methods to survey the effectiveness of BMPs.

Sediment and Flow

In a study conducted on a watershed triplet in eastern Kentucky, Arthur and others (1998) found that clearcutting without BMPs increased suspended sediment loads by a factor of 30 in the 17 months during and following treatment and that clearcutting with BMPs increased sediment loads by a factor of 14 during this period. The effect of clearcutting on sediment fluxes disappeared after 5 years. The increase in load was attributable partly to increases in water yield (138 percent without BMPs and 123 percent with BMPs, respectively, in the first 17 months after harvest), but was attributable mostly to increases in suspended sediment concentrations. Most of the streamflow effect also disappeared within 5 years of treatment, although some flow effect was detectable when the study was completed 9 years after harvest.

Wynn and others (2000) analyzed a watershed triplet in eastern Virginia. They found that median storm total suspended sediment (TSS) concentrations increased by a factor of eight after clearcutting without BMPs. After site preparation, median storm TSS concentrations in the no-BMP watershed were 13 times as great as they had been prior to harvest. In the watershed in which BMPs were employed, there was no increase in TSS when TSS was converted for climatic variations observed in the control.

Using a cross-landscape comparison of first-order watersheds with complete randomized block design, Keim and Schoenholtz (1999) compared water quality for four treatments: (1) unrestricted harvest, (2) SMZs with cable thinning, (3) no-harvest SMZs, and (4) reference. Harvesting was group selection of hardwood species on Mississippi loessal bluffs with steep slopes with highly erodable soils. Grab sample and machine-composited TSS concentrations were higher in the watersheds with unrestricted harvest and with cable-thinned SMZs than in the references. TSS concentrations in the no-harvest SMZ watersheds were not different from these in references. Keim and Schoenholtz concluded that BMPs should focus on eliminating machine traffic within 10 m of streams.

Nutrients

Arthur and others (1998) found that mean nitrate concentrations rose from < 1 mg/L to almost 5 mg/L in the first 3 years after harvesting. The nitrate pulse was similar in no-BMP and in BMP watersheds. Concentrations of PO_4^{3-}, K^+, Ca^{2+}, Mg^{2+}, Na^+, SO_4^{2-}, and alkalinity did not respond detectably to harvesting. Wynn and others (2000) observed a similar pulse of NO_3^- from their no-BMP watershed but not from their BMP watershed. They found that total P loadings increased in the no-BMP watershed, but that this was explained by P bound to sediment, and was not soluble P.

The use of controlled drainage to improve water quality has been studied in a poorly drained loblolly pine plantation on the North Carolina Coastal Plain. Amatya and others (1998) reported that controlled drainage with a raised weir at the field outlets reduced annual export of TSS, NO_3+NO_2-N, and total Kjeldahl N by as much as 57 percent, 16 percent, and 45 percent, respectively, by reducing drainage volume and peak flow rates. The annual total P and NH_4-N loadings were also reduced by 7 to 72 percent. Amatya and others (2002) examined the effects of controlled drainage with a raised weir and an orifice on water quality. The authors reported that this system reduced flow volume and peak rates, and sediment and P loading, but had limited effects on other water-quality parameters.

Water Temperature

Changes in surface water temperatures as a result of forest harvesting activities conducted in riparian areas can have dramatic effects on aquatic biota (Wallace 1988, Webster and others 1988). Shading provided by trees in forested riparian areas cools aquatic habitats and moderates temperature fluctuations by insulation (Swift and Messer 1971). Intensive harvesting of riparian areas has been shown to increase maximum daily stream temperatures from 5 to 10 °C (Lynch and others 1985).

Because harvesting in riparian areas increases water temperatures and affects aquatic biota, BMPs have been designed to minimize changes in water temperature. BMPs have been developed that allow some overstory removal (generally ~ 25 to 50 percent) within riparian areas of perennial streams. Although many studies have shown stream temperature effects following intensive harvesting near streams (National Council for Air and Stream Improvement 2000), few have been designed to test the efficiency of these BMPs in moderating water temperature impacts of harvesting in ripirain areas. Within unharvested riparian areas, 15- to 30-m riparian buffer widths provide 85 to 100 percent effectiveness in mitigating increased solar radiation (National Council for Air and Stream Improvement 2000). Studies in northern Florida found no stream temperature increases in harvested riparian areas ranging from 10.6 to 60.9 m in width when 50 percent of the canopy was removed in the zone and a stringer of trees was left along the stream

(Vowell 2001). At the Fernow Experimental Forest in West Virginia, there were small (~1 °C) increases in stream temperature following a "light" removal of timber in a riparian zone 20 m in width (Kochenderfer and Edwards 1990). At Coweeta in North Carolina, the removal of 22 percent of the basal area had no effect on stream temperature (Swift and Messer 1971). Thus, the few studies of the effects of BMP design on stream temperature in the Southeast do suggest that 25 to 50 percent basal-area reductions within the riparian area lead to little or no increase in stream temperature.

Aquatic Biota

Forestry BMPs, especially those related to riparian areas, have been designed to lessen the impact of harvesting activities on water quality, and protection of water quality is generally considered to be a surrogate for the protection of aquatic communities. Therefore, the condition of aquatic communities has rarely been assessed directly during BMP effectiveness studies.

Intensive forest harvesting or land clearing in riparian areas increases insolation, raises stream temperatures, increases flows, increases both stream sediment and nutrient loads, and generally leads to greater primary productivity and shifts in faunal communities (Barton and others 2000, Richards and Hollingsworth 2000, Wallace 1988).

In northern Florida, there were no changes in habitat or stream condition index, which is based on macroinvertebrate populations, when 50 percent of the riparian overstory was removed and trees adjacent to the stream were not removed (Vowell 2001). In South Carolina, studies indicate that riparian BMPs, when implemented, have little to no effect on stream habitat and macroinvertebrate communities (Adams and others 1995). However, when riparian BMPs are not implemented or are implemented incorrectly, stream habitat and macroinvertebrate populations are affected negatively.

MODELING TOOLS FOR EVALUATING THE EFFECTS OF FOREST MANAGEMENT

Computer models cannot replicate the complex processes that take place in forests, but they are powerful and effective tools in forest management. If they are used properly, models can help us understand the processes and synthesize data at different scales, and may be a cost-effective tool for answering "what-if" questions. Because the Coastal Plains and the uplands have different hydrologic processes, we classify the existing computer models as wetland or upland models according to their applicability. Only those models that were developed for or have been applied to southern forest ecosystems are reviewed.

DRAINLOB and DRAINWAT

The DRAINLOB model (McCarthy and others 1992) is a forest version of the DRAINMOD-based models that were well tested for poorly drained (ditched) conditions in North Carolina and around the world. It is a physically based, lumped, and field scale hydrologic model. Using approximate analytical methods, the model predicts the full daily forest hydrologic cycle including rainfall interception, infiltration, subsurface drainage, surface runoff, ET, and soil water storage based on an hourly water balance conducted for a soil profile at the midpoint between two parallel ditches. ET is simulated using the Penman-Monteith method. Subsurface drainage rate is computed using a "table lookup" procedure that employs tabulated results of numerical solutions to the nonlinear Boussinesq equation. McCarthy and Skaggs (1992) applied DRAINLOB to evaluate the long-term water budget and hydrologic impacts of water-management practices for thinned and unthinned regimes of a pine plantation. This model has been modified to DRAINWAT by the addition of flow routing algorithms, and subsequently applied to forested watersheds with multiple fields and ditches (Amtaya and others 1997b). Major outputs from DRAINLOB and DRAINWAT include ground-water level and total outflow at the field edge and the watershed outlet on a daily basis.

FLATWOODS

The FLATWOODS model is classified as a physically based, distributed, and watershed-scale surface ground-water model (Sun and others 1998a). It was developed and tested specifically to examine the hydrologic impacts of forest harvesting in the heterogeneous cypress-pine flatwoods landscape (Sun and others 1998b). The model simulates the full daily hydrologic cycle of each uniform segment or cell of a watershed and links each cell with shallow ground-water flow. The vertical unsaturated water flow is computed using a simplified Darcy's equation while the 2-D lateral ground-water flow is simulated by the standard ground-water flow equation with Dupuit assumptions. ET is the sum of canopy interception, soil and surface water evaporation, and tree transpiration. Potential ET (PET) is computed using the temperature-based Hamon's PET model. The interception is modeled as a function of leaf area index (LAI), precipitation, and PET. Soil and surface evaporation are modeled as a function of LAI and ground-water level. Transpiration consumes the rest of the PET, but is limited by soil moisture status. Total outflow that is affected by averaged ground-water table and saturated areas is calculated using an empirical power function derived from experimental data. Major outputs from this model are total daily flow and distributed ground-water levels. Because this model explicitly simulates the ground-water fluxes, it has potential applications to isolated wetland systems, e.g., Carolina bays, that are common in the Coastal Plain in the South.

WETLANDS

WETLANDS (Mansell and others 2000) was developed to simulate the dynamic linkages of ground water and surface water in isolated depressional wetlands, such as cypress swamps. It is an altered form of the VS2DT model, a two-dimensional water and solute transport model for variably saturated media (Healy 1990). Radial symmetry and cone-shape geometry was assumed for the seasonally flooded wetland that is surrounded by uplands. ET is estimated by the Priestley-Taylor equation from a minimum set of daily weather data. Water-table levels in the wetland, lateral, and vertical water movement are simulated by solving two coupled equations simultaneously: the Richards equation and the water-balance equation for the wetland-upland system. Major model outputs are water-table distribution across the wetland-upland continuum, ET, and soil moisture dynamics.

PROSPER

PROSPER is a lumped parameter model that was developed to estimate water stress for an upland forest stand by describing the atmosphere-soil-plant water-flow processes (Goldstein and others 1974). As the major component of the model, ET is modeled by a combined energy balance-aerodynamic method. Soil water is depleted by ET, and its movement between layers is modeled by Darcy's law and mass balance by an approximate numerical solution. Major climate data requirements for this model include daily values of precipitation, air temperature, relative humidity, solar radiation, and wind speed. Other parameters include mean values of albedo; leaf area of vegetation; typical resistance values for water movement through soils, plants, and atmosphere; soil hydraulic conductivity; and root distribution. Major outputs from the model are daily ET and soil water potential at different soil layers. PROSPER has been used to examine the hydrologic effects of forest conversions (Swift and Swank 1975) and climate change (Vose and Maass 1999).

ANSWERS (Forest Hydrology Version)

The ANSWERS model represents the first generation of physically based, spatially distributed, watershed-scale models that were designed to simulate the effects of agricultural BMPs on runoff and sediment loss from agricultural watersheds (Beasley and Huggins 1981) on a storm event basis. Thomas and Beasley (1986a) modified the original ANSWERS model with the goal of giving forest managers a tool for evaluating management practices (logging and prescribed burning). Major modifications include the addition of interflow components of seepage and macropore or pipe flow at the surface soil layer, alternation of the canopy interception submodel, and estimation of initial soil moisture distribution. Major input data requirements include soil physical characteristics, topography (digital elevation model), and rainfall intensity. Major outputs are storm flow volumes and storm hydrograph.

This event-based model has been validated successfully on five upland watersheds in the upper Coastal Plain in Mississippi (Thomas and Beasley 1986b). However, unsatisfactory results were reported when the model was tested on two steep mountain watersheds at Coweeta in North Carolina where soils and topography were believed to be unique and baseflow rates are relatively higher than those of the Piedmont watersheds.

PnET-II

The PnET-II model is a lumped-parameter, monthly-time-step, generalized stand-level model that describes the C and water dynamics of mature forests (Aber and others 1995). It simulates both C and water cycles in a forest ecosystem using simplified algorithms that describe key biological and hydrologic processes. This model has been validated and modified for southern upland forest ecosystems (Aber and others 1995, Liang and others 2002), southern pines (McNulty and others 1996, Sun and others 2000a), and hardwoods (Hanson and others 2003). It has been employed to assess the potential effects of climate change on forest hydrology at a regional scale (McNulty and others 1996). Input parameters for vegetation, soil and site locations, and climate may be derived from the literature or measured at a local study site. Stand-level vegetation parameters include those regulating physiological and physical processes such as photosynthesis, light attenuation, foliar N concentration, plant and soil respiration, and rainfall interception. Only one soil parameter, soil water-holding capacity, is required. Climate input variables include minimum and maximum monthly air temperature, total monthly photosynthetic active radiation, and total monthly precipitation. The PnET-II model closely integrates hydrology with the biological processes. ET is defined as the sum of plant transpiration and canopy interception. Transpiration is simulated as a function of C absorbed during photosynthesis and water-use efficiency. The model simulates the C cycle by tracking absorbed C during photosynthesis; allocation of C to foliage, wood, and roots; and respiration from leaves, stems, and roots. The hydrologic cycle is simulated by the water-balance equation. Water that is not subjected to ET eventually ends up as water yield. Major model outputs include annual forest net primary productivity, monthly and annual ET, and water yield.

SCALING-UP WATERSHED HYDROLOGY FOR REGIONAL ASSESSMENT

There have been several attempts to generalize experimental results from small watersheds to guide regional forest management. Douglass and Swank (1972) and Douglass (1983) derived a general empirical equation to estimate water-yield response to forest management in the Appalachian Mountains. However, the model does not include precipitation as an independent variable, and thus has limited applicability for other similar mountain regions. Huff and others (1999) presented empirical methods and a computer program for evaluating water-yield impacts of proposed forest or vegetation thinning over a large area. They tested the system in the Central Sierra Mountains in California and found that the size of the management area has an important bearing on water-yield response. It is not known how well the modeling system works for the Southern United States. Sun and others (2002) tested and modified a conceptual catchment-scale ET model (Zhang and others 2001) using forested watershed hydrologic data from across the Southern United States. A Geographic Information System (GIS) was used to integrate regional databases for forest cover, climate, topography, and predicted potential ET at a 4-km resolution. The regional analysis shows that hydrologic response, as represented by water-yield increase, varies greatly across the complex physiographic gradients in the Southern United States (fig. 19.5).

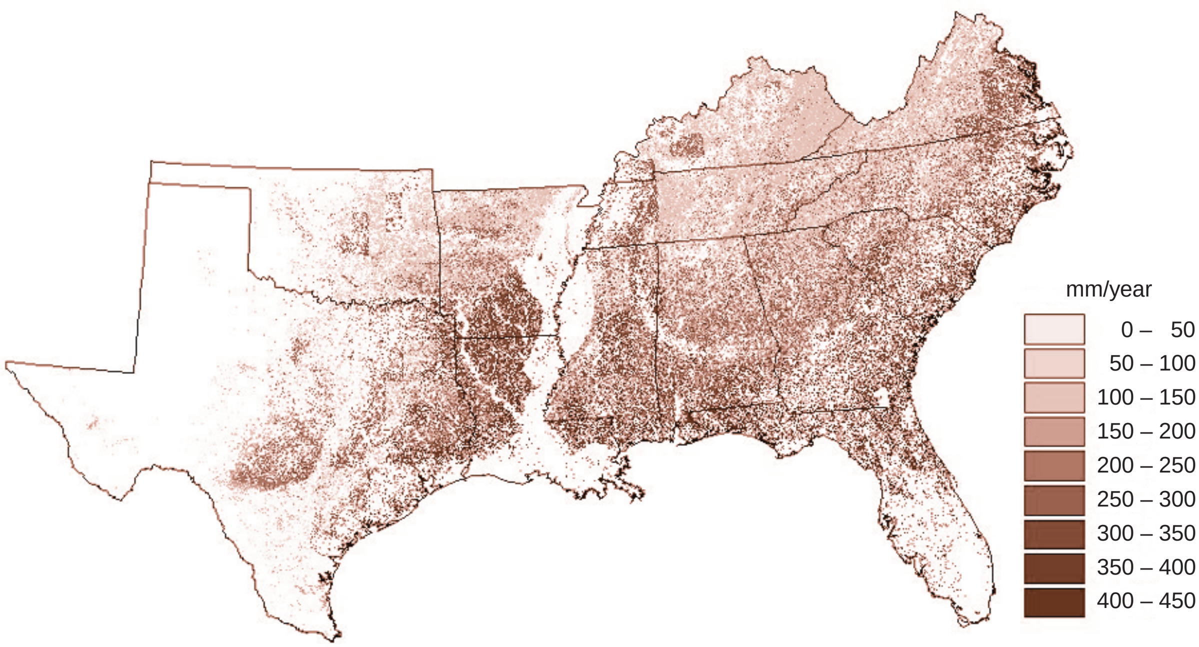

Figure 19.5—Predicted long-term annual water yield response to forest removal at a 4-km resolution. Values are displayed at a 30-m land use/landcover resolution.

SUMMARY AND RECOMMENDATIONS

Research findings regarding water-yield responses to deforestation and aforestation in the Southern United States are consistent with those of studies conducted elsewhere (Bosh and Hewlett 1982, Stednick 1996, Whitehead and Robinson 1993). The greatest increases in water yield occur immediately following harvesting. As more tree cover is removed, the higher the response of water yield and ground-water table increases. The conversion of a forest to a cover type that requires less water, such as agriculture, grazing, and fodder production, significantly increases water yield. Conversely, conversion of a forest to another forest type that intercepts more water, such as conversion from mixed oak-hardwood to eastern white pine, significantly reduces water yield. Regrowth or reforestation increases the interception capacity and consumptive use of water, thus reducing streamwater yield. Large-scale forest manipulation to increase water availability is not practical due to water quality and other ecological concerns. The overall water-quantity effect of silvicultural operations is much less in wetlands than in areas having greater relief and shallow soils. Compared to hilly uplands, southern wetlands on the Coastal Plains or large flood plains have low ratios of runoff to precipitation (< 40 percent). Hydrologic responses of wetlands to tree removal are expected to be low because ET is often near potential and because management activities generally have only minor effects on ET. Wet-weather harvesting in forest wetlands often results in soil compaction, rutting, and churning, but hydrologic responses to forest management are much smaller than hydrologic responses to vegetation changes. Hydrologic recovery appears to be faster in wetlands than in uplands. Climate gradient also influences the effects of timber management on hydrology, because climate affects the recovery of vegetation and the way in which environmental conditions change as a result of forest disturbances. Effects of harvesting in colder and drier water regimes, such as those in the Appalachian Mountains, may last longer simply because it takes longer to establish a forest under such conditions. Intensity of forest management practices can also affect hydrologic responses. Stormflow volumes and peak flow rates are expected to increase when forests are cut heavily or converted to other land uses, especially during nongrowing seasons. Few studies have addressed the relations between forest cover change and stormflow relations. Such studies are important in forest hydrology in the 21st century, when urbanization activities have been intensifying.

Forest watersheds produce better water quality than other land uses. Silvicultural practices in the South cause relatively minor water-quality problems. Forest removal, prescribed burning, and chemical applications cause immediate responses in water-chemistry concentration and loading, but these effects diminish rather quickly. Reductions in nutrient export occur following conversion of grasses to forests. Reductions in forest standing crop as a result of insect outbreaks also increase nutrient export. The major water-quality concern related to forestry activities is sedimentation. The impact of forest harvesting on sediment yield is directly related to harvesting methods and road building. Foresters in modern times have been improving their methods to protect water quality. When BMPs are used, forest harvesting does not necessarily cause stream sedimentation. Numerous road construction practices that minimize erosion and sedimentation have been identified. The cumulative effects of upstream land use conversion and changes in land use composition over time on streamwater quality can be mitigated by proper forest management.

Forestry BMPs have been seen as the best tools for controlling nonpoint pollution and protecting water quality. However, the riparian BMPs for the Southern States are not based solely on the best available knowledge; rather they are the product of battles among forestry groups, environmental groups, and policymakers within each State. Our knowledge of the effects of existing BMPs is imperfect, and we could probably design better BMPs if our knowledge of these effects were increased.

Recent studies show that sediment, nitrate release, stream temperature, and biotic response continue to be issues when BMPs are implemented. Pesticide movement from silvicultural operations remains largely unstudied. Process-based studies are needed to develop specific information on how, when, and where silvicultural BMPs fail to provide adequate protection of water quality. Models and regional analyses are needed to evaluate how BMPs perform at regional scales (National Council for Air and Stream Improvement 1999b). A key question in BMP development and TMDL implementation is: How much nonpoint-source pollution is too much? For instance, what are the ecological thresholds for sediment and nitrate concentrations, and how do these thresholds differ for river and lake systems? Should we protect ephemeral streams during forestry operations, and how? In general, there is a need for research on the linkages between hydrology, water quality, and biological responses (National Council for Air and Stream Improvement 1999a).

There have been few studies of the cumulative effects of different land uses on hydrology and water quality at a large basin scale. Such studies (Trimble and Weirich 1987, Williams and others 2002), which are reviewed in this chapter, present new views on the role of forests that may contradict presumptions or results from traditional small watershed-scale studies. With the development of new technology, such as remote sensing, GIS, and explicit regional hydrologic and water-quality models, the roles of forests and effectiveness of forestry BMPs in reducing nonpoint pollution on complex large landscapes can be evaluated.

Computer models are useful tools for generalizing and scaling-up the findings from individual studies and applying the knowledge to management practices. Most of the existing watershed-scale forest hydrology models lack nutrient, soil erosion, and sediment transport components. There is a need for research that will produce physically based, distributed watershed-scale models that couple hydrologic processes, forest nutrient cycling, and soil erosion on forest lands. The complexity of forested watershed processes has limited progress in development of such models (Band and others 2001, Zhang and others 2002). We should recognize that distinct hydrologic processes exist across the different physiographic provinces in the South. Different types of models in the South are needed. For example, ground water-dominated systems in the Coastal Plain require a model that can describe ground water water-table dynamics, while those upland systems dominated by overland flow or subsurface unsaturated flow require models that can describe hillslope processes. Several models such as WEPP (Nearing 1989), ANSWERS-2000 (Bouraoui and Dillaha 1996), and SWAT (Arnold and others 1998) have been widely used for modeling nonpoint pollution from agricultural lands, but significant modification and revisions are needed before they can be applied to forest systems.

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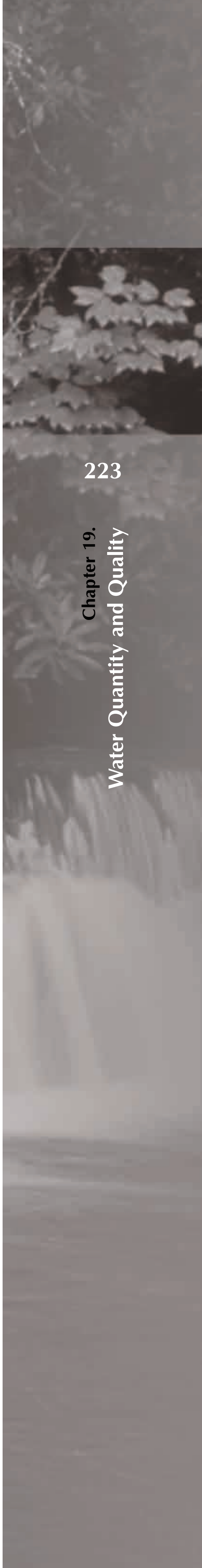

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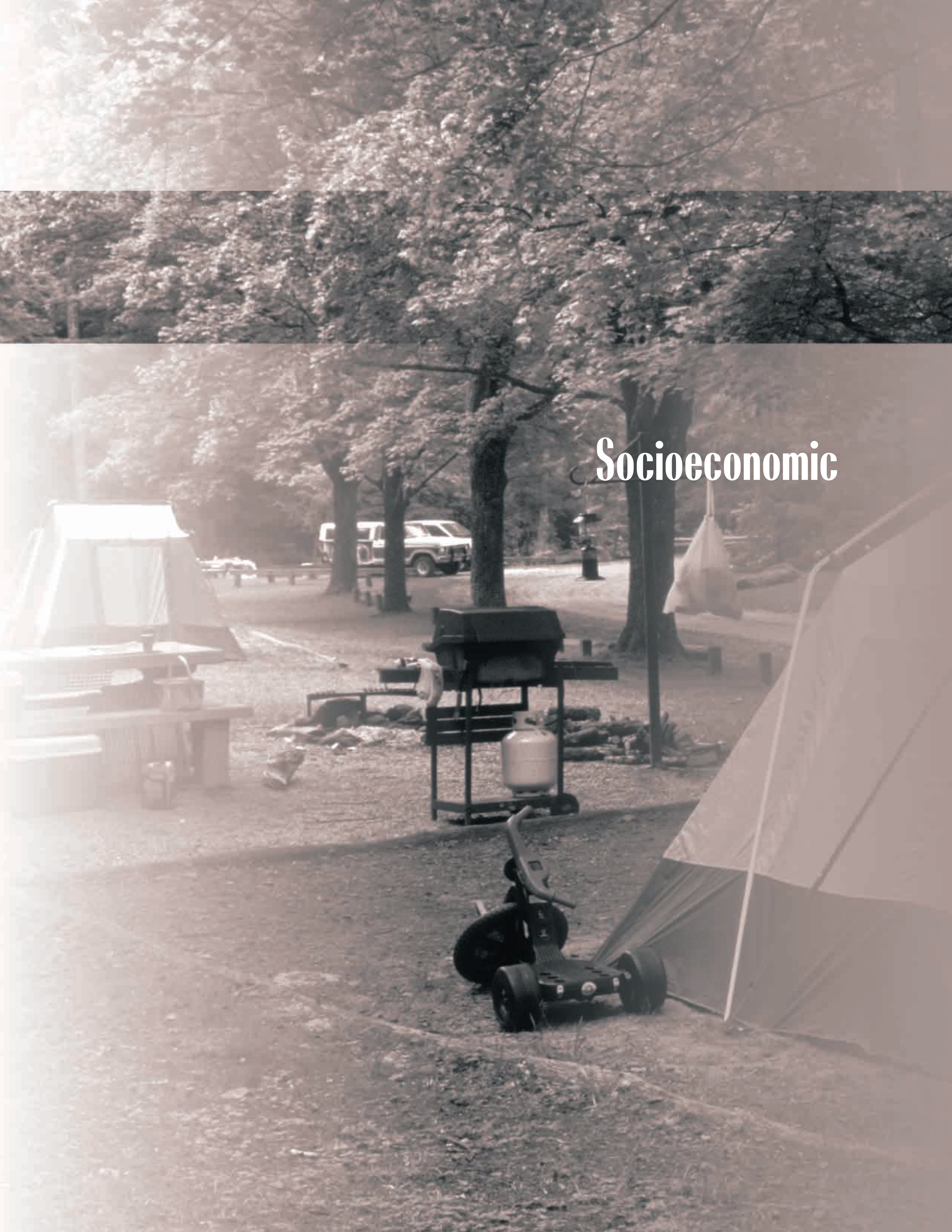

Socioeconomic

Chapter 20.

Policy, Uses, and Values

H. Ken Cordell[1]

The South has changed dramatically in the last 100 years. It was a rural, agrarian society; it has now become a predominantly urban one. This has changed forever the region's forests and their management, use, and protection. In 1900, there were just over 20 million people living in the South. By 2000, the South's population was almost 89 million, making the region now one of the fastest growing in the country. Projections by the U.S. Census Bureau indicate the region's population will continue to grow at a rate greater than the national growth rate, reaching over 110 million by 2020. By the year 2000, 74 percent of the region's population was urban, and as much as 80 percent of the region's population will be urban by 2020 (Tarrant and others 2002). The population of the South is now mostly concentrated along the coast, in the Piedmont cities, e.g., Atlanta, GA, Charlotte, NC, and Columbia, SC; in the major cities of Texas, e.g., Austin, Dallas, and Houston; and in Florida. In 1990, the South's rural population was concentrated in the Southern Appalachians, parts of the Mississippi River Basin, and the western Texas and Oklahoma Panhandle. But, overall, the entire region experienced a general decrease in rural residency between 1980 and 1990, a trend that continues today.

The future of the South's forests will be determined within the context of rapid population growth and increasing urbanization. The Southern Forest Resource Assessment forecasts that 12 million more acres of the region's remaining forest land will be lost to urbanization by 2020 (Wear and Greis 2002). These trends make the management of the remaining forests, and those we will have in the future, extremely important.

Because we must deal with the growing human pressures on forests, we must understand the human dimension of forestry. In these chapters of the book, we review research on forest values, forest uses, and forest policy in the South over the last several decades.

The chapter "Forest Values and Attitudes in the South; Past and Future Research" by Michael A. Tarrant and R. Bruce Hull, examines public viewpoints on forests over the past 100 years. At the turn of the 20th century, most people viewed forests as a resource for economic growth—a means of livelihood. Forest utilization was preeminent and concerns about protection were just emerging. Today many southerners put environmental protection and nonuse values over economic values. This change in attitudes is significant for forest policy and forest management. Increasingly, public opinion and the threat of challenges, such as in the courts, have reoriented forest policy and management, especially policy and management that relate to public forests. Tarrant and Hull offer a vision of forest science and management shaped to reflect the changing values and attitudes of southerners. They discuss (1) increasing pluralism and conflict, (2) the need for more collaboration and citizen science, (3) creation of politically viable indicators of environmental quality, and (4) moving beyond a preservation-intervention polarization.

In the chapter "Nonindustrial Forest Landowner Research: A Synthesis and New Directions" by Gregory S. Amacher, M. Christine Conway, and J. Sullivan, an econometric examination of nonindustrial forest landowners is provided. Nonindustrial private forest (NIPF) landowners own more than two-thirds of the forest land in some Southern States. Because of the importance of NIPF lands as a source of wood supply, the behavior of these landowners has been a frequent topic in forest economics, rural sociology, and policy research. In this chapter, the authors review the large amount of research literature on the topic, and then propose new directions for future research. An emphasis has been on recent empirical work regarding the economics of nonindustrial forest landowner behavior. The majority of research undertaken prior to the late 1980s involved identifying and understanding factors that influence reforestation

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or harvesting decisions. More recently researchers have studied a broader set of issues, including the relationships between nontimber ownership objectives and uses and other ownership factors, such as bequests and owner characterization. Another recent emphasis has been spatial mapping of owner decisionmaking and intentions. The authors conclude with recommendations for future research. They recommend that reservation prices for various activities be studied as a way of assessing likelihood of market entry, that the influence of adjacent owners be studied, that substitution between various types of land use decisions be investigated, and that individual ownership data be integrated further into spatial landscape models and Geographic Information System applications.

The chapter “Recreation and Nontimber Forest Products” by H. Ken Cordell and James L. Chamberlain reviews research conducted in the South during the last five decades on forest recreation and the gathering of nontimber forest products (NTFP) for personal as well as commercial uses. Research on forest recreation has been voluminous; research on NTFPs much less so. Forest recreation research had its beginnings in the late 1950s within a few southern universities and with two Federal Agencies—the Forest Service and the Economic Research Service. Much of the recreation research in these early years emphasized identifying who recreates, where they recreate, their impacts on the resource, and whether recreation and tourism can be used to address persistent poverty in some areas of the South. Through the 1960s and 1970s, recreation research expanded tremendously with greater participation among universities and public agencies. Both practical problems and advances in theory and methods of research were addressed. Through the 1980s and 1990s, many topics of management concern and of science concern were studied as the need for science-based information for recreation management expanded.

Unlike recreation research, research on NTFPs is relatively new in the South. NTFPs are forest plant materials that may include fungi, moss, lichens, herbs, vines, shrubs, trees, or parts thereof. Only a modest amount of research dealing with NTFPs has been undertaken over the last 50 years. Most of it has focused on describing the varied uses of the forest plants, their site requirements, and other botanical factors. Until very recently, within the last decade, NTFPs were not well recognized as a management concern, nor as a recreational or commercial pursuit. Much of the early research focused on defining and understanding how people used these products. Currently more university and agency scientists are looking at various aspects of nontimber forest products, from management, recreational use, commercial use, and ecological impact perspectives. The chapter ends with the authors’ observations about future research that needs to be carried out for improved management of forests.

Another chapter “Timber Market Research, Private Forests, and Policy Rhetoric” by David N. Wear and Jeffrey Prestemon interprets the workings or failings of timber markets as core issues for the conservation movement in the United States. The South is the only major timber-producing region of the United States where private forests dominate and where free interaction between private buyers and sellers determines timber prices and harvests. Private owners currently control 89 percent of timberland in the region; 20 percent is held by the forest industry and 69 percent is held by nonindustrial entities. Because the South is the clearest example of private forest management, it has provided a setting for evaluating core assumptions regarding markets, market failure, and conservation rhetoric. In this chapter, the authors examine the history of research into private timber management and the function of private timber markets in the South. In particular, they examine research into the behavior of private owners and of private timber supply. They also examine how this private forest land research has been influenced by policy rhetoric about forests in the United States.

The authors contend that the rhetoric of timber famine led to the establishment of forestry programs in the Federal Government and to designation of national forests. Regulation of forestry activities at the State level also was a result in parts of the United States. The profession and practice of forestry can also be linked to urgent concerns regarding timber shortages in the 19th century. Timber shortages can be viewed as market failures caused by overharvesting or a lack of information regarding overall timber inventories. Overharvesting can be the result of uncertainty about future timber demand and prices, which gives landowners a strong incentive to harvest early. Without information on overall inventories, landowners cannot anticipate oncoming shortages and so fail to recognize the potential for additional returns from delaying their harvests. Both cases would lead to suboptimal harvesting over time. A related concern regarding timber markets has been a perceived failure of landowners to protect or invest enough in the productive capacity of their forests. But issues concerning the effectiveness of private timber management and markets in providing a sustainable timber supply have largely been answered. The research emphasis now is shifting to understanding how these markets work so that the future extent and structure of the forests of the South can better be predicted. Better knowledge of how markets work will enhance understanding of how human occupation and utilization of forest lands will influence ecosystem structure and function in the future.

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Forest Values and Attitudes
in the South: Past and Future Research

Michael A. Tarrant and R. Bruce Hull IV[1]

Abstract—*At the turn of the 20th century, southerners favored economic utilization of forests over environmental protection. Today with few exceptions, southerners rate environmental protection and noneconomic values as higher priorities than economic uses of forests. We consider a vision of forest science and management that reflects the changing values and attitudes of southerners. We highlight four issues that we feel will help create such a vision: (1) increasing pluralism and conflict, (2) more collaboration and citizen science, (3) the need for politically viable indicators of environmental quality, and (4) the need to move beyond a preservation-intervention polarization.*

INTRODUCTION

Over the last 100 years, the forestry profession has undergone a dramatic shift that, to a large degree, reflects changes in public attitudes about forests and their management (Bengston and Fan 1999, Manning and others 1999, Rolston and Coufal 1991, Steel and others 1994, Tarrant and Cordell 1997, Tarrant and others 2002, Xu and Bengston 1997). During the early and mid 20th century, forest management endorsed a resource utilization philosophy that emphasized the exploitation, use, and development of resources, dominance of economic over noneconomic values, and human control over nature (Bengston 1994, Steel and others 1994). This approach is probably best captured by the still popular "greatest good for the greatest number for the longest time" motto. It is also reflected in the Multiple-Use Sustained-Yield Act of 1960 (Public Law 86–517), in which the economic utility of timber, mining, recreation, and other uses was emphasized. In the last 40 years, there has been a growing recognition and respect of noneconomic benefits, the rights of nonhuman parts of nature, and the importance of public involvement in management decisions. This later era, which reflects ideas expressed much earlier in the writings of Muir and Leopold among others, has been characterized by the Federal Land Policy and Management Act of 1976 (Public Law 94–579) and by recent U.S. Department of Agriculture Forest Service (Forest Service) Agency programs, such as new perspectives and ecosystems management.

At the beginning of the 20th century, the South was producing more lumber than any other region of the country (Williams 1989). Despite some calls for sustainable logging practices and protection and rehabilitation of the forests at that time, production continued without substantial changes in practices for the next 20 to 30 years. As long as there was money to be made, the public asked few environmental questions (Clark 1984). It was not until new technologies in transportation and harvesting, new chemical processes, and tax incentives introduced in the middle of the century that these dominant opinions changed. For example, the introduction of a severance tax on lumber removed from the land paved the way for extensive reforestation efforts that led to a reduction in cutover forests. (However, it should be noted that most of the harvested forests were replenished with pine (*Pinus* spp.) species to satisfy increasing demands for paper and pulpwood.) Furthermore, new chemical processes and other applications meant relatively cleaner and more efficient utilization of forests in the South and such utilization received much popular support (Hansbrough 1963). The balance began to shift again in the 1960s and throughout the remainder of the 20th century following the publication of books such as "Silent Spring"

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(Carson 1962) and the rise of environmental organizations with concerns about air, land, and water (Clark 1984). Today, the general public seems to favor environmental conservation over economic use, in part because of heightened public interest and awareness of forest issues and practices.

Questions about who has the authority to make decisions about public forests and controls over private forest land have increased the political nature of forest management, shifting power to a more diverse set of players and most notably to the general public. For example, while public forest managers have had decisionmaking authority delegated to them by the public, that public is increasingly demanding a greater level of power in determining how forests are managed. The public (often through special-interest groups) is also seeking greater involvement in actions limiting the freedom of private landowners to manage forests, especially where environmental impacts are likely.

Definitions and Theory

Before considering southerners' values and attitudes toward forests, the terms must first be defined. A value is a relatively enduring concept of the good, importance, or worth of an object. Once a value is internalized, it becomes a standard for guiding action and developing or maintaining attitudes toward relevant objects (Rokeach 1973). An attitude is a learned predisposition toward an object, issue, or situation that is emotionally toned (Cacioppo and others 1981, Fishbein and Ajzen 1975, Theodorson and Theodorson 1969). Attitudes are more transient than values and describe the extent to which individuals or groups find an object or a behavior desirable.

Values and attitudes are considered important because they are thought to influence (predispose) future action. For example, by understanding the values and attitudes that individuals or groups of people, e.g., political constituents, special-interest groups, activity-user groups, etc., hold toward forests, planners and managers are better equipped to deal with a range of natural resource actions that include mitigating potential conflicts among stakeholders; establishing new policies, programs, and goals; and defining new planning strategies (Bengston 1994, Decker and others 1989, Manfredo and others 1995, Manning and others 1999, Purdy and Decker 1989, Tarrant and others 1997a). Predicting and influencing support for management actions is essential in successful forest management. For example, disagreements between groups holding conflicting attitudes and values are likely to require special mediation if decisions are to be implemented in the forest rather than stalled in the courts.

Over the past few decades, the general public has become increasingly aware of forestry and environmental issues (Dunlap 1991, Dunlap and Scarce 1991, Steel and Lovrich 1997, Steel and others 1997) and increasingly supportive of noneconomic values of forests (Bengston and Fan 1999, Bourke and Luloff 1994, Jacobson and others 1996, Manning and others 1999, Xu and Bengston 1997). This has resulted in greater public involvement in forest management decisions (Fortman and Kusel 1990), and especially through the proliferation of interest groups representing the diversity of values held regarding appropriate uses of natural resources. Indeed, it has been argued that the core problem facing traditional forestry is a need to adjust to changing social and environmental values (Bengston 1994). Support for a shift toward noneconomic values has also been shown to exist among Forest Service employees, especially newly appointed district rangers (Cramer and others 1993).

Traditionally, the public has placed high values on marketable commodities such as timber, range, and minerals, and these values have the characteristic of being easily measured using a monetary scale. Increasingly, the public is placing importance on noneconomic values. Various types of forest values have been identified (see, for example, Rolston and Caufal 1991) and broadly include amenity values, e.g., lifestyle, scenery, wildlife, and nature; environmental quality values, e.g., air, soil, and water quality; ecological values, e.g., habitat conservation, sustainability, threatened and endangered species, and biodiversity; public use values, e.g., subsistence, recreation, and tourism; community values, e.g., property values, community identity and stability, and sustainable economic development; and spiritual values. The overriding social trend in these forest values is the idea that humans are inextricably linked to the natural resources they depend upon.

Attitudes of note include public beliefs and evaluations of specific forest management activities and issues including ecosystems management (Manning and others 1999, Reading and others 1994, Tarrant and others 1997b), management of nonindustrial private forest (NIPF) land (Bourke and Luloff 1994), and roads in national forests (Bengston and Fan 1999).

Forest Values and Attitude Research in the South

Few empirical studies of public opinions about forests were conducted prior to 1940, and we rely on anecdotal evidence in the early popular and scientific literature to draw tentative conclusions about forest values in the South during the first 40 years of the 20th century. Prior to 1920, a majority of the public favored exploitation of forests for lumber (Williams 1989). A small, vocal, and growing minority of easterners began to voice concern about aesthetic and other noneconomic values of natural lands. During this time, remote, forested resorts were popular tourist destinations of the upper classes; the idea of creating the Great Smoky Mountains National Park was born; and romantic and picturesque views of nature matured. Technological advancements in the 1920s led to new attitudes toward forest conservation and calls for reforestation to heal the destruction and raping of southern forests that had occurred since 1880 (Mobily and Hoskins 1956). However, even with reforestation efforts beginning in the 1930s, industrial capitalism (with a focus on resource utilization and efficiency) continued to be a dominant attitude of forest owners and the general public in the South through the middle of the 20th century. During and immediately following the Depression period, few protests against the wood-producing industries were heard, as "communities asked only that the [timber] companies bring them fat payrolls" (Clark 1984).

The period from 1940 through at least the 1960s witnessed the emergence of multiple-use management. Forests were no longer managed for timber exclusively and the economic benefits of other uses (range, recreation, mining, water, etc.) were recognized. Public opinion surveys conducted by the American Forest Products Industries (AFPI) from 1941 to 1962 (Hansbrough 1963) showed that while southerners knew very little about private forestry, most respondents had a favorable impression of private forestry practices; for example, more than 66 percent expressed favorable attitudes toward the pulp and paper industry. Their attitudes clearly reveal a strong economic orientation; southerners valued the forests as an industry, as being essential to America's growth, and as offering good career opportunities. It was not until the 1970s that attitudes and values of forests shifted toward an ethic more inclusive of noneconomic values.

Studies conducted in the last 30 to 40 years in the South show (1) a relative decline in utilitarian and economic forest values among the general public, (2) a concomitant increase in noneconomic values and attitudes held by the general public, and (3) a continued emphasis on economic values of forests by NIPF owners (but with increasing interest in noneconomic attributes of forests). A theme emerging from work conducted in the past decade is that southerners favor a balance of environmental protection and economic development in public and private forests, but with a very strong tilt in favor of the environment. For example, in a study conducted in the Midsouth, Bliss and others (1994) found that most respondents believe a mix of economics and environment is necessary, but nearly three times as many chose the environment over the economy as chose the reverse. A balance of environmental and economic values is also reported in studies of NIPF owners in the Southeast (Brunson and others 1996, Williams and others 1996), in studies of North Carolinian (University of North Carolina 1993) and South Carolinian (University of South Carolina 1992) residents, and in studies of residents of southern Appalachia (Cordell and others 1996). Other work suggests that southerners assign a higher priority to environmental protection than to economic utilization of forests (Bliss and others 1997, Cordell and others 1996, Tarrant and others 2002).

Cordell and others (1996) found that responding residents of southern Appalachia exhibited proenvironmental values and attitudes that were moderately stronger than the national average. For example, more respondents were against increasing timber harvesting on private land (46.5 percent) than were in favor (35.8 percent) and a much larger proportion were against (72.1 percent) than were in favor of (17.6 percent) timber harvesting on public lands. Furthermore, most respondents supported harvesting of dead and downed trees (70.0 percent), but were against the use of fire as a management tool (59.3 percent) and having a landscape consisting of "brown and dead trees" (68.5 percent). Respondents also held slightly stronger proenvironmental attitudes toward protecting fish and wildlife, and on aquatic and clean air issues, than toward forest practices. Overall, these findings are consistent with an emerging noneconomic orientation to forests. However, since most respondents were not in favor of using fire as a management tool (which could include letting forests burn naturally) or having a dead landscape (which could be a natural occurrence), the public may have low knowledge about many ecological processes or management practices. Such gaps in knowledge about forest activities have been reported in other studies of the South (see Bliss and others 1994, Hansbrough 1963, Tarrant and others 1997b).

Other studies also reveal a relatively high level of environmental concern among southern residents. A University of North Carolina (1993) study reported that 48 percent of southern respondents (vs. 43 percent of nonsoutherners) felt that the environment had become worse in the past 10 years, and 13 percent (vs. 19 percent of nonsoutherners) felt that the environment had improved. In a University of South Carolina (1992) study, 81 percent of South Carolina residents indicated that it was more acceptable to maintain an acceptable level of water quality than to increase the number of jobs in the State. In other work, Bengston and Fan (1999) found that the most strongly held attitudes about roads in national forests were that they provided recreation access and contributed to ecological damage. Consistent with results from other regions of the country, eastern (including southern) residents rated commodity-related benefits of forests roads, such as access for timber harvesting or mining, less important than noneconomic values, such as access for scenic viewing and recreation.

A few studies have examined the forest values and attitudes of one special-interest group: NIPF landowners. NIPF owners manage about 70 percent of the forest land in the South and 58 percent in the Nation as a whole, although many do not depend on their forest cover for an income (Jacobson and others 1996). Studies around the country report a preference by NIPF owners for environmental over economic objectives for managing forests that is consistent with attitudes of the general public (Bourke and Luloff 1994, Brunson and others 1996). This ordering by NIPF owners of environmental over economic values may not be as strong in the South as in other regions. In a study conducted in the Coastal Plain of South Carolina, Jacobson and others (1996) found that while over 75 percent of NIPF owners supported nontimber benefits of forests, commodity values ranked highest overall in importance. When asked to identify their top three reasons for managing forest land, timber value and overall land value ranked much higher (42.1 and 37.8 percent, respectively, reporting these as one of their top three choices) than nontimber reasons such as improving water quality (5 percent) and increasing nontimber revenues (10.2 percent). Williams and others (1996) found that Arkansas NIPF owners supported environmental protection initiatives on private forests but also strongly believed that private forest owners should have a right to use their land in any fashion without regulations. NIPF owners in the delta and southwest regions of the State especially emphasized a utilitarian approach to forests (supporting their use for growing and selling trees). Hodge and Southard (1992), however, found Virginia forest owners to value scenery and wildlife over commodity production. Similarly, Birch (1997) found that noneconomic ownership objectives ranked higher for many NIPF landowners living in the South, especially the increasing majority of people who own smaller acreages. The rapid turnover of forest lands in the South suggests that people with more urban and more environmental conservation orientations are becoming the new owners and neighbors of southern forests (Hull and Stewart 2002). Interestingly, while most of the NIPF owner respondents considered themselves to be "middle of the road" environmentalists, the majority were not familiar with the Endangered Species Act or the Clean Water Act, suggesting that many may lack information or be misinformed about natural resources.

Current studies suggest that the general public's preferences for environmental protection may be growing even stronger. In a survey of southern residents, Tarrant and others (2002) found that wood production was rated as the least important of four listed values associated with forests and clean air as the most important. However, their work also showed that there were some differences between views of public and private forests. The provision of wood products was not valued as low for private forests as for public forests, and the provision of clean air was not valued as high for private forests as for public forests. These results suggest that southerners hold stronger (more restrictive) values about public than private forests; i.e., they believe strongly that public forests should provide clean air in preference to wood products, but do not hold such restrictive values for private forests. In the same study by Tarrant and others, forest values were significantly influenced by age and gender. For example, younger people (16 to 24 years) placed significantly less importance on wood products and significantly more on heritage values of private forests than did older people (50+ years). For public forests, the younger generation valued scenic beauty significantly higher than did the older generation. Generally, younger people attributed more noneconomic values to forests than did older people. Males were found to value private forests for wood production significantly more than did females, while females valued public forests for heritage values significantly more than did males. Overall, females demonstrated less support for commodity values and more proenvironmental attitudes than males. These findings are consistent with other national and regional studies showing that younger people and females are more likely to exhibit proenvironmental orientations toward forests than are individuals in other categories. Kellert and Berry (1987) found gender to be the most important demographic influence on forest wildlife values. Men demonstrated significantly stronger utilitarian and scientific beliefs, while women had stronger moralistic and humanistic beliefs. Steel and others (1994) reported that women have higher proenvironmental values of forests than do men and that younger persons have higher proenvironmental values of forests than do older persons.

Steel and Lovrich (1997) have argued that the movement toward an environmental protection approach to forests and forest management in North America reflects a postindustrial society in which "higher order" needs for self-development and self-actualization have supplanted "subsistence" needs that are satisfied through material acquisition. Factors that have contributed to this change include (1) a shift in population from rural to urban areas and (2) an increase in economic growth. An increasingly urban population is thought to have a stronger association with a biocentric orientation because the physical connection between people and the realities of natural resource systems has been removed. Also economic growth in urban areas may have created public desire for nonmaterial uses (and, therefore, less resource extraction) of natural systems (Steel and Lovrich 1997).

In the South, fairly rapid and large increases in wealth and urbanization (along with higher education levels) might help explain why southerners have begun to favor environmental protection over economic and utilitarian uses of forests. Since 1980, the South's population has increased at a higher rate (14.16 percent) than in the Nation (9.78 percent), with most of the increase occurring in major urban areas such as Atlanta, GA, Austin, TX, Dallas, TX, and Miami, FL, and along the eastern coastline (Tarrant and others 2002). In the South, the population declined only in rural areas, including the Southern Appalachians, the Mississippi River Basin, and the western Texas and Oklahoma Panhandle. Incomes have increased in the South, with the highest gains in median household income in the eastern half of the South, especially in major cities, in the Carolinas, and along the Florida coast. Income levels decreased in the Mississippi River Basin, the Southern Appalachians, Texas, and Oklahoma, and along the coast of Louisiana.

CONCLUSIONS

The purpose of this conclusion is to proffer a vision of forest science and management reflecting the changing attitudes and values reviewed above. Gazing into a crystal ball can be both empowering and sobering. The forestry profession is empowered when it recognizes that it is as much about conflict resolution, communication, perceptions, and values as it is about soil erosion, volume estimates, and tree biology. Social science not only provides a critical tool for forest management but it helps professionals be much more sophisticated in defining and solving forest management problems. We are sobered, however, when we recognize that we know very little about the social dynamics of forest management and still struggle just to ask relevant questions about this subject.

Below, we discuss four value-related issues we expect to have profound implications for forest science and management. These are (1) pluralism and conflict—in the future, the conduct of debate about matters of forest science and forest management will be characterized by more pluralism and more conflict; (2) more collaboration and citizen science—the general public will have more influence in matters formerly decided largely by specialist professionals; (3) politically viable indicators of environmental quality—those in the social and natural sciences will need to collaborate to develop politically viable indicators of environmental quality; and (4) the preservation-intervention dichotomy—forest science and management need to move beyond the polarizing preservation-conservation dichotomy.

Pluralism and Conflict

An increasingly pluralist society will increase the diversity of stakeholders demanding and deserving a place at the decisionmaking table. Diversity springs from many sources. The ethnicity of the South's population is changing and the increasing political power of groups that formerly had little influence will likely affect the management of forested lands. Migration from rural to urban areas leaves many remote forested areas without much political representation. While this phenomenon is more characteristic of Western

States, some Southern Appalachian and west Texas counties are still losing population to fast-growing urban and suburban counties. The result is that State and Federal forestry agencies will be redirected by legislators to favor the values and concerns of urban and suburban constituents over the needs of rural residents and industries.

Migration from urban to rural areas presents a different set of challenges in that forests get new neighbors and new owners. People are bypassing traditional suburbs to live on small, forested estates. Trends in forest ownership show more and more people own smaller and smaller holdings, so that a decade from now the average forest landowner will own < 15 acres. These owners have new ideas about forest management and tend to be politically savvy and more insistent on the use of formal mechanisms for making decisions (Fortmann and Kusel 1990). Not only are the owners and neighbors of forests different, but so is the cast of professionals. More disciplines and professions involve themselves in decisions about forested areas. Planning, landscape architecture, ecological economics, environmental engineering, industrial ecology, conservation biology, and restoration ecology are just a few of the disciplines that now join with forestry and wildlife biology in providing professional expertise and science about forest land management issues.

One can debate whether urban values will replace or evolve into rural values, and whether hunting, timber harvesting, and other consumptive activities will decline or increase, but we can state with some confidence that the number and diversity of views about what should happen on forested lands will increase.

More Collaboration and Citizen Science

People are increasingly aware of the limitations of positivist, bureaucratic, modernist science, and decisionmaking approaches that seek optimal solutions using unbiased information to maximize the greatest good for the greatest number for the longest time (Lee 1993, Stankey 2000). Science is limited in what it can offer natural resource management (Robertson and Hull 2001). The uncertainty in future conditions provides just one compelling example of this limitation. The world and how it works is so utterly complex (chaotic and changing) that relative to what might be known about it, we now know very little, and we are not likely to ever know all that much. Yearley (2000) defines four levels of uncertainty. Conservation decisions are and must be made at each level, but the role of science in the decision differs dramatically depending on the level of uncertainty. At the first level of uncertainty, risk is estimated and characterized through science with statistical estimates of error, reliability, and precision. The next level involves more uncertainty because the system is not understood well enough so that its properties can be quantified, but most of the main parameters likely to affect the outcome are known. For example, ecosystems are difficult to define as ecologically significant units due to their dynamism and their indefinite boundaries, but we know that energy flows, population dynamics, and keystone species are important parameters for most ecosystems. The third type of uncertainty is ignorance. In cases of ignorance, we don't know what we don't know. In other words, we don't even know the main parameters; e.g., the impact of global warming on forest productivity. Lastly, indeterminacy is the highest level of uncertainty. It is impossible to know or predict how some systems will work because the system's operation depends in large part on human behavior that is likely to change in the future and, thus, is entirely outside the scope of scientific prediction. For example, this is the case with estimations of the long-term health and sustainability of humanized ecosystems in which energy consumption, waste production, tastes, and technological improvements in efficiency are not only unknown but likely to change in unanticipated ways.

Scientists find themselves in an awkward position. On the one hand, the public asks for policy formation and management decisions based on the "best available science." On the other hand, there is declining public trust in science, increased recognition of scientific uncertainty, growing demand for scrutiny of all decisions, and increased disenchantment with any authority. Citizen science, which involves and respects citizen concerns during key stages of the knowledge generation process, is offered as one possible response to these concerns (Fischer 2000, Shutkin 2000). Other responses call for a less rigid, less self-conscious, and more adaptable management approach that makes it easier for scientists, managers, and the public to learn from and adapt to changing situations as they emerge (Holling 1978, Lee 1993, Norton 1998).

Politically Viable Indicators of Environmental Quality

Indicators of environmental quality are used prescriptively and descriptively. They describe what is and prescribe conditions that should be. These terms are important because (1) they direct scientific inquiry, (2) they are used to set policy goals and evaluate management outcomes, and (3) they both inform and reflect public perceptions and expectations of current and possible environmental conditions. Indicators of environmental quality are powerful tools for environmental management (see Bergquist and Bergquist 1999, Rapport and others 1995). Indicators are the qualities of the environment that science monitors; e.g., "acid" producing gases for air quality, threatened and endangered species for biodiversity loss, and site index for forest productivity. Indicators trigger corrective management action when they exceed some negotiated level. Their use also enhances accountability by providing measurable evidence of progress towards agreed future conditions. Developing indicators requires a sophisticated combination of social and natural sciences. Social sciences are necessary because effective indicators must reflect the values, norms, and goals of the society for which the environment is being managed. They must reflect the qualities of the environment that society cares about and is willing to allocate its limited resources to maintain. Natural sciences are necessary to make indicators descriptively precise, reliable, and theoretically rigorous representations of environmental conditions. For example, when a community decides that it wants to manage water quality, it selects indicators of water quality, such as amount of surface water retention and nutrient load, to direct management and gauge success. These indicators prescribe desired future conditions (the community wants more water retention and less nutrient load). The community could have selected other indicators (ground-water pollution or water turbidity) and, thus, prescribed different future conditions.

The Environmental Monitoring for Public Access and Community Tracking (EMPACT) project at the U.S. Environmental Protection Agency provides an important illustration of this approach (http://www.epa.gov/empact/) as do certification programs that develop and assess indicators of sustainable forestry. The current international Montreal Process on the Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (http://www.mpci.org) represents one of the most comprehensive efforts to integrate social and biophysical indicators in addressing forest management in the South and elsewhere. These indicators of environmental quality must reflect an increasingly diverse set of values being attributed to forests. As illustrated by the first section of this chapter, forests are valued as much more than sources of water, wood, wildlife, recreation, timber, and range. Indicators of forest quality that serve as guides for management should reflect the deeper symbolic meanings attributed to diverse, sustainable, forest ecosystems as well as the property value, community identity, and sense of stability that living near forests provides.

The Preservation-Intervention Dichotomy

Preferences for management often polarize around the role of humans in nature, and around the extremes of preservation and intervention. The preservationists have characterized the interventionists as environmental rapists promoting irresponsible development. They argue that humans can only soil nature's goodness. The interventionists have characterized the preservationists as privileged urbanites who do not understand or value the role of human culture in nature. They argue that humans can improve upon nature's randomness and inefficiencies. Disagreements regarding the appropriate role of humans in the natural landscape are a key factor polarizing discussions about natural resource management (Callicott and others 1999, Dizard 1994, Hull and other 2001, Ingerson 1994, Senecah 1996).

Bioculturalism offers an alternative. It encourages stakeholders to recognize human society as an integral component of ecological systems and seeks ways for people to interact with and live sustainably in nature. Bioculturalism is increasingly accepted by the international conservation community, which has long recognized the limited effectiveness of preservation strategies that favor biological diversity over cultural diversity (Droste and others 1995, West and Brechin 1991, Zimmerer and Young 1998). Another place to look for inspiration and direction is in the innovative ideas of contemporary bioculturalists such as William Jordan, Frederick Turner, and Michael Pollan (Jordan 1994, Pollan 1991, Turner 1994). These three thought-provoking writers are among a growing contingent of biocultural activists who are designing creative approaches to the human-nature relationship based on the belief that humans can be artful agents of landscape change. "Sunflower forests," the biocolonization of neighboring planets, and "the cultivation of a new American garden" are among bioculturalists' ideas for a better, more democratic, sustainable, and desirable future.

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Chapter 22.

Nonindustrial Forest Landowner

Research: A Synthesis and New Directions

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Abstract—*In this chapter, we review recent empirical work related to the economics of nonindustrial forest landowner behavior, discuss emerging problems involving these landowners, and suggest topics for future research. Before the late 1980s, most work in this area was aimed at identifying variables affecting reforestation or harvesting decisions. Recently, researchers have studied a broader range of subjects, including the relationship between nontimber preferences and decisions, such as bequests, examination of the influence of type of landowner on decisionmaking, and use of landowner-level responses in spatial landscape models. We propose that future research characterize reservation prices for various activities, evaluate the extent to which a landowner's behavior influences that of adjacent landowners, investigate the substitution between various types of decisions, and integrate landowner-level models into spatial landscape models.*

INTRODUCTION

Nonindustrial private forest (NIPF) landowners are an extremely important group of forest owners, accounting for about 70 percent of land ownership in many States. Not surprisingly, the behavior of nonindustrial landowners has been one of the most frequently visited topics in forest economics, rural sociology, and policy research. Several books and hundreds of papers have been written about this subject, and there are several good surveys of the early literature. The purpose of this chapter is to review the voluminous recent literature, and then propose new directions for future research.

RECENT LITERATURE

Nonindustrial landowners are of interest to forest economists because of their relatively low timber productivity. Given that these landowners control the majority of timberland in the South and elsewhere in the United States, the decisions they make are critical to future timber supplies. Many landowners are reluctant to invest capital in long-term ventures such as timber production. The lack of insurance covering such investments can also be a deterrent to timber investment by landowners. Furthermore, landowners are thought to place considerable value on nontimber benefits associated with standing forest stock. Much recent work has been directed to explaining these preferences.

The Government has responded to timber supply concerns by offering a variety of incentive programs to landowners, most taking the form of cost-share payments for reforestation efforts following harvest, or incentives for afforestation of lands held in other predominantly agricultural uses. Most program funding has gone to southern landowners, as detailed by Goodwin and others (2002).

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In this section, we discuss a core of recent econometric studies. However, a word about our literature review is needed before proceeding. Early on, researchers attempted to identify the most important determinants of landowner harvesting and reforestation investment behavior. As Government programs grew in scope, researchers increasingly examined the decision to participate in reforestation cost-share programs or the decision to leave timber and land as bequests. Twenty years ago researchers began to believe that nonindustrial landowners view their problem as one of maximizing utility rather than one of maximizing profits (Binkley 1981, Boyd 1984, Hyberg and Holthausen 1989, Max and Lehman 1988). It is this utility-oriented post mid-1980s literature that we primarily concentrate on here. Readers are referred to Boyd and Hyde (1989) and Hyde and Newman (1991) for a discussion of the earlier literature on nonindustrial landowners, and to Pattanayak and others (2002) for an excellent review of the timber supply literature as it is related to NIPF landowners.

The behavior of private landowners is far less predictable than industry behavior, because of the multiobjective nature of their ownership and the difference in time horizons for management decisions. NIPF landowners may not always respond to prices in the same way that forest industry does; this makes predicting timber supply from NIPF land quite difficult, as noted first by Dennis (1989) and Newman and Wear (1993). Newman and Wear estimated a restricted profit function for NIPF and industrial landowners in the Coastal Plain region of the Southeast. While the two ownership groups were found to respond similarly to input and output price changes, NIPF owners differed from their industrial counterparts with regard to the value attached to growing stocks for the amenity values they provide. As a result, Newman and Wear concluded that NIPF landowners can be characterized as profit maximizers, who have preferences for amenities. Hultkrantz (1992) compared results from econometrics studies in the United States and Scandinavia during the 1980s, showing that NIPF landowners respond to prices, costs, and interest rates in a way that is consistent with profit maximization. However, he also concludes that it is necessary to determine what specific land, ownership, and market factors drive the various management decisions made by these landowners.

Nontimber management goals are thought to be a major reason for private ownership of forest land (Binkley 1981, Birch 1992, Boyd 1984, Conway and others 2003, Hartman 1976, Newman and Wear 1993, Pattanayak and others 2002). Nonindustrial owners do not typically own forest land primarily for the purpose of producing timber (Alig and others 1990, Hodges and Cubbage 1990, Marler and Graves 1974). One explanation, noted by Alig an others (1990), is the effect increasing wealth has had on the desire to produce nontimber benefits. Nevertheless, landowners often appear to have an interest in joint production of timber and forest amenities (Conway and others 2003, Egan 1997, Kline and others 2000, Newman and Wear 1993, Pattanayak and others 2002). Worrell and Irland (1975) list difficulties NIPF landowners must overcome if they are to produce timber and amenities successfully. These include lack of knowledge, incompatibility of nontimber and timber production goals, and low-profit potential.

Public intervention is often viewed as necessary to induce landowners to manage their land for timber (Bell and others 1994, Boyd and Hyde 1989), and design of tax and incentive programs has been an ongoing concern (Amacher 1997). The U.S. Government has relied on incentives much more than governments of other countries. Many of these programs for reforestation date from the 1930s (Goodwin and others 2002). Recent incentives have taken the form of funds for research, extension, and technical assistance, as well as tax benefits and input subsidies such as sharing of costs for tree planting (deSteigeur 1984).

Landowner Harvesting Decisions

Harvest, reforestation, and program participation decisions of landowners are often explored by means of qualitative response models. In these models, the probability that a landowner will undertake some activity is related to prices, costs, interest rates, physical land characteristics, and landowner demographics and preferences. Binkley (1981) modeled the harvest behavior of NIPF landowners in New Hampshire. He found that stumpage price was a significant predictor of harvest behavior, and this suggests that the substitution effect of a price increase is stronger than the income effect (Dennis 1989). Boyd (1984) investigated the effect of reforestation cost sharing on the harvest decision, and found that the cost-share payment is not a significant harvesting predictor. Variables significant to harvesting included stumpage price, technical assistance, size of landholding, farm occupation, and education. Hyberg and Holthausen (1989) presented both harvest and reforestation models based on survey data collected in Georgia. Several variables were found to be significant in predicting harvesting, including income and land values, which were inversely related to the probability of harvesting. This suggests that wealthier landowners forego harvest for the amenity values their forest land provides. Stumpage price was negatively correlated with harvesting, while tract size, knowledge of cost-sharing programs, technical assistance, and farming as an occupation were positive predictors. Dennis (1989, 1990) found that harvesting decisions were influenced by income, education, and relative values landowners place on amenities and consumption, as represented by standing stock. The negative coefficient he obtained for the income variable also suggests, like others, that affluent landowners might be less interested in timber production. In a similar study of Finnish landowners, Kuuluvainen and others (1996) concluded that high stumpage prices, standing stock, and forest growth are all important indicators of timber harvesting by NIPF owners. Conway and others (2003) investigated the behavior of NIPF landowners in Virginia, observing that risk perception associated with growing trees and tract size are important predictors of timber harvesting, and that absentee ownership (defined by location of residence > 50 miles from the land parcel) negatively influenced harvesting.

It is suggestive that the estimated coefficient of the tract size variable has been positive for all of the harvest probability models discussed here. In fact, Dennis (1989) predicted that changes in timber supply would be attributed to changes in total land area in production, rather than to increases in per-acre volume. A higher probability of harvesting on larger tracts also is consistent with observed higher net prices; i.e., the market price net of logging costs (Conway and others 2003, Dennis 1989, Hyberg and Holthausen 1989). The current trend towards parcelization of NIPF land into smaller land units, as urbanization and economic growth spreads from city centers, may, therefore, have important implications for policy. The bulk of research suggests that parcelization may reduce timber availability over a range of prices.

The treatment of timber prices differs among these studies. Dennis (1989, 1990) and Hyberg and Holthausen (1989) used aggregate prices in their models, while Conway and others (2003) used actual returns for those who harvested and predicted prices for those who did not. Kuuluvainen and others (1996) used annual prices from written contracts with the individual landowners for the years in which the landowner made a sale, and regional prices for the years in which the landowner did not sell. Not surprisingly, there has been considerable debate about the role that prices play in harvesting decisions. Dennis (1989) argues that stumpage price increases induce both income and substitution effects, and this implies that the effect of price on probability of timber harvesting depends on the relative strength of each effect. He further suggests that the influence of price on harvesting is necessarily ambiguous. Other work has supported this, finding a lack of responsiveness of landowners to stumpage prices in various management decisions (Alig 1986, Brooks 1985, Conway and others 2003, Dennis 1989, deStiegeur 1984, Klosowski and others 2001, Newman and Wear 1993). While these studies are numerous, others have identified a significant influence of price on management decisions, particularly for sawtimber harvests (Binkley 1981, Cohen 1983, Hyberg and Holthausen 1989, Kuuluvainen and others 1996, Royer 1985). The price influence is positive in all but Hyberg and Holthausen (1989).

Landowner Reforestation Decisions

The decision to reforest land following harvesting may be important for meeting long-term softwood timber production goals. In the South, most tree planting takes place on cutover timberland (Royer 1985, 1987). Royer (1985) modeled the reforestation behavior of southern NIPF owners. His results suggested that pulpwood prices, knowledge of cost sharing, income, and contact with professional foresters were important predictors of pine (*Pinus* spp.) tree planting on cutover timberlands. Higher reforestation costs and farming as an occupation reduced the likelihood of reforestation. Brooks (1985) found that cost-sharing payments significantly increase the likelihood of tree planting. Similarly, higher reforestation costs negatively influenced tree planting in the Southcentral United States. Stumpage prices had no effect on reforestation in his study. Romm and others (1987) relate forestry land investment in northern California to a variety of owner and ownership characteristics. High income and full-time residence emerged as significant predictors of investment behavior, (e.g., reforestation) in their model. Midrange income, absentee ownership, and greater landowner age preclude forestry investment. Hyberg and Holthausen (1989) found that knowledge of cost sharing not only increases likelihood of harvesting, as mentioned above, but also affects the probability of reforestation. Stumpage prices, household income, and technical assistance also positively affected tree planting, while higher reforestation costs led to decreased tree planting. Finally, Conway and others (2003) and Amacher and others (1998) found that access to the resource, timber bequest intentions, and the ratio of landowner debt to income were important predictors of reforestation for Virginia landowners.

Models of timber management and reforestation behavior based on information have also been used to study landowner decisions. For example, Straka and Doolittle (1988) developed a "diffusion of innovations" model, of a kind widely used in agricultural technology adoption studies, to assess how information about a new product or practice is communicated to individuals, and how individuals decide to accept or reject it. Their model is used to determine the rate of reforestation among NIPF owners. The specific research question they were concerned with was whether owners who spend resources to regenerate are more likely to be innovative than those who do not. They found that landowners who reforest were more venturesome and innovative, with higher incomes, and were more likely to belong to organizations, had higher levels of education, and owned more land.

Landowner Decisions to Participate in Programs

Many studies of participation in forestry assistance programs were undertaken in the 1990s (Bell and others 1994, Crabtree and others 1998, Esseks and others 1992, Nagubadi and others 1996). Bell and others (1994) analyzed landowner participation in Tennessee's Forest Stewardship Program. Individuals most likely to participate had a household income of $50,000 or greater, had previous experience with forestry, actively sought information regarding land use programs or practices, supported conservation, and had unmanaged forest, pasture, or cropland as primary land uses. Bell and others concluded that a Government should concentrate resources on promoting education, rather than increasing the amount of cost sharing, if the goal is to promote forest management. Esseks and others (1992) found that Conservation Reserve Program (CRP) participation was positively correlated with involvement of landowners in technical assistance and forestry experience, and was negatively correlated with income. Nagubadi and others (1996) studied cost-sharing program participation in Indiana. Tract size, membership in forestry organizations, age, and residence on the land emerged as important determinants of program participation.

Romm and others (1987) investigated NIPF landowner propensity to invest in forestry or respond to public policies and programs. They suggest that public programs for nonindustrial private forestry cannot be targeted effectively unless the program's purpose is defined narrowly. Hyberg and Holthausen (1989) believe that incentive programs can actually reduce timber supply. They argue that as landowner wealth increases, landowners may substitute amenities for timber production, reducing their future harvesting. Kluender and others (1999) feel that incentive payments often do not lead to additional production from NIPF land, and that cost-share programs have not kept real prices from rising. Brockett and Gephard (1999) studied the Tennessee Greenbelt Program. This program provides preferential property tax treatment for landowners who do not develop their land. Their land is then valued in its current use, rather than in its "highest and best" use. Brockett and Gephard conclude that tax incentives are too small to affect long-term behavior of NIPF landowners faced with pressures to develop their land. They argue that such tax programs simply reward landowners for making forestry investments they would already make without the tax relief.

Landowner Bequest Decisions

Harvesting, reforestation, and forestry assistance program participation are not the only important management decisions made by NIPF landowners. Royer (1985) argued, for example, that "additional modeling efforts should address other forestry decisions to provide a more comprehensive look at the landowner behavior." Bequest motives are also critical to meeting timber demand, since timber and land bequests affect the future contiguity and size of forest cover. There has been some, but not extensive, progress in this area (Amacher and others 2002, Conway and others 2003, Hultkrantz 1992). Since many NIPF landowners in the South are approaching retirement age (Alig and others 1990), their bequest decisions will become very important to the continued use of forest land. In fact, timber bequests from one generation to another may actually be more important in promoting long-term timber investment than Government incentives, according to Hultkrantz (1992). Royer (1985) found that plans to sell forest land within the next 20 years resulted in a 22-percent decline in probability that a landowner would reforest following a timber harvest. Conway and others (2003) and Amacher and others (2002) related timber bequest intentions (plans to leave a timber bequest to heirs in the future) to a variety of land, owner, and market parameters. They determined that stumpage price, time spent in nonconsumptive recreational activities, absentee ownership, and tract size are significant predictors, among others. Except for tract size, each of these variables positively affected the probability of bequests. Increasing tract size negatively influenced the likelihood of leaving timber to heirs.

Landowner Participation in Nontimber Activities

Recent NIPF research has examined in more detail the nontimber amenity tradeoffs that forest landowners face. In particular, researchers have become interested in the substitution between harvesting and nontimber preferences (Conway and others 2003, Pattanayak and others 2002) and willingness to accept payments to postpone harvesting and capture wildlife benefits (Kline and others 2000). Conway and others assumed that harvesting and reforestation decisions are not determined independently of nontimber activity and bequest decisions; i.e., that they are not separable (e.g., see Koskela 1989). The nontimber activity decision is modeled explicitly as an endogenous variable by considering the choice of activity and the time spent in an activity. In other studies, forest inventory or land area in forests has been used as a proxy for amenity preferences (Binkley 1981, Pattanayak and others 2002). Conway and others (2003) examined actual use, finding that nonconsumptive activities such as hiking, camping, and observing wildlife were positive indicators of timber bequest intentions, but recreational activities were not correlated with harvesting or reforestation behavior. Kline and others (2000) conducted a telephone survey of NIPF owners in western Oregon and western Washington to determine willingness of landowners to accept incentive payments and forego harvesting (for the sake of protecting wildlife habitat). Willingness to accept was related to ownership objectives, socioeconomic characteristics, and incentive offered. Landowner age, education, income, multiobjective ownership, and incentive payment were positive predictors of willingness to accept, while size of landholding, sales income, and plans to cut trees were negative predictors.

Predicting the Intensity of Forest Practices

Most of the above studies were efforts aimed at estimating the probability that a landowner undertakes an action. There are some studies that have examined the intensity of either harvesting or reforestation. For example, deSteigeur (1982, 1984), Cohen (1983), and Hardie and Parks (1996) examined the levels of reforestation landowners undertake on their land. Cohen (1983) found that reforestation implemented by Southern U.S. landowners was positively correlated with stumpage prices, cost sharing, and household income, but reforestation costs and interest rates did not emerge as significant factors. De Steiguer (1984) considered whether Government payments (specifically the Forestry Incentive and Agricultural Conservation Payment) programs substituted for private investment through changes in tree planting. He showed that planting investment level was influenced positively by income and negatively by interest rates. Government cost-share payments were not significant, supporting his hypothesis that cost-share payments have not significantly altered reforestation investment by NIPF landowners. Goodwin and others (2002) also finds this to be the case using aggregate time series cross-section data for several Southern U.S. States. Finally, Hardie and Parks (1996) examined the intensity of reforestation in response to CRP payments in the South. Their results indicated that sawtimber price, cost-share payments, household income, size of landholding, technical assistance, and inheritance of the property have highly significant positive coefficients.

Sociological Studies

Although this section has focused on econometric studies, one cannot ignore the large body of literature that seeks to identify sociological factors associated with NIPF ownership. This line of research developed in the 1970s (Egan 1997) and stemmed from the heightened awareness that forest landowners often hold land for nontimber benefits and embrace multiple ownership objectives. Some recent studies have appeared in the forestry literature. These include a paper by Bliss and others (1997), who found that the views of nonindustrial owners regarding forestry and environmental issues are similar to those of the general public, contrary to previous conjectures. Bourke and Luloff (1993) also provided evidence that NIPF landowners and the public have common concerns with respect to forests and management policies. Johnson and others (1997), who considered how NIPF owners view forest regulations, found that possible future regulations were not important in landowners' most recent harvest decisions. Bliss (1994) argued that researchers tend to focus too exclusively on the timber supply question and should instead focus on landowners as individuals. Egan (1997) agrees, arguing that the success of forestry assistance programs is dependent on understanding the many objectives of NIPF landowners.

NEW RESEARCH DIRECTIONS

The preceding review of recent work hints at many new and fruitful areas for landowner research. In this section we comment on several topics that have not been studied but have important policy implications.

Investigate the Price Acceptance Behavior of Landowners

Although there are some exceptions, previous empirical landowner behavior models have largely focused on estimating probabilities and levels of harvesting or reforestation. A separate set of theoretical literature describes how landowners approach the decision to participate in harvesting activities [see Fina and others (2001) for a recent review of this literature]. In this work, the existence of a "reservation price" is established for each landowner. A reservation price for harvesting represents an offer or payment a landowner must receive before harvesting and selling his or her timber. Although reservation prices have intuitive appeal for the timber harvesting decisions, the reservation price approach should in principle apply to other landowner market activities, such as selling land, or converting land use from agricultural uses to forest production through reforestation and afforestation efforts.

To date, there has been little empirical testing and estimation of reservation prices among nonindustrial landowners. Yet, such research might be important to predicting future timber supply obtained from any given landowner or collection of landowners. This is especially true for landowners and markets affected by urbanization or forest parcelization. Many of these landowners are usually absentee, or are not actively engaged in harvesting or reforesting at any one time. The preferences of these landowners are important determinants of their reservation prices and hence their propensity to enter timber markets in the future.

Estimating reservation prices represents a challenge, as they are unobserved and obviously functions of both landowner preferences and market parameters. Only when the landowner is offered a bid (or observes a market price) that exceeds his or her reservation price, will the landowner choose to harvest. Similarly, if the landowner is offered some payment or incentive to plant trees on currently open or agricultural land, the landowner will undertake such an activity only if the payment is greater than the minimum he or she is willing to accept for the change in land uses. This willingness to accept is equivalent to a reservation price for land use activities, and like the timber sale reservation price, it will depend on preferences of the landowner, market characteristics, and income derived from forest and agricultural activities.

In some cases, landowners who do not harvest will never do so, either because their reservation price path over time is consistently higher than prevailing market prices and offers, or because their preferences are such that their reservation prices are above the practical range of market prices. Reservation prices capitalize landowner preferences for timber and nontimber products and income or wage possibilities. Thus, differences in attitudes about harvesting and other forest management activities will be realized through differences in reservation prices across landowners. For example, landowners with very high reservation prices might be those who have higher incomes, attach higher values to nontimber benefits, or those who associate higher risk with establishing forests. In addition, expectations about the path of future prices (price risk) may influence reservation prices for harvesting timber. Ownership type (absentee or onsite owners) and ownership objectives (land speculation or forest management preferences) may also have substantial influences on reservation prices. The decision to accept any price for harvesting timber and the decision to switch land use should depend on variables such as these.

To understand how likely it is that different types of landowners will eventually harvest, or understand how various policies will affect the decisions of landowners to enter the market, we need to identify the most important factors affecting reservation prices for different types of landowners. A similar problem arises when one considers the participation of landowners in land use decisions. It is well known that frequent land sales in already fragmented areas may be contributing to increased parcelization and decreased prospects for sustainable forest management, or production of amenities that require contiguous forest blocks. As with timber, a landowner's reservation price for land will give some indication of whether the landowner will participate in the land sale market. Reservation prices for land sales are also important indicators of landowner behavior and market outcomes with respect to timber harvesting.

A comparison of reservation prices and market prices for landowner activities is also needed. Landowners are price takers. If an individual landowner's reservation price for harvesting is higher than the prevailing market price, then the landowner will not enter the market. Understanding the difference between the two, one of which is observed and the other of which has to be estimated, will, therefore, give some indication of how much markets need to change before landowner harvesting changes by certain amounts. The difference between reservation prices and market prices should reflect costs incurred searching for buyers, differences in information possessed by landowners and timber buyers, and specific characteristics of forest tracts that are valued in the market. Identifying the gap between reservation prices and market prices will improve the prediction of future land and timber sale activity, in that it will provide a means to determine what type of landowners exist at the economic "margin," that is, are closest to participating in sale activities. It will also indicate how far certain landowners are from participating in the market. These landowners would not typically be included in a sample of landowners who harvest in any given period.

It is this predictive capacity of empirical reservation price work that might be the next contribution to timber supply modeling, or to forecasting changes in timber availability. Most landowners in a given sample may not harvest. In some cases, this may be because their reservation prices do not coincide with market prices, or in other cases their timber may not be mature enough to harvest. In the former case, without knowing how far landowners are from the margin of activity, there is no way of knowing how far landowners are from participating in forest harvesting. The harvesting and reforestation choice models reviewed earlier require substantial data about landowners who have recently harvested. Landowners who do not intend to harvest at the time of data collection, i.e., at prevailing market conditions, and those who have not harvested in the past, are often treated in different ways with respect to the prices they are assumed to face.

How does one estimate reservation prices for harvesting or for converting land to forest use? One way is to use a revealed or stated preference approach in which landowners are given various offers for undertaking a harvest or land use activity, and then asked to indicate whether they would accept or reject the offer. Two versions of this method have been applied recently. One version employs referendum voting—a single price is offered and landowners can either accept or reject this price. Kline and others (2000) make use of this approach to determine when landowners will choose to preserve forests over a certain time period. The other version is to use a payment table to offer a range of prices, and then allow landowners to indicate how likely they are to accept these prices if offered them. This approach is taken by Amacher and others (2001). The advantage of these methods is that they can be used to identify thresholds for prices that landowners would accept to undertake some activity. They can also be used to determine market prices a given landowner would be willing to accept for harvesting under varying probabilities. Thus, both methods can be used to identify the most important predictors of reservation prices.

Empirical analysis of reservation prices could be used to improve targeting of Government policies in new ways. For example, suppose that a policymaker wished to achieve a certain acreage target for land in forests, perhaps in response to a carbon sequestration goal. Estimated reservation prices for land use decisions would indicate the minimum payment landowners would need to receive in order to achieve the land use target. Typically, economists assert that the compensation for converting a unit of land to forests should equal returns from the current use foregone by switching. The importance of reservation prices in this decision is often overlooked, but it is important when the landowner attaches a value to the nontimber benefits produced by forests. For example, a landowner's preference for nontimber goods could lower the reservation price for shifting land to the extent that it is smaller than the foregone returns from the current use. A landowner for whom this is true would be willing to accept a payment that is smaller than the foregone financial returns in order to switch land from a nonforest use to forests. Any Government program seeking to influence land use behavior at minimum cost should, therefore, focus on reservation prices, and not just on lost returns, as reservation prices better reflect the opportunity cost of switching land use.

Investigate Importance of Adjacent Landowners

Forest ecosystems cut across the many stands that constitute any forest unit. Biologists have long known this and have argued that trees of many age classes and species mixes are necessary for conservation of biodiversity or contiguous habitat for certain animal species (Franklin and Foreman 1987, Giles 1978). Forest stands are also linked by human needs and actions. For instance, the recreational opportunities presented by larger forest areas may be dependent on the interaction or coordinated management of several stands.

Economic models have rarely acknowledged the interdependence among stands, but it is a fact of nonindustrial forest management that management decisions made by the owners of one stand can affect the welfare of other landowners holding adjacent stands. One can easily imagine that the quality of nontimber benefits obtained from forests, such as wildlife amenities, should depend importantly on decisions made by adjacent landowners. It is, therefore, reasonable to expect that landowners may make decisions concerning their forests with the effect of their decisions on adjacent landowners in mind, or in anticipation of management decisions of adjacent landowners.

There are very few analytical treatments of the economics of stand interdependence. Stand interdependence was originally discussed by Bowes and Krutilla (1985, 1989), who proposed a linear programming approach for maximizing the rents associated with multiple stands under a single (Government) owner. Swallow and Wear (1993) and Swallow and others (1997) were the first to formulate explicit spatial interactions for nontimber amenity benefits between two adjacent stands. Koskela and Ollikainen (2001) evaluated the rotation age decision for a landowner who makes decisions for a single stand under the assumption of a purely exogenous adjacent stand. There is also very recent literature on stand interdependence in other contexts, such as species conservation.

The extent to which a landowner takes into account the effects of his or her management on other landowners is unknown, but it is an important question. The behavior of landowners who do not coordinate, or who anticipate actions of other landowners, could be socially costly. In fact, the impact of one landowner's decision on the forest ecosystem used by another landowner can represent a type of economic "externality" associated with private forest management. Only a social planner who managed the forest ecosystem as a whole would have incentives to solve for the economically efficient rotation age of each stand, conditional on its impacts on all other stands. The challenge for policy, therefore, becomes finding an instrument that encourages each landowner to act as if he or she were a sole owner, managing all of his or her stands in concert. Such an instrument would obviously need to target the individual landowner and, thus, it may not be feasible to implement in practice. The most efficient instrument would also depend on the types of property rights arrangements governing ownership and management of forest land. It certainly seems difficult to identify such an instrument at this stage given our current understanding of landowner behavior.

In light of this difficulty, empirical work should be directed at determining how serious lack of coordination among landowners can be, and also how various property rights arrangements (full or partial) affect incentives for landowners to coordinate actions. The most promising line of research would seem to involve linking adjacent stand effects to observed and planned landowner decisions. This might be achieved through a survey targeted at groups of landowners, determining to what extent they view their decisions as important to adjacent landowners, and how much they anticipate the behavior of others when making harvesting, reforestation, and land use decisions. Most of the social costs associated with lack of coordination may come from a landowner's ability to effectively commit to an action with regard to his or her neighbors. For example, a landowner may agree not to harvest a specific area of wildlife habitat because an adjacent landowner has also committed to doing so, and because both landowners are hunters of late-successional wildlife species. However, in periods of high prices, one landowner may be inclined to harvest after such an understanding is reached. This is because each landowner's reservation price is specific to each person's preferences. Understanding how landowners react to one another, if they do at all, will help us understand how landowners respond to policies targeting use of their forest land.

Investigate Substitution Between Landowner Decisions

Existing literature suggests that we have considerable understanding about the harvesting and reforestation decisions of nonindustrial forest landowners, and some emerging understanding of other decisions and substitution between various decisions. What this newer work teaches us is how other decisions impact harvesting and reforestation, and why it is important not to examine one decision, such as harvesting, in isolation from other decisions. Timber supply depends on the interaction of all relevant decisions landowners make. Take, for example, the case of nontimber activities. Interest in those that are complementary with harvesting influence behavior very differently than would interests in nontimber activities viewed as substitutes by the landowner. If we do not know how landowners choose between nontimber activities, then we will have an incomplete picture of harvesting behavior. The problem becomes even more complicated when one considers the interaction of land use, nontimber activities, and timing of harvesting. For example, landowners may consider it equivalent to either forego harvesting for amenities, or simply bring more land into forest production. Stand interdependency is also potentially important. If a landowner can substitute nontimber goods on adjacent land for production of these goods on their own land, such as hunting or maintenance of wildlife habitat quality, then this will also affect harvesting decisions. Obviously, an important factor here is the timing of decisions. Provencher (1997) provides some support for the existence of this substitution. He argues that linearity in econometric specifications of nonindustrial timber harvesting decisions is a troublesome assumption, as it imposes certain restrictions on substitutability across decisions and activities for a landowner and, thus, may not give a complete picture of the relationships between landowner decisions and important variables.

Integrate Landowner Models into Large-Scale Policy Models

Many studies have sought to estimate the probability that landowners undertake some activity, such as harvesting or reforestation. There is now a growing literature about landscape models (e.g., Wear and Bolstad 1998). Many of these models are not based on actual landowner data defining responses of land use to external market changes. The challenge now is to integrate landowner response models into larger scale landscape models that can be used for policy analysis.

Landscape models may be used to understand forest fragmentation. Fragmentation of parcels into smaller units has been associated with changing landowner characteristics and the current structure of estate taxation. Arguments are often made that parcelization of land into smaller pieces will eventually decrease timber supplies through reduced land access and higher wood costs. Fragmentation may also reduce nontimber benefits by disrupting wildlife corridors. These changes would also lead to a different type of forest industry organization, and could also lead to changes in landowner composition on large land area scales. Recall that recent work also establishes that landowner characteristics are changing. Increasingly, nonindustrial private landowners are absentees, and absentee landowners are known to have different preferences for land and timber sales than the historically abundant resident landowners. As we noted earlier, landowner differences are often realized through differences in reservation prices for harvesting or the willingness to leave timber as a bequest.

Clearly, fragmentation and parcelization can be understood by first integrating models for predicting landowner behavior into spatial land use models. Landowner decisionmaking would then be an endogenous factor driving the spatial realization of land use change. The benefits from greater integration of landowner responses into landscape predictions will be better prediction of landscape change in response to market changes or demographic changes in landownership, and better prediction of the pattern and size of environmental benefits and costs associated with landowner and market-driven change.

Expand Our Understanding of Information Asymmetries Involving Landowners

One assumption made in nearly all empirical work is that markets are “perfect” in terms of the information available to landowners. For example, it is implicitly assumed that landowners have the same information as timber buyers regarding prices for harvesting, and they know with certainty the market desirability of their land. However, new evidence suggests that landowners may not have perfect information. Hardie and Larson (1994) discuss a model in which buyers and sellers of timber have asymmetric information with regard to the market. Munn and Rucker (1994) showed that landowners with access to consultants tend to obtain higher prices for timber harvesting than those who do not have such representation. Most recently, Sullivan and others (2002), who studied a sample of actual timber bids, concluded that the competitiveness of a timber sale, i.e., whether it was negotiated or based on elicited bids, affects the marginal valuation of forest land characteristics in the timber price by a timber buyer.

These studies collectively suggest that information externalities may be present in timber markets. Empirical work should continue to identify the costs to landowners of not having perfect information. The implications for how timber markets respond to changes in economic variables, such as prices, will depend on how competitive timber markets are. Thus, the existing literature on landowner responses to external variables, which assumes that landowners make decisions on the basis of perfect information, may be flawed. There is much scope for future empirical work examining the implications of information differences to landowner behavior and timber supply. Such work will give us a better understanding of the social costs associated with information asymmetries, and a better understanding of the scope for Government intervention in these cases.

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Chapter 23.

Recreation
and Nontimber Forest Products

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Abstract—*Research on forest recreation over the last 60 years has been voluminous. Research on nontimber forest products (NTFP) has been much less voluminous. In this chapter the history of these two tracks of research has been reviewed. Not all studies are mentioned; rather, a representative selection of the subject matter is discussed. Forest recreation research had its beginnings in the late 1950s within a few southern universities and with two Federal Agencies—the U.S. Department of Agriculture Forest Service and the Economic Research Service. In these beginnings the challenge was to shed more light on who recreates, where recreation occurs, what impacts it has on the resource, and whether recreation and tourism is one way to address persistent poverty in some areas of the South. Through the 1960s and 1970s, research expanded tremendously, with greater participation among universities and public agencies. Not only were practical problems being addressed, but also advances in theory and methods were being forged as the science of forest recreation matured. Through the 1980s and 1990s, many topics of management concern and of scientific concern were addressed as outlets for recreation and leisure sciences grew and the needs for scientific information for recreation management expanded. This recreation research is reviewed in brief in the chapter that follows, as is research on NTFPs.*

INTRODUCTION

Unlike recreation research, the study of nontimber forest products (NTFP) is a relatively new topic in forestry in the South. The products of concern are forest plant materials that may include fungi, mosses, lichens, herbs, vines, shrubs, trees, or parts thereof. Only a modest amount of research dealing with NTFPs has been undertaken over the last 50 years. Most of this research has focused on describing the varied uses of the plants, their site requirements, and other botanical factors. Until very recently, within the last decade, NTFPs were not well recognized as a management concern or as a recreational or commercial pursuit. Much of the early research focused on defining and understanding how people used these products. Currently, more university and agency scientists are looking at NTFPs from management, recreational, commercial, and ecological impact perspectives.

This chapter covers research over the last five decades in the South regarding two related but mostly distinct forest uses. The first is forest recreation. The focus is to overview the research applied to understanding recreation in forest settings. The author listed first for this chapter is principally responsible for the text covering forest recreation, which, because of the vast volume of this research, is limited to brief overviews of what has been accomplished. The second topic is gathering and using NTFPs. These products are mostly plant based and do not include lumber or pulpwood. While gathering forest products is often recreational, it is different than almost all other recreational activities in that it involves removal of natural materials. The second author is principally responsible for covering research on this topic.

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Historical Overview of Outdoor Recreation Research

Prior to the Outdoor Recreation Resources Review Commission (ORRRC), which started its work in 1958 and published its results in 1962, very little forest recreation research had been done anywhere in the country, especially in the South. In fact, prior to World War II, there was little policy or management emphasis, let alone research, applied to recreational uses of forest lands, public or private. As demand for outdoor recreation grew after the war years, however, and as the U.S. economy rebounded from the war's impacts, participating in outdoor activities and taking outdoor-oriented family vacations grew rapidly. That growth sparked creation of the ORRRC and drew national attention to the need for research to better understand the implications of this fast-growing phenomenon.

As of the end of 1962, there were six known outdoor recreation research studies in progress by university faculty and graduate students in the South. At that time, a number of university park and recreation administration academic departments were creating outdoor recreation curricula throughout the region. Examples included Clemson University, North Carolina State University, the University of Arkansas, and Texas Agricultural and Mechanical University. The national visibility of the ORRRC reports gave energy and justification to these emerging programs and to building research capacity within some of them. In these early years, outdoor recreation research was underway at the University of Florida, University of Arkansas, University of Georgia, and at Virginia Polytechnic Institute and State University. The topics ranged from income earning potentials of outdoor recreation in rural areas to management evaluations of national forests and to recreation use estimation procedures (Graves 1963).

As with the universities in the South, Government agencies were just beginning to institute recreation research programs. The U.S. Department of Agriculture Forest Service (Forest Service) and Economic Research Service were early to establish recreation research programs in the South (van der Smissen 1963) and elsewhere in the country. The few scattered publications beginning to emerge from the Forest Service, primarily the Southeastern Forest Experiment Station (SEFES) with headquarters in Asheville, NC, covered use impacts on developed recreation sites, hunting and fishing use, private land access issues, and how to include recreation in forest management planning. There were two Forest Service research locations in the South. The principal one was located in Asheville, NC, and had as its primary objectives the development of methods for measuring and predicting recreation use, mitigating use impacts, and assessing aesthetic values in forest environs. A second was located in Raleigh, NC, and affiliated with the School of Forestry at North Carolina State University. Its mission was to study outdoor recreation issues on industrial and nonindustrial private land. Research of this period by the Economic Research Service in the South was primarily focused on examining the potential for earning income from rural outdoor recreation development, including forest recreation. The issue driving this work was the prevalence of low-income communities and poverty in some areas in the region.

Historical Overview of NTFP Research

Research on NTFPs is a new topic in forestry in the South. The products of concern are typically defined as plant materials harvested from forests and may include fungi, mosses, lichens, herbs, vines, shrubs, trees, or parts thereof. Many plant parts are harvested, including the roots, tubers, leaves, bark, twigs, branches, fruit, sap, and resin, in addition to the wood. Until very recently, within the last decade, NTFPs were not recognized as natural resources being harvested from the forests. Historically, the primary focus of research on these products has been on human use, botanical identification, taxonomy, and ecological distribution. Much of the early research focused on defining and understanding how people used these products.

The long history of using nontimber products gathered from the forests of southern Appalachia is not reflected in the scientific knowledge base. Native Americans used forest plants as tools, food, medicine, and religious ceremonial implements. They used bark for housing, branches and stems for utensils and tools, and wood for containers and other household products. Plants and plant products were fully integrated into and essential to their personal lives. Much of the knowledge gained from Native Americans is the foundation of the herbal medicinal industry today in the United States (Ody 1993). Over the course of three centuries, more than 400 medicinal forest products used by the Cherokee have been documented (Hamel and Chiltoskey 1975). This traditional knowledge was shared with early European settlers, who used the products for personal use, as well as in commercial trading.

During the 1800s, the United States and the NTFP industry changed dramatically. The political turmoil in the United States during the mid-1800s increased the need to explore the forests for new and substitute products. By 1863, due to port blockades, the South was in dire need of most medicinal products that previously had been purchased from abroad. A field surgeon, pulled from his duties to explore the forest resources of the Confederate States, reported finding more than 400 substitutes for medicinal plants that had been imported from Europe (Porcher 1970). Porcher (1970) reported that species "to be collected by soldiers while in service in any part of the Confederate States" included dogwood (*Cornus* spp.) as a quinine substitute, tulip poplar (*Liriodendron tulipifera* L.) for fevers, sweetgum (*Liquidambar styraciflua* L.) for diarrhea, and mayapple (*Podophyllum peltatum* L.) as a laxative. Beyond this cursory examination to identify potential medicinal uses, more advanced research on these products was lacking throughout most of the next century.

FOREST RECREATION RESEARCH IN THE SOUTH THROUGH THE 1980S

The following sections cover the history and accomplishments of recreation research in the South from the late 1950s through the 1980s. Five major recreation topic areas are overviewed, starting with onsite use estimation. The other four topics include visitor profiles and preferences, use impacts and carrying capacity, large-scale assessments, and a variety of other topics such as economic impacts and private land recreational access. A primary source for these descriptions is the proceedings of the Southeastern Recreation Research Conference (SERR), an annual regional conference first convened on February 6–7, 1979. The senior author of this chapter was one of the original organizers and sponsors of this conference. Although the SERR does not capture the full complement of recreation and related publications done in the South or by southern researchers, it is a good sampling and is used here as the major source. SERR was the first of a number of annual outdoor recreation research conferences now held in several regions of the country. The 24th annual SERR was held in Athens, GA, on February 20–22, 2002. Scientists known to have been engaged in recreation research in these earlier years were sent a request to forward their career publication list for use in developing the history in this chapter.

Onsite Use Estimation

This area of recreation research was one of the earliest topics of emphasis in the South, and elsewhere in the country. In the 1950s, very little was known about the amount, type, and location of forest recreation use. The most notable of the early work to help fill this knowledge gap was done by the Forest Service recreation research work unit in what was then known as the SEFES (now known as the Southern Research Station). The project was located in Asheville, NC, and George A. (Jim) James was the first of this unit's project leaders. His work in recreation use estimation methods became very well known and used nationally. His research focusing on use estimation was done cooperatively with national forests, State agencies, and the Washington Office of the Forest Service. The work progressed along two main lines—estimating use on developed recreation sites and estimating use in dispersed forest areas. The term "dispersed forest areas" refers to the general forest area accessible by trail, road, or overland, but having no other development.

Estimating use on developed sites—Research to develop reliable and cost-effective methods for estimating recreation use at developed sites received much attention in these early years of Forest Service recreation research (James 1971). Researchers designed and tested methods for estimating the amount of use, by activity, on developed sites such as campgrounds and on day-use sites such as swimming beaches. Correlated measures such as traffic flow counts or water metering were monitored to allow updates of initial onsite count estimates. Some of the earliest work drew attention to the use of pneumatic traffic counters to derive estimates of recreation visits and use (James and Ripley 1963). Monitoring traffic flows or other use indicators along with sampling actual use and users is a technique that became known as double sampling. It is an approach still much used in use estimation or other onsite studies, and it is currently being applied by the Forest Service nationally.

Advancements in these early years included correlating traffic flows using one or more traffic counters with simultaneous samples of different recreation activities and affiliated sites for ultimately deriving estimates of total use by type and site. Traffic counts were obtained using single-location counters devoted to monitoring traffic flows at the entrance to a single site. As well, monitoring proceeded using two or more traffic counters in tandem on trunk routes to a number of developed recreation sites (James and Rich 1966). Tests showed that estimates of visits by activity could be derived for up to eight developed sites based on traffic counts along only one trunk road. An extension of double sampling on developed sites was its application to estimation of use at visitor information centers (Cordell and others 1970). In this application, regression was used to estimate relationships among use of a visitor center, use of its peripheral sites, traffic counts, volume of shuttle bus ticket sales, center entrance counts, and other variables known to be a function of the number of recreation visitors flowing through a site or area.

Since the early work by James, Cordell, and a few others in the 1960s and 1970s (James 1971), and some work in the early 1980s, little additional research to develop more efficient techniques for estimating use of developed sites has occurred (Siderelis and Tyre 1975). During the 1970s and into the early 1980s, limited testing of techniques was done by the U.S. Corps of Engineers, the National Park Service, and the Forest Service (Coughlin and others 1978). A level of accomplishment had been reached which called for synthesis of earlier work to create handbooks and guides for application of sampling techniques (e.g., Mischon and Wyatt 1979).

A modest amount of new work was underway to take advantage of emerging computer technology to assist in more efficient sampling, data collection and management, analysis, and estimation (Erickson and others 1980). A few studies sought to evaluate field applications of various sampling techniques. For example, one study looked at double sampling as it was being applied across 34 sites in Region 5 of the National Forest System (California) and found a number of misapplications and resulting errors (Tarbet and others 1982). Additional work in the 1970s and 1980s focused on establishing systems for maintaining and reporting recreation use statistics at subregional, regional, or national levels (U.S. Department of the Interior 1986). Some work focused on extending application of tested forest recreation use sampling systems to municipal settings. For example, Tyre and Siderelis (1979) reported on instant-count sampling as a technique for estimating recreation use in municipal settings. For the most part, however, the methods engineered for estimating developed-site use and the double sampling techniques developed by James and others have persisted as the accepted state-of-the-art in developed site recreation use monitoring (Tarbet and others 1982). In the 1970s and 1980s, attention and interest was beginning to shift to the more difficult job of estimating dispersed recreation use.

Recent work pertaining to use of developed sites has focused on applying existing techniques of use estimation for national applications to produce mandated national and regional reports by the Forest Service and other Agencies. In the South and nationwide, the National Park Service, U.S. Corps of Engineers, and Forest Service have in place advanced systems for estimating management area, regional, and national scale use by type of activity and season of the year. The Forest Service assembled a guidebook on "Techniques and Equipment for Gathering Visitor Use Data on Recreation Sites" (Yuan and others 1995). This publication was based largely on early research done in the South by James and his associates at the SEFES. Most recently, a national system has been developed for application on national forests and is comanaged by the Forest Service's Southern Research Station. That national system is designed to estimate recreation use across the National Forest System (English and others 2002). It includes both developed sites and dispersed areas, and like the guidebook, much of it builds upon the research done in earlier years within the SEFES.

Estimating use in dispersed areas and wilderness—In the late 1950s, the Forest Service organized and staffed a number of forest recreation research work units around the country. Fourteen problem areas were identified as high priority for these research work units (Van der Smissen 1963). Of these 14 problem areas, one was "Determination of Techniques and Procedures for Measuring Forest Recreation Use." The newly formed unit at the SEFES was ultimately assigned the lead in developing and testing methods for estimating forest recreation use. The most challenging problem facing this unit was that of conceptualizing approaches for sampling and estimating use in dispersed forest areas. Dispersed areas then and now constituted most of the acreage of the national forests, and of other public lands. It was widely thought that 70 percent of the use of public lands at that time was dispersed use, as opposed to use in developed sites such as campgrounds, visitor centers, picnic areas, and interpretive trails.

Dispersed areas (including designated wilderness) include large bodies of water, recreation roads and trails, natural lakes, rivers, open range, and general forest areas. Use of such areas is typically of low intensity and highly dispersed and, thus, is difficult and costly to sample. Examples of dispersed activities include hiking, backpacking, birding, driving forest roads, and fishing. One of the first published studies of dispersed use was done by Cushwa and McGinnes (1964). This study revealed that a stratified random sampling approach produced good estimates of dispersed uses within an area of over 100 square miles in a portion of an eastern national forest. A second study (James and Harper 1965) extended these methods to an entire eastern national forest. Further extensions of such work included multiple dispersed areas, large bodies of water, trout streams, trails and designated wilderness areas (James 1971, James and Schreuder 1972). Because wilderness is often quite remote and unmonitored otherwise, affordable methods successfully tested included use of self-registration systems and a variety of devices for counting trail use. There was relatively little work in development of estimation techniques after the retirement of James in 1974. H. Ken Cordell, who took over as project leader in 1976, carried on the work begun by James. One advancement was testing and refining the use of directional traffic circuits using dual-input, time-interval recorders in forested areas with multiple entry and exit roads (Erickson and Liu 1982). Research sponsored by the SEFES provided an evaluation of use sampling on the Arapaho and Roosevelt National Forests and the Pawnee National Grassland (Saunders 1982). Current applications were evaluated, and updated estimates were provided to these administrative units of the National Forest System. Technology for estimating recreational use in dispersed forest settings is currently being applied nationally, employing independent regional samples by the Forest Service through the Agency's National Visitor Use Monitoring System (English and others 2002). National forests sampled in Region 8 up to the time of this writing include the National Forests of Florida, the Caribbean National Forest in Puerto Rico, the Ouachita National Forest in Arkansas, and the George Washington and Jefferson National Forests in Virginia.

Visitor Profiles, Preferences, and Behavior Studies

When the Forest Service established a national branch of Forest Recreation Research in 1957, its staff was limited and budgets were small. But the new branch was viewed as important, and with considerable field support it began to grow. Cooperative research work units were established at three universities across the country. One of the emphasis areas of this growing branch was the characterization of forest recreation visitors and their preferences for recreation sites, facilities, and services.

The need to know more about the visitor underlay many of the studies in outdoor recreation in the late 1950s and 1960s. National studies, such as those done by the ORRRC, pointed out just how little was known about the recreation participant of that time (Outdoor Recreation Resources Review Commission 1962). Use estimation studies usually devoted some peripheral attention to describing the visitors being sampled and to describing generally their preferences for amenities, facilities, and services. But the results were far from adequate, especially in probing visitor preferences for site attributes, facilities, and other characteristics important in planning and managing a recreation setting.

The SEFES established a number of studies to learn more about visitors, their characteristics, and their preferences. Included were onsite surveys of campers and users of other types of developed forest sites. Campers in that period were predominantly family or extended family groups on weekend camping trips. Some were vacationing for 2 to 3 weeks and camping at sites being studied as part of their multisite travel agenda. Camping was a fast-growing activity in the 1960s, growing nationally by 35 percent between 1960 and 1965 (Cole and Wilkins 1971). Most southern campers were middle to upper-middle income, white, and suburban, and they worked mainly in white-collar jobs.

Campers' preferences for the makeup and location of a campsite included features such as adequate space between campsites for privacy, and shaded sites close to restrooms, trails, and swimming opportunities (Cordell and James 1971, Cordell and Sykes 1969, James and Cordell 1970). Other visitor profile studies done by the Forest Service covered day users, water users, and general forest area users. Then, as today, males were much more prevalent in these types of outdoor recreation pursuits, and most recreation visitors tended to be people living within 50 miles of the areas they were using.

Other agencies doing work in the South at that time in the area of forest visitor characteristics and preferences included the National Park Service, the Tennessee Valley Authority, the U.S. Fish and Wildlife Service, the U.S. Corps of Engineers, and numerous State agencies. While these efforts did not always focus on forest recreation, they nonetheless had direct implications for forest recreation planning and management. Studies of hikers indicated that about 7 percent of the population hiked in the 1960s. Most of those who hiked covered a distance between 1 mile to just a few miles (Lucas 1971). Hikers tended to be about evenly divided between males and females, and they tended to be young, middle income, and white, with a high school or college education. Hikers then as now preferred well-groomed trails, natural settings devoid of development, destinations for the hike that focused on some prominent natural or historical feature, and absence of crowding. Wellman and Buhyoff (1980b) reported on a study of off-road vehicle use and social conflict at Cape Hatteras National Seashore, a problem persisting today and perhaps growing. Roggenbuck (1979) conducted a field experiment that provided a usable method for evaluation of interpretive programs. Buhyoff and Wellman (1979a) studied environmental preferences, and Buhyoff and others (1979) took the study of preferences and perceptions further to report on the aesthetic effects of southern pine beetle (*Dendroctonus frontalis* Zimmermann) in southern forest landscapes. Wellman and Buhyoff (1980a) also examined and reported on the effects of regional familiarity on forest landscape preferences.

For Federal and State resource management agencies in the 1960s and 1970s, studies of hunters and anglers were very prominent and much in demand (Bond and Whittaker 1971). In these decades and in earlier decades, hunting and fishing were viewed as two of just a handful of primary forest recreation activities and were given prominence in forest management. James and others (1969) reported that in the 1960s small-game hunters' age averaged in their late 30s, while the anglers averaged in their early 40s. Most hunters and anglers had participated in these activities as youths and most had lived in rural communities in their youth. Seventy percent of the population was urban in the late 1960s, and most hunters and fishermen of that time, as now, were urban. This is a highly significant change; the majority of hunters and anglers were known to be rural in previous decades, when the South was largely an agrarian region. Both groups of forest recreationists preferred good road, trail, and water access; well-managed wildlife and fish populations; and absence of crowding.

Water recreation, especially river floating and running, was a fast-growing interest in the 1970s and into the 1980s. A number of studies examined river floaters including kayakers, canoers, rafters, inner-tube floaters, and swimmers. One such study looked at the characteristics and wild river management preferences of Chattooga River users (Howard and others 1977). Wellman and Killeen (1979) studied the status of existing research and analyzed social conflicts associated with river recreation in the Southern Appalachians for the Forest Service. Another study found that two-thirds of Chattooga River users were males and that they averaged around 30 years old, had some college education, were mostly in white-collar occupations, and had a number of previous river recreation experiences (Townsend and Tarbet 1982). River users, like other forest recreation users, preferred clean and safe recreation settings with minimal crowding, good access to areas and facilities, and lack of interuser conflicts. Roggenbuck and others[2] reported on the relationships between specialization, displacement, and depreciative behavior among canoeists on Virginia rivers. Hammitt and McDonald (1982b) studied the influences of experience level as a determinant of choices in managing recreation resources, such as rivers.

Finally, a number of studies of forest recreation visitors in the 1970s and 1980s focused on visual aspects of forest recreation experiences. For example, Hammitt and others (1984) reported research on visitors' visual perceptions and preferences along forest trails, at scenic overlooks, and along edge environments in Tennessee. In these studies, it was found that trail users preferred seeing small streams and ravines and that other users preferred varying viewpoints of interiors, edges, and exteriors of forest settings. Hull (1988) reported on the scope and accomplishment of forest visual quality management and research. Ruddell and Hammitt (1987) studied visitors to a State park to identify factors associated with preference for edge settings.

In other studies dealing with visual preferences, surveys identified the importance of seeing wildlife in the overall recreation experience. For example,

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[2] Roggenbuck, J.W.; Wellman, J.D.; Smith, A.C. 1980. Specialization, displacement and definition of depreciative behavior among Virginia canoeists. 109 p. Unpublished report. Report to U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. On file with: North Central Forest Experiment Station, 1992 Folwell Avenue, St. Paul, MN 55108.

Hastings and Hammitt (1985) reported that viewing wildlife was secondary in importance only to viewing scenery. In addition to seeing wildlife, visitors also wanted information on the wildlife they saw. An example of the range of other visual quality research is work that examined the aesthetic qualities of forest trees (Cook 1972). Another example was a study of the influence that remnants of tree cutting had on overall visual quality of a forest setting (Cook and others 1985). It was found that controlling the visibility of limbs, tops, and other evidence of timber thinning by mechanically lowering their profiles improved visual quality as perceived by forest visitors. Bryan explored more broadly what Americans wanted in the way of aesthetic qualities from their forests (Bryan 1976). Buhyoff and others (1978) worked to clarify land-space architectural interpretations of people's landscape preferences, experimented with manipulating dimensionality in landscape preference judgments (Buhyoff and Riesenmann 1979), and noted seasonality bias in landscape preference research (Buhyoff and Wellman 1979b).

Use Impacts and Carrying Capacity Studies (Sites, Trails, and Rivers)

Use impacts on recreation sites—As Federal and State agencies became more and more engaged in forest recreation management through the 1950s and 1960s, and as use levels rose, greater attention was being paid to the impacts of increasing and repeated use on the vegetation, soils, and other conditions of forest recreation sites. In a number of studies, mostly by Forest Service scientists, both the deteriorating condition of developed campsites and results of tests of rehabilitation options were examined. In one study (Cordell and Talhelm 1969), trial plantings of various species of turf grass indicated that such practice would be ineffective in widespread application aimed at improving deteriorated recreation sites. Soon after the test sites were reopened to use, all varieties of planted grasses were suffering badly from trampling associated with site use. In another study, small trees and shrubs were planted on recreation sites to see if they would grow and provide visual barriers and vegetative cover (Cordell and James 1971). Results were mixed, but mostly the study showed that the benefits of planting heavily used sites are marginal because ongoing site use continues to have damaging effects. Because tests showed that plantings had little effect, researchers generally agreed that "hardening" sites with pavement, stone, or other materials is a better approach for developed sites such as campgrounds (Cordell and others 1974).

Other work focused more on the effects of use on trails and forest conditions in general. Saunders[3] studied the effects of recreational disturbance on the Southern Appalachian spruce-fir (*Picea* spp.-*Abies* spp.) forests, which were then and continue to be under pressure from a variety of insect, disease, air pollutant, and recreation use factors. Saunders (1979) further studied vegetation cover differences among randomly selected forest plots with and without recreation use. Plots with use showed impacts on vegetation and soil condition. Lockaby and Dunn (1977) also examined the impacts of sustained recreation use, but mostly they focused on forest soil properties in the eastern Piedmont. Whittaker (1978) compared the surface impacts of hiking and horseback riding in the Great Smoky Mountains National Park and found that they differed significantly in magnitude on a per-unit-of-use basis. Another study in the Great Smoky Mountains National Park (Bratton and others 1979) looked at trail erosion patterns and overall level of severity of foot traffic impact. Kuss (1982) studied the effects of footgear and boot-tread design on trail wear and this led to reconsideration of tread design by boot manufacturers. Subsequent work focused on monitoring processes (Klein and Burde 1991), including monitoring of impacts at backcountry campsites and shelters in the Great Smoky Mountains National Park.

Use capacity and management—Beyond site use impact research, little work was done on site and area capacity in the South in the decade of the 1960s. For practical management at that time, the essential ingredients of capacity decisions were knowledge of the interrelationships between management objectives, user attitudes, user preferences, and site use impacts (Lime 1976). Although not based on research done in the South, some of the most definitive work on carrying capacity, as applicable in the South as anywhere, was that synthesized by LaPage (1963) and Wagar (1964). Not until the late 1960s and 1970s did work on recreation carrying capacity again assume a high profile.

[3] Saunders, P.R. 1977. The effect of recreational disturbance on the Southern Appalachian spruce-fir forests. 25 p. Unpublished report. Paper presented at the third annual conference on science and research in national parks, southeastern region, Gatlinburg, TN. On file with: H. Ken Cordell, Southern Research Station, 320 Green Street, Athens, GA 30602–2044.

In 1974, Hammon and others (1974a) began publishing their work on capacity of water-based recreation systems. Initially this work focused on reviewing and digesting existing published works for application to reservoir management in the Southeast. Later in 1974, they published a synthesis and systems-approach interpretation of the capacity literature as it applied to management of water-recreation systems (Hammon and others 1974b). Cordell and others (1975) published the final part of their research on water-based recreation systems the following year. They examined the interrelationships between spatial distribution of use, user satisfactions under different use levels, and apparent displacement of users. From this work it became clear that beyond some threshold of use, satisfaction and spatial distribution of use is significantly altered by increasing system use loadings. Followup application of this work was published in 1977 (Cordell 1977) in proceedings of the River Recreation Management and Research Symposium in Minneapolis. Overall findings from this research provided reservoir management guidelines and pointed out the complexity of applying standards and quantitative analysis to capacity questions. However, approaches were developed that have subsequently been adopted.

Other, more basic research was being conducted on better defining the concept of carrying capacity and its theoretical foundations. For example, Schreyer and Roggenbuck (1978) examined the influence of experience expectations on perceptions of crowding as related to the notion of social psychological carrying capacity of forest recreation areas. Noe and others (1982) examined normative responses and norm activation among off-road vehicle users within a managed seashore recreation environment. Bryan (1979) studied and published on potentials of use conflicts in outdoor recreation as a consideration in capacity planning. Smith and others (1983) studied and reported on priorities for river recreation management in the Southern Appalachians that centered on carrying capacity and other use issues. Hammitt and others (1982a) examined perceptions among users of needs for use management controls and strategies. As a result of these studies and others around the country, the concept of capacity evolved to an understanding that capacity was not some magical upper limit on recreation visits per unit of time and space, but that in addition to some range of persons per unit, it must include visitors' preferred conditions, which can vary widely across sites, conditions, and cultures (Chilman and others 1981).

Further capacity research in the South was spotty through the 1980s. Chilman was a leader in advancing the principles of and development of tools for analyzing capacity questions (Chilman and others 1989). His work advanced the concept that capacity is a desired set of conditions that emphasize quality factors. He developed and published a revised carrying capacity analysis system. This work was linked to the evolving concept of limits of acceptable change (LAC) (Stankey and others 1985). Absher studied and found valid application of LAC in planning wilderness management and capacity considerations on the Cumberland Island National Seashore (Absher 1989). Wellman and Belcher (1989) reported on the nature and importance of managerial perspectives in determining appropriate river recreation use policies for the mid-Atlantic region for the National Park Service.

Large-Scale Recreation Assessments

U.S. Public Law 85–470 established the ORRRC in 1958 (Outdoor Recreation Resources Review Commission 1962). The work of this commission was the first comprehensive, national scale assessment of outdoor recreation demand and supply in the United States. Several were to follow, many of which were done by recreation research scientists in the South in the years after 1980. On the basis of ORRRC's recommendations, a Bureau of Outdoor Recreation and the Land and Water Conservation Fund (LWCF) were created in the 1960s. To be eligible for matching grants from the LWCF, a State had to conduct and submit to the Bureau a Statewide Comprehensive Outdoor Recreation Plan (SCORP). The bureau and its successor agencies were also required to conduct and submit to the Congress a nationwide outdoor recreation plan. Both the State and national plans required comprehensive assessments, which were the source and inspiration for numerous State, regional, and national participation surveys, supply studies, demand and needs analyses, and efforts to build forecasting models. Examples of the assessment work undertaken in the South are described in the paragraphs that follow. Examples are used because this work is too voluminous to fully discuss in this chapter. Interestingly, that portion of the 1960 ORRRC national participation survey analysis that dealt with relationships between demographics and participation was done in the South by Charles Proctor at North Carolina State University (Proctor 1962).

Examples of research done at the State level in the South include work reported by Howard (1968) of Clemson University. Howard did a statewide survey of outdoor recreation facilities for the State of South Carolina. Siderelis, at North Carolina State University, conducted a modeling study to develop computerized (mainframe) techniques for forecasting recreation participation (Siderelis and Hassel 1975). Jarvis and others (1978) developed models and forecasts of recreation demand for the Upper Savannah River Basin as a part of their work to better assess future outdoor recreation demand in South Carolina. Roggenbuck (1978) conducted the outdoor recreation demand survey for the State of Virginia as a part of that State's SCORP assessment. Roggenbuck and Kushman (1980) studied riparian landowners' attitudes toward a State wild river program. Senter and McLellan (1982) examined the compatibility of data used in SCORP to describe private recreation providers for use in statewide planning. There were numerous SCORP or other statewide assessment projects in the South in the 1960s, 1970s, and 1980s. Unfortunately, most of these followed ad hoc formats so there was little State-to-State compatibility of data.

Regarding national recreation assessment research originating in the South, in 1977, the SEFES was assigned by the Washington Office to conduct nationwide and region-by-region assessments of recreation demand and supply under the authority of the 1974 Forest and Rangeland Renewable Resources Planning Act (RPA). The first report resulting from this assigned research was published in the 1980 RPA Assessment report (U.S. Department of Agriculture, Forest Service 1980). Stemming from that work was publication of a follow-on national assessment report published by the American Forestry Association (Cordell and Hendee 1982). The Forest Service's southern research work unit reported its regional and national outdoor recreation and wilderness assessment work in the "Third Nationwide Outdoor Recreation Plan" published by the Department of the Interior in 1979, the Rockefeller Outdoor Recreation Policy Review group report "Outdoor Recreation for America" in 1983, reports by the President's Commission on Americans Outdoors in 1986, and proceedings of the 1988 National Outdoor Recreation Benchmark Symposium (Siehl 1989).

In continuing to build data and research capacity for future rounds of recreation assessments, and to improve coverage of private recreation supply trends, an examination of potential conflicts between private recreational property developments and forest land ownership and management in the South was conducted (Cordell and others 1982). Wellman and others (1980) studied response rates and patterns to mailed questionnaire surveys and identified the reluctant respondent as an important survey target by examining the differences between early and late respondents. Wellman and Marans (1981) looked at the use of time budgets as an aid to research, assessments, and planning for recreation. Wellman (1987) wrote a book on wildland recreation policy, and this book included a discussion of the need for assessments in making policy and planning decisions.

For the 1985 RPA Assessment update, Cordell and Hartmann (1984) studied trends in outdoor recreation in the two decades since the original nationwide assessment done by the ORRRC between 1958 and 1960. In examining ways to assess the overall effectiveness and adequacy of supply of recreation opportunities, Cordell and English (1985) studied recreational trip distances as a criterion for defining relevant supply inventory radii. Roggenbuck and Ham (1986) examined the methods and kinds of information used in recreation management and planning as a contribution to the nationwide assessment for the President's Commission on Americans Outdoors.

Much of the above assessment work was summarized and used as background material for the 1989 RPA Assessment (Cordell and others 1990b). Papers covering work in the areas of supply conditions and trends, participation trends, demand forecasting, international demand, wilderness, and social factors in recreation trends were published in the 1988 National Outdoor Recreation Forum (Watson 1989).

In the 1990s, statewide, subregional, southern region, and national assessment work in the South continued and even accelerated. The sophistication of this research has also improved. In 1996, results of an assessment for the Southern Appalachians were published (Cordell and others 1996). In 1999, the Third Nationwide RPA Assessment of Outdoor Recreation and Wilderness was published (Cordell 1999). In 2002, the "Southern Forest Resource Assessment" was published, and included a Southwide assessment of recreation demand and supply (Cordell and Tarrant 2002). These and other research efforts over the last 2 1/2 decades have led to development of a system of data, models, and reporting technologies that is used throughout the country and in many other countries.

Additional Recreation Research Topics of the 1980s

Assessing economic impacts—In 1984, a national meeting was convened by southern researchers to evaluate abilities to assess the economic impacts of recreation and tourism (Propst and others 1985). From that meeting came a coalition between the Forest Service, U.S. Corps of Engineers, Tennessee Valley Authority, National Park Service, National Association of State Park Directors, and other organizations to develop data collection technology and to improve input-output modeling capacity for recreation and tourism. The results of that meeting fed development and improvement of numerous onsite surveying approaches, including the Public Area Recreation Visitor Survey (PARVS) and improvement of the input-output economic accounting model. Following that very positive result, Propst and others (1986) began applying updated technology by studying trends in outdoor recreation consumer expenditures to see if visitor expenditure profiles are stable over time. Aiken (1988) looked at the regional economic impacts of visitor spending near and at the Chincoteague National Wildlife Refuge. Jackson (1988) evaluated different measurements of economic impacts associated with recreation use at U.S. Corps of Engineers projects in the South. Paterson (1988) examined the usefulness of economic impact assessment as a tool for regional tourism development. Watson and Cordell (1988) discussed use of economic impact assessments as a means for demonstrating the importance of outdoor recreation relative to other, sometimes competing, uses of natural resources. Fritschen (1989) reported on advances in measuring the economic impacts of recreation at U.S. Corps of Engineers water-resource projects, and methods of accounting for spending associated with users accessing a reservoir from places outside formally designated reservoir recreation sites. From data generated from the PARVS, Bergstrom and others (1989) examined and estimated rural economic development impacts of outdoor recreation in Georgia.

Wilderness research—From its genesis in 1964 and an initial total size of around 9 million acres, the National Wilderness Preservation System (NWPS) has grown to more than 106 million acres of public land managed by four Federal Agencies. Fifty-six percent of National Park Service lands, 20 percent of U.S. Fish and Wildlife Service lands, and 18 percent of Forest Service lands are in designated wilderness status. The Bureau of Land Management has only 5 million acres of wilderness, but has 17 million acres set aside as wilderness study areas. A modest amount of research regarding wilderness management and the status of the NWPS has been conducted in the South. Some of that work is summarized in this chapter.

Roggenbuck and Berrier (1981) studied communication techniques for dispersing wilderness campers, and in related work Roggenbuck and others (1982a) looked at the role of interpretation in managing recreational carrying capacity. Roggenbuck and others (1982b) studied wilderness management as it was practiced in the Southern Appalachians in the early 1980s.

Cordell and others (1986) summarized previous studies of visitor needs and user impacts in wilderness in the East. Watson and others (1987) examined techniques for producing accurate wilderness use estimates, using some of the dispersed-use methods described earlier in this chapter. Hartmann and others (1987) conducted regional comparisons of Forest Service wilderness users with an emphasis on eastern wilderness users and the implications for further policy and research refinement. Region-to-region differences were small. Roggenbuck and Watson (1989) summarized the wilderness recreation use situation in the region and nationally for the Outdoor Recreation Benchmark meeting held in Tampa, FL. Watson and others (1989) studied visitor characteristics and preferences on three national forest wilderness areas in the South. Most such studies were of particular wilderness areas in the South and focused on wilderness visitors. From these and other studies, much has been learned about wilderness use, wilderness visitors, and wilderness management options. Management and policy for wilderness in the region and to some extent nationally has been much influenced by the information flowing from this research.

Based in part on this earlier work, Cordell and Watson (1987) conceptualized a framework for wilderness assessments and related future research. Reed and others (1989) wrote regarding optimizing nonrecreational wilderness uses and values as a contribution to ongoing wilderness system assessment. Watson and others (1989) summarized the knowledge of the characteristics of wilderness users. Cordell and others (1989) summarized research on marketing based on research pertaining to wilderness experiences.

Private land recreational access—As in the North, industrial and nonindustrial private land dominates in the South, relative to public land in Federal or State ownership. Most of the forest science dealing with private owners and lands has focused on timber supply potentials and the effectiveness of a variety of incentive programs for nonindustrial owners. In more recent studies, reference is given to the increasing recognition given by landowners to the amenities of their land, relative to the income-earning potentials of these lands. The rising relative importance of amenities has been acknowledged by its assuming a much higher profile in private land research (Amacher and others 2004). Research from the mid-1980s on has typically given full recognition to the rising importance of amenity values (Boyd and Hyde 1989, Hyde and Newman 1991).

Little of the early research on private lands and owners focused specifically on the issue of public recreational access or use. Of the limited research that was undertaken, prominent was research on landowner liability (Kaiser and Wright 1985, Kozlowski and Wright 1988) and access rights (Gramann and Bonnicksen 1985). Other studies examined the relationship between timber or other income-earning motives and recreation, (e.g., Jones and Self 1991).

As part of the RPA national assessment of outdoor recreation, work was begun in the South cooperatively with Clemson University to develop a national database on recreational use and access to private lands. The first resulting national survey to determine public outdoor recreation opportunities on nonindustrial private forest and rangelands was conducted in 1975–76, cooperatively with Clemson University and the Soil Conservation Service (Cordell and Stevens 1984). Based in part on this work, a study of trends in recreational access to private rural lands was reported in 1985 (Cordell and others 1985), and a study to validate procedures for the next nationwide survey of private landowners, to occur in 1985–86, was conducted in 1984 (Sale and others 1987). Results of that next national survey, done by the SEFES, were reported in several sources and used in the 1990 RPA Assessment (Cordell and Wright 1989, Wright and others 1989). In all these studies, access for persons not associated with the owner by way of family or other close personal relationship was quite limited and found to be diminishing over time in all regions of the country. In the South, this diminishing access was found in part to be offset by increased leasing by persons unrelated to the owner.

Behavior, perceptions, and motivations— A significant number of scientists studying forest recreation in the South have been trained in social psychology theory and methods. A more limited number are grounded in either sociology or economics. The makeup of studies of behaviors, perceptions, and motivations among outdoor participants reflects the disciplinary backgrounds of the scientists who conducted those studies. Some examples of the numerous examinations and rich literature on behaviors, perceptions, and motivations follow. One notable early publication was written by Bryan (1977); it concerned specialization among trout fishermen and the implications of the findings for resource management. Groves and others (1975) presented a multiframe reference approach to studying and better understanding leisure motivations. McLellan and Gahan (1976) studied recreation user characteristics and behaviors on Hartwell Reservoir in South Carolina. Hull and Buhyoff (1982) reported on the effects of distance on the perception and rating of scenic beauty. Wellman and others (1981) studied the accuracy of predictions by park managers of the motivations of visitors to two National Park Service areas. Burrus-Bammel and others (1982) reported on a study of the perceptions of hunting and hunters by various groups. Burrus-Bammel and Samuel (1984) also studied the sources of introduction to and motivations for wild animal trapping.

There were a wide array of places and recreation settings where behavior, perceptions, and motives were studied. In 1982, Mulligan and others reported on the interactive effects of outdoor noise and visible aspects of vegetation on behavior in urban settings. Noe and others (1982) examined perception of conflict between off-road vehicle and non-off-road vehicle users in a leisure setting. Ruddell and Hammitt (1985) studied motives for visiting a South Carolina State park and provided interpretations for visual management of park edge environments. English and Cordell (1985) conducted a cohort-centric analysis of outdoor recreation participation trends and found significant cohort effects on participation behavior changes. A comprehensive coverage of studies done on behaviors in the South in the 1980s is too voluminous to cover in this chapter, but suffice it to say that this work has had profound impacts on forest recreation management in the region.

RESEARCH IN THE 1990s

Following is an overview of some of the outdoor recreation and related research published between 1990 and 2002. Much of it was sponsored by Federal Agencies, some by State agencies, and other by private interests.

Broad-Scale Assessments

In 1990, broad-scale assessment work was continuing, mostly stemming from the Forest Service's RPA assessment work. Cordell and others (1990b) produced their third nationwide assessment of outdoor recreation and wilderness demand and supply trends. Findings indicated rapid and continuing recreation demand growth in the United States. An important finding was that participation is growing at significantly different rates among different ethnic groups, in different regions, and between different activities. In 1991, as national and regional demand and supply assessment work progressed, focus moved to technical aspects such as methods and data for assessing demand and supply (Cordell and Bergstrom 1991), estimating demand functions (Peterson and Cordell 1991), and inventory approaches for broad-scale database development (Burkiewicz 1991). In the 1990s as never before, there was growing awareness of the unprecedented social change taking place, and studies were being initiated to look at the consequences of these changes. For example, Murdock and others (1992) studied the implications of demographic change for fisheries management and fishing.

A number of assessment studies dealt with marketing and markets for outdoor recreation. Examples include English and others (1993) reporting on regional market projections, Miles and others (1993b) studying a proposed segmentation framework for outdoor recreation markets, Bayless and others (1994) assessing the market demand for wildlife viewing sites, and Miles and others (1993a) reviewing environmental attitude scales and their utility in consumer marketing. As updates to the 1990 RPA Assessment, Cordell and others (1993) studied the effects of rural land subdivision on public recreation access, and English and Cordell (1993) examined the utility of the Marion Clawson concept of effective recreation opportunity indexing, an important step in assessing the adequacy of supply. In the early 1990s, use of Geographic Information Systems (GIS) in outdoor recreation planning and assessment was taking hold. One of the early works was by Chubb and Hammitt (1993), who developed a GIS procedural manual for the Blue Ridge Parkway. In 1994, additional broad-scale assessment work by Bergstrom and others (1994) examined the use and potential future of the RPA assessments of outdoor recreation among managers and policy personnel in the Forest Service. During 1995 and 1996, a number of studies were reported that dealt with identifying who the recreation participants and potential participants are as information essential to effective marketing. Bixler and others (1995a) wrote concerning getting the novice into natural environments as a way of introducing a broad base of the population to those environments.

In 1995 and 1996, broad-scale assessment work continued, with Cordell and others (1995) reporting on long-term outdoor recreation participation trends, Flather and Cordell (1995) publishing an analysis of historical and anticipated trends in wildlife-related recreation activities, Cordell and others (1996) assessing the demographic and economic changes underway in the Southern Appalachians, and Hayden and others (1996) assessing outdoor recreation demand and supply in the Southern Appalachian region. This last work was part of the comprehensive Southern Appalachian Assessment of forest resources. Other studies in 1995 and 1996 included Lewis and others (1995), which segmented outdoor recreation markets using behavioral data, and Hull and others (1996), which dealt with the ebb and flow of brief leisure experiences. In 1997, Cordell and others (1997b) profiled participants in fish- and wildlife-related outdoor recreational activities in the United States, Teasley and others (1997) studied the use of private lands in the United States for outdoor recreation, and Cordell and others (1998a) described trends in outdoor recreation and their implications for private land management in the East. The third national survey of private landowners was done in 1996 and used in the 2000 RPA Assessment, as well as being published in other places (Teasley and others 1999). Hull (2000) looked at romantic biases in natural areas recreation management and has written extensively about the concept and application of forest aesthetics (Hull and others 2000).

As a result of the nationwide surveying of public participation for the RPA assessment, several spinoff studies were published. They included Cordell and others (1999) describing the rapid and substantial growth in popularity of birding in the United States, based on the National Survey on Recreation and the Environment (NSRE) data;

Cordell and Super (2000) describing trends in Americans' outdoor recreation participation across a wide range of activities; and Fly and others (2000) looking at knowledge of and attitudes, which were mostly favorable, toward wilderness in the Southern Appalachian ecoregion. Followup studies of recreation participation, and especially participation in birding, included estimating recent trends in participation by Cordell (2001) and by Cordell and Herbert (2002). Fedler and Ditton (2001) looked at factors associated with taking up or dropping out of recreational fishing participation. Other broad-scale research included Robertson and Hull (2001), which reported a case study of the nature of landscape perceptions at Whitetop Mountain. It also included publication of work to assess public understanding of nature, especially local knowledge of what constitutes natural forest conditions (Hull and others 2001).

Social Group Differences

The growing diversity of the population in the region prompted a number of studies of social group differences. Recreation participation differences by race were studied by Brown (1994) and Miles and others (1994) who studied African-American participation patterns in forest and other wildland outdoor recreation activities. Bixler and others (1995b) looked at negative perceptions of natural environments among various social groupings, especially by race, and how these perceptions related to preferences for outdoor activities. Floyd and others (1995) studied the effect of race on environmental and recreation preferences, and Ditton (1996) reported on work aimed at understanding diversity among largemouth bass anglers. Betz and others (1998) compared amenity uses and recreational access among social strata making up U.S. private landowners, Bowker and Leeworthy (1998) studied the effects of ethnicity in recreation demand estimation, and Johnson and others (1998) examined marginality and ethnicity in outdoor recreation in the rural South, and compared inner city and rural residents. Tarrant and Shafer (1998) compared preferred experiences and setting conditions of eastern and western wilderness areas.

In the later 1990s, Tarrant and Cordell (1999) helped bring more visibility to the issue of environmental justice in recreation management by looking at the spatial distribution of outdoor recreation sites relative to residence locations of different social groups. Johnson and Bowker (1999) compared onsite wildland activity choices among African-Americans and white Americans in the rural South and described the management implications of their findings. Bowker and others (1999) conducted a national assessment of the use and predicted effects of user fees for recreation services on public lands, including equity considerations. English and others (2000) continued to study economic effects of dependence on tourism on communities in the rural South and elsewhere. Bixler and Morris (2000) identified factors differentiating participants in water-based wildland recreation from nonparticipants and interpreted the implications of this work for recreation activity instruction provided to different social groups. Porter and Tarrant (2001) conducted a case study of environmental justice related to Federal tourism sites in southern Appalachia; Cordell and others (2002) examined cultural emphasis on recreation and the environment; Hunt and Ditton (2002) described freshwater fishing participation patterns among racial and ethnic groups in Texas; Krause (2001) described the roles played by dogs in solo recreation by women; and Johnson and others (2001) examined constraints on outdoor recreation by race, gender, and rural dwelling across regions of the country.

Economic Studies

As a follow-on to the important work of the 1980s to improve data and models for economic impact research, a number of secondary economic effects studies were reported. These included Bergstrom and others (1990b) who looked at economic impacts of State parks on State economies in the South; Clonts and others (1991) who studied economic impacts of hunting land access; and Cordell and others (1990a) who estimated the economic effects of river recreation use on local economies in the Southern Appalachians. Bergstrom and others (1990a) looked at the economic impacts of recreational spending on rural areas of the South. All of these studies found modest income and employment multipliers and modest overall income and employment impacts.

Economic impact research continued in the early 1990s, and began to focus more on applications of technological improvements brought about by the work done in the 1980s. Examples include Cordell and others (1991), who looked at the effects of outdoor recreation on State and local economies in the South; Lee and Propst (1994), who studied the benefits of segmentation to reduce variance in estimates of spending profiles;

Watson and others (1991), who studied the impacts of resource-based tourism on local economies; and Cordell and others (1992), who estimated economic growth stimulus from State park management. Other economic impact studies in the early 1990s included Betz and Perdue (1993), on the role of amenity resources in rural development. English and Bergstrom (1994) studied the links between recreation site development and regional economic impacts. Hawks and Bowker (1994) estimated the local economic impacts of lake recreation in northern California using approaches developed in assessing lake recreation impacts in western North Carolina.

Later in the 1990s, Bergstrom and others (1996) studied the effects of reservoir aquatic plant management on recreational expenditures and regional economic activity, again using some of the same approaches used in the earlier research in western North Carolina. In 1995, English questioned the widespread belief that resource-based recreation was a major solution for rural economic growth because of limited impacts often associated with rural recreation. English and Thill (1996) assessed methods for estimating regional economic impacts of recreation travel where survey data are limited. Cordell and others (1997a) estimated the economic effects on the regional economies of the Rocky Mountains and Appalachians of outdoor recreational visits and spending associated with use of Forest Service sites. English (2000) calculated confidence intervals for regional economic impacts of recreation by bootstrapping visitor expenditures, a much needed addition since most impact estimates do not consider confidence intervals on the estimates. English and others (2000) also examined tourism dependence among counties in rural America. In all of the above cited studies, as with numerous other studies not covered here, economic impact and interdependency effects were found to be important to local economies; but unless the recreation visitation is substantial and sustained throughout the heavy-use season and the rest of the year, and unless the local economy is reasonably diverse and well developed, those effects are almost always modest.

Other economic studies focused on demand for and valuation of outdoor recreation experiences and sites. Prominent examples included work based on results from the 1990 RPA Assessment, such as Bergstrom and Cordell (1991), which reported an analysis of the demand for and value of outdoor recreation in the United States, and Cordell (1992), which reported on amenity, conservation, and environmental values in the United States. Other “demand” studies looked at revenue capture potentials from charging fees (Teasley and others 1993), measurement of recreation benefits using contingent valuation and the question whether the payment vehicle matters (Bowker and others 1993), and recreation use values for alternative reservoir water-level management scenarios (Cordell and Bergstrom 1993). Bowker and others (1994) looked at sensitivity of contingent valuation estimates of recreation trips to the elicitation approach used, and English and Bowker (1994) examined an alternative technique for estimating the demand for river outfitter services. Choi and others (1994) studied the influence of various intervening variables in recreation substitution decisions, an area important in valuation and other behavioral studies. Siderelis and Moore (1995) estimated the net benefits of recreation use of rail trails.

In the second half of the decade of the 1990s, Bowker and others (1996) estimated values for guided rafting trips on southern rivers, and Siderelis and others (1995) developed a boating choice model for the valuation of lake access. Economics research during 1997 and 1998 indicated progress in methods and attention to important resource issues. Examples included Bowker and others (1997), who conducted a demand analysis of off-road motorized recreation; Leeworthy and Bowker (1997), who estimated nonmarket economic user values in the environmentally sensitive Florida Keys; Bhat and others (1998), who tested an ecoregional approach to the economic valuation of land- and water-based recreation in the United States; and Siderelis and Moore (1998), who estimated the influence of site preference variables on recreation demand. Bowker and others (1998) studied benefits transfer and count data travel cost models. Zawacki and others (2000) used a travel cost analysis to examine nonconsumptive wildlife-associated recreation participation, and Siderelis and Moore (2000) developed approaches for incorporating perceptions by users of site quality into recreation travel cost models. In all of the above demand and valuation research, net benefits were found to be substantial, valuation methods reliable, and recreation demand overall somewhat price sensitive.

Motivations, Perceptions, and Behaviors

Studying recreation use, users, motivations, perceptions, and other aspects of participation in the outdoors continued as an important topic in the 1990s. Roggenbuck and others (1990a) studied the learning benefits from leisure. Hull (1990) studied mood as a product of leisure, its causes and its consequences. Chilman and others (1991) reported on design of recreation monitoring systems using participant observers. Cornell and Leary (1991) examined family participation in developed camping. Patterson and Hammitt (1990) studied back-country encounter norms, actual encounters, and their relationship to wilderness solitude. Van Cleave and others (1991) looked at attitudes of summer visitors to the Great Smoky Mountains region. Roggenbuck and others (1991) applied encounter norms in a study of river float trips and as a result questioned the use of the social norms concept. Hull (1991) contributed research on mood as a product of leisure and as a predictor of visitor satisfaction. Caldwell and others (1994) studied zoo visitors' satisfactions. Bixler and others (1992) examined restrictive and nonrestrictive approaches in recreation management. Hammitt and Shafer (1992) analyzed visual dimensions for parkway planning. Stewart and Hull (1992) compared the post hoc and real-time construct validity of the concept of satisfaction. Adams and Hammitt (1993) reported on behavior in relationship to interpretive encounters with wildlife. Hammitt and Patterson (1993) looked at use patterns and solitude preferences of shelter users in back country. Shafer and Hammitt (1993) examined effects of management conditions on wilderness recreation experiences. In 1994, Fedler and Ditton reported on angler motivations in fisheries management. Hammitt and others (1994) studied approaches to identifying and predicting visual preferences for Southern Appalachian forest recreation vistas. Hull and Michael (1994) looked at the relationship between nature-based recreation, mood change, and stress restoration. Rutlin and Hammitt (1994a) examined functions of privacy in the Ellicott Rock Wilderness. Rutlin and Hammitt (1994b) also surveyed users and use patterns of Ellicott Rock Wilderness visitors.

Schneider and Hammitt (1995) studied visitor response to outdoor recreation conflicts. Shafer and Hammitt (1995) examined congruency among wilderness experience dimensions, condition indicators, and user coping behaviors. Examples of later visitor studies included Frauman and others (1997) on the application of means-end theory to understanding interpretive service users, and Noe and others (1997) on park user perceptions of resource and use impacts. Research covering river recreation included Tarrant and others (1997), who examined the effects of situational and personal factors in measuring perceived crowding for high-density river recreation; Tarrant and English (1996), who developed a crowding-based model of social carrying capacity for application to recreational boating; and Hammitt and Lin (1997), who examined the literature on establishing use-level standards for river recreation. Onsite use studies included Symmonds and others (1999) on recreational carrying capacity for managing mountain bike use in the Southern Appalachians, and Thigpen and Siderelis (2001) on the use of paddle trails in coastal North Carolina. Walker and others (1998) studied onsite optimal experiences and their relationship to offsite benefits. Tarrant and others (1999) provided a summary of onsite research on motivations, attitudes, preferences, and satisfactions among outdoor recreationists. Onsite studies included Schuster and Hammitt (2000) on stress experienced by visitors and reported hassles in the Shining Rock Wilderness Area and Schuster and others (2001) on rock climbers' attitudes toward the management and use of bolts. Siderelis and Moore (2000) studied and modeled the effects of perceptions of site quality as a determinant of recreation trip choices.

Wilderness Research

Wilderness continued as a topic of focus in the 1990s. Roggenbuck and others (1990b) examined the wilderness classification process and its application to land management. Hammit and Patterson (1991) considered coping behaviors in relation to wilderness users' desire for greater privacy. Hammitt and Dulin (1991) reported on the significance of encounters with wildlife during wilderness visits. Roggenbuck and others (1993) reviewed relevant research on defining acceptable use, resource, and other conditions for wilderness. Hammitt and Rutlin (1995) developed use encounter standards and estimated relational curves for evaluating achieved privacy in wilderness. Tarrant and others (1995) identified factors affecting visitor evaluations of the noise and visual intrusiveness of aircraft overflights of wilderness.

In 1997 and 1998, a moderate amount of wilderness research was done in the South. Tarrant and Shafer (1997) looked for uniformity of condition indicators used in wilderness management; Walker and others (1998) studied the relationship between onsite experiences and offsite benefits; Hammitt and Rutlin (1997) wrote concerning how well visitors achieved privacy in wilderness; and Johnson and Bowker (1997) presented data on wilderness awareness and potential participation in wilderness recreation across diverse social groups. In other research, Cordell and others (1998b) examined survey results indicating how the public values wilderness. Cordell and Teasley (1998) reported on estimated recreational trips to wilderness, using the NSRE. Cordell and Stokes (2000) wrote about the importance of wilderness as a social value held broadly across the U.S. population, while Hammitt and Schuster (2000) speculated on potential for growth of wilderness use in the next 100 years. Roggenbuck and Driver (2000) provided an article on the benefits of nonfacilitated, i.e., individual, uses of wilderness. Fly and others (2000) examined knowledge of and attitudes toward wilderness among persons living in the Southern Appalachian region. A national assessment of the values of wilderness began in 2003 and is being led by the Forest Service research group in Athens, GA.

Methods

Studies were also progressing to develop research tools. For example, Chubb and others (1991) reported on work using GIS technology for integrating multiple management datasets; Henderson (1994) reported on the growing use of qualitative data methods; Chilman and others (1994) developed approaches for monitoring off-road vehicle riding areas; Janiskee and others (1994) reported on inventories of rails-to-trails resources; and Siderelis and Roise (1991) developed optimal strategies for managing park operations.

Also being reported were advances in methods and theory. For example, tests for homogeneity across waves of mail surveying were reported by Choi and others (1992); tests for the validity of photo-based scenic beauty judgments were reported by Hull and Stewart (1992); Hull and Stewart (1992) also reported on their examination of the construct validity of the concept of satisfaction; and work was completed that examined recreation specialization as a social conceptualization (Ditton and others 1992). Further work on specialization included investigation of the relationship between constraints and specialization (Norman 1992). Wood and others (1996) identified the determinants of satisfaction for participants where quality deer management is practiced. Research evaluating recreation opportunities and visual aspects included Buhyoff and others (1995), which examines the validity and reliability of expert visual assessment approaches.

Later in the 1990s, several additional studies were carried out. Tarrant and English (1996) estimated a crowding-based model of social carrying capacity to be applied to river recreational boating management. Siderelis and Perrygo (1996) applied the concept of recreation benefits to neighboring sites for assessing riparian rights. Overdevest and others (1997) operationalized place attachment through mapping and planning for place values on national forests. Buhyoff and Miller (1998) evaluated an expert system for assessing visually perceived values of landscapes. Borrie and others (1998) studied the use of verbal reports by study subjects in recreation research. During 1999 and 2000, methods studies included Tarrant (1999), on variability of a perceived crowding scale, and Tarrant and Green (1999), on the validity of outdoor recreation as a predictor of environmental attitudes. Tarrant and Cordell (1999) employed GIS technology to analyze the environmental justice implications of the spatial distribution of outdoor recreation sites in the Southern Appalachians. Porter and Tarrant (2001) extended our understanding of the usefulness of GIS in studying environmental justice related to Federal tourism sites in southern Appalachia.

NTFP RESEARCH IN THE SOUTH

Southern forests provide many products that are plant based, but that are not timber. Long before advanced technology existed to harvest timber, people collected natural forest materials for various uses. While research on timber harvesting and managing forests for wood products expanded greatly during the 20th century, studies of nontimber products and uses were few. Today, many local collectors can track their heritage and relationship with NTFPs back several generations. The collection and trade of these products are important to the economies of Appalachian and other southern households and communities. But, in addition, the plants are also critical components of healthy forest ecosystems. Over the last decade, demand for and collection of nontimber products has increased significantly. Because of this increased demand, there has been growing concern about the sustainability of NTFPs and the effects of increasing harvesting on ecosystem sustainability.

Defining NTFPs

NTFPs are plants, parts of plants, fungi, and other biological materials that are harvested within and on the edges of natural, manipulated, or disturbed forests. They may include fungi, moss, lichen, herbs, vines, shrubs, or trees. Many different plant parts are harvested, including roots, tubers, leaves, bark, twigs and branches, fruit, sap and resin, and wood (Chamberlain and others 1998). One useful method of classifying these products organizes them into four major product categories:

1. Culinary products include mushrooms, ferns, and the fruits, leaves, and roots of many plant species. Perhaps the most important of the Southeast's culinary forest products are ramps (*Allium tricoccum* Ait.). Another important culinary species, black walnut (*Juglans nigra* L.), which is native to the Eastern United States, also is used in the medicinal and dietary supplement industry.
2. Wood-based NTFPs are produced from trees or parts of trees, but not commercially sawn wood. Some of the more important wood-based NTFPs include the stems of sassafras (*Sassafras albidum* Nutt.) for walking sticks, willow (*Salix* L.) stems for furniture, and the knees of cypress (*Cupressus* L.) for carvings.
3. Floral and decorative products include crooked-wood [*Lyonia ferruginea* (Walt.) Nutt.] from the forests of Florida to compliment dry flower arrangements, grapevine for wreaths and baskets, and galax (*Galax urceolata* L.) for a variety of uses. Moss harvested from hardwood forests of Appalachia is used domestically and exported to the European floral industry.
4. Medicinal forest products include roots and herbaceous materials from more than 50 plant species, and are used for a variety of medicinal or dietary applications.

Research

A modest amount of research dealing with NTFPs has been undertaken over the last 50 years. Most of this research has focused on describing the varied uses of the plants, their site requirements, and other botanical factors. Some of the more popular products have had extensive research, although most of the research focuses on areas tangential to forestry and forest management. For example, there is a large body of knowledge about the medicinal uses of plant species, but forest managers lack basic knowledge about the population biology and ecology of many of the plants that are harvested as nontimber products.

A modest amount of research has focused on personal use and recreational collection of nontimber products. Prominent among recent work is the 2000–01 NSRE conducted by the Forest Service. Specific questions were asked of respondents to the NSRE concerning their gathering of products from forests (Cordell and Tarrant 2002). The specific trigger question asked was, "During the past 12 months, did you gather mushrooms, berries, firewood, or other natural products?" In the South, 31 percent of the respondents reported that they gather natural products. Of these, almost 54 percent did their gathering activity in a forest setting. Over 96 percent did their gathering for personal use and only 2 percent did it for income. Nine percent of gatherers collected mushrooms, 47 percent picked berries, 73 percent collected firewood, 35 percent collected rocks and minerals, 43 percent tree materials, and 43 percent herbs and flowers. Among the many miscellaneous things gathered were insects, feathers, walnuts, arrowheads, gold, moss, pine needles, Spanish moss, water, wild honey, and sea shells. Over the last 12 months, 29 percent had gathered on 3 or fewer days; 34 percent had gathered on 4 to 10 days; and about 11 percent had gathered on 30 or more days.

The demographics of people collecting for personal use are enlightening. Forty-two percent of the people gathering were male and 58 percent were female. Thirty percent were under age 35 and 20 percent were 55 years or older. Eighty-six percent were white, 9 percent black, 3 percent Hispanic, 2 percent American Indian, and the remaining < 1 percent Asian Americans. By income, the largest group (36 percent of gatherers) earned between $25,000 and $50,000 per year. The next largest group earned between $50,000 and $75,000 (about 17 percent). Those earning < $15,000 per year made up just over 1 percent of all gatherers in the South. Forty-one percent of gatherers live in rural areas and 59 percent in urban areas. Almost 12 percent of gatherers had less than a high school education; and 59 percent had some college, up to a doctorate.

Other research has looked at the major products resulting from gathering. The large number and diversity of plant species that yield NTFPs make this research challenging. Krochmal and others (1969) identified more than 125 medicinal plant species specific to Appalachia. Botanists of the Forest Service estimate that approximately 35 species of medicinal plants are collected for commercial purposes in the National Forests in North Carolina (National Forests in North Carolina 2000). Discussions with medicinal plant dealers in the region reveal that approximately 50 species native to the area are commonly collected. Culinary forest products include mushrooms; ferns; tubers, e.g., ramps; and the fruits and leaves of more than a dozen species. The number of forest species harvested to produce wood-based nontimber products is equal to the number of species of trees, shrubs, and vines that grow in the region. Floral products include more than 50 species of moss and lichen, several species of berries, ground covers, vines, and twigs and stems of numerous species.

Overall, research on NTFPs is modest. Beyond basic taxonomic identification, little information has become available to aid forest management decisionmaking. Some of the more popular products, such as ginseng (*Panax quinquefolium* L.), have been the focus of some literature. But this work has centered mostly on cultivation and folk history (Davis 1997, Hankins 2000, Hufford 1997). Robbins (1998) provides an overview of ginseng, but emphasizes markets, trade, regulations, and the need for conservation. In reports to the U.S. Fish and Wildlife Service, Gagnon[4] [5] examines the sustainability of ginseng and goldenseal (*Hydrastis canadensis* L.) and provides recommendations for monitoring of wild populations. Other species, such as galax, bloodroot (*Sanguinaria canadensis* L.), and pine straw (*Pinus elliottii* Englem. and *P. palustris* Mill.), all of which are important nontimber products, have received much less research.

Galax, also known as wandflower and beetle-weed, is native to the southeastern portion of the United States. The single round or heart-shaped leaves are preferred in floral arrangements as background foliage (Noland 1997). Most literature concerning the ecology of galax focuses on its distribution, range, and habitat (Evans 2000, Fern 1997–2000, Hathaway 2002, Horticopia 2001, Reed 2001). Several studies have examined the genetic makeup of the plant (Burton and Husband 1999, Nesom 1983). One of the distinguishing characteristics of galax is its distinct odor; yet according to Amoroso (2002), the source of the odor is still unknown.

Bloodroot, an ephemeral spring-blooming herbaceous perennial, is found throughout Southern Appalachian forests. Like the literature on galax, most of the literature concerning this important medicinal plant has focused on botanical aspects. The flowers of bloodroot have 8 to 10 petals, significantly more than those of other species in the Papaveraceae family (Lehmann and Sattler 1993). According to Lehmann and Sattler (1993), these extra petals replace some of the stamens in a process known as homeosis. The dispersal of bloodroot seeds is based on a symbiotic relationship with ants (Marshall and others 1979) that feed on a lipid-rich appendage called an elaiosome. After consuming the elaiosome, ants discard the intact and viable remaining portion of the seed in their underground nests, which increases germination and reproduction of the plant (Beattie and Culver 1982, Handel 1976, Hendershot 2002). Seeds that are "planted" in the nests are safe from predation, can avoid competition with parent plants, and have access to essential nutrients (Czerwinski and others 1971, Heithaus 1981, Pudlo and others 1980). While the bright red sap exuded from the roots of bloodroot is the desired product, the alkaloids found in the sap can be poisonous, causing nausea, vomiting, and dizziness or fainting (Russell 1997). Bennett and others (1990) found that plants located in the Southern Appalachian forests have higher concentrations of active ingredients than those found along the West Virginia-Pennsylvania border.

As is common with most NTFPs, the greatest amount of literature about bloodroot concerns its medicinal values (Fern 1997–2000, Haughton 2003, Plyler 2001–2002). Cough lozenges can be made by mixing root sap and maple syrup (Miller 1988, Sanders 1995). According to Grieve (1931), Haughton (2003), and Plyler (2001–2002), small doses have been used to stimulate heart rate and may help in combating heart disease. A profusion of clinical studies have debated the effectiveness of bloodroot products to inhibit plaque and gingivitis (e.g., Drisko 1998, Hannah and others 1989, Harper and others 1990, Kopczyk and others 1991). In the early 1990s, bloodroot was used as an active ingredient in a commercial toothpaste (Damm and others 1999).

[4] Gagnon, D. 1999. An analysis of the sustainability of American ginseng harvesting from the wild: the problem and possible solutions. 53 p. Unpublished report. Final report to the Office of Scientific Authority of the U.S. Fish and Wildlife Service. Groupe de recherché en écologie forestière. Université du Québec à Montréal. On file with: Southern Research Station, 1650 Ramble Road, Blacksburg, VA 24060-6349.

[5] Gagnon, D. 1999. A review of the ecology and population biology of goldenseal, and protocols for monitoring its population. 27 p. Unpublished report. Final report to the Office of Scientific Authority of the U.S. Fish and Wildlife Service. Groupe de recherché en écologie forestière. Université du Québec à Montréal. On file with: Southern Research Station, 1650 Ramble Road, Blacksburg, VA 24060-6349.

Ramps are perhaps the most common spring edible among NTFPs. Several studies have examined soil factors, mycorrhizal status, root anatomy, and the phenology of ramps and related species (Andersson 1993, Brundrett and Kendrick 1988, DeMars 1996, Whanger and others 2000). Other research has looked at the chemistry of the edible portion to identify the active ingredients (Calvey and others 1997, Carotenuto 1996). Botanical observations, demographic studies, and examination of ecological patterns of wild populations have been undertaken (Hanes 1953, Hanes and Ownbey 1946, Jones and Shildneck 1980, Nault and Gagnon 1993). Some aspects of the plant's pollination ecology and biomass production have been examined (Nault and Gagnon 1987, 1988). Rock[6] and Nantel and others (1996) have studied population viability and the impact of harvesting.

Research on pine straw is better developed than that on many other nontimber products. Silvicultural guidelines for pine straw management in the Southeastern United States are readily available (Duryea and Edwards 1992, Morris and others 1992, Woodland Owner Notes 1995). A significant amount of research has looked at the impact of pine straw raking on associated vegetation (Kelly 1996, Litton 1994, Wild 1993, Wolters 1972). While Litton (1994) and Kelly (1996) focused their research on the impact of removing longleaf pine straw on plant populations, Wild (1993) examined the effects of removal on slash pine (*P. elliottii* Englem.) growth and soil productivity. Wolters (1972) found no significant effect of pine straw mulch on southern bluestem (*Andropogen* spp.) production. Other research has examined the potential of pine straw in agroforestry systems (Blanche and Carino 1997, Blanche and others 1997, Brauer and others 2002).

Collection as a commercial activity has been studied only lightly and, thus, little exists in the way of formal estimates of the value of the various NTFP markets in this region. There are some data that illustrate the economic importance of these products. In 1996, collectors of black walnut were paid more than $2.5 million.[7] One company located in rural southwest Virginia and specializing in pine roping had sales in excess of $1.5 million in 1997 (Hauslohner 1997). A volunteer fire department in western North Carolina generates approximately 35 percent of its budget from its annual ramp festival. Based on 2001 prices, the average wholesale value of ginseng harvested from the southern forests exceeds $18.5 million. Certainly, the aggregate value of NTFPs to the Appalachian economy far exceeds these examples.

Although ginseng can be found growing naturally from north Georgia to Southern Canada, this popular medicinal plant is collected primarily from the Appalachian region. Based on data from the U.S. Fish and Wildlife Service, wild ginseng harvested in seven States accounted for approximately 82 percent of the harvest from 1978 through 1998. Of those States, West Virginia, Kentucky, Tennessee, and North Carolina account for approximately 47 percent of all forest-harvested ginseng. The others, i.e., Indiana, Ohio, and Virginia, account for approximately 35 percent.

These States also have higher than average unemployment rates and proportions of people below the poverty level. For example, the proportion of people in Kentucky below the poverty level exceeds the national average by 3 percentage points (U.S. Census Bureau 2002). The unemployment rate in that State is almost three times the average for the entire country. In North Carolina, Kentucky, Tennessee, and Virginia, the average unemployment rate is more than 3 percentage points above the national average. Clearly with such high unemployment, the possibility of supplementing family income by collecting and selling NTFPs must be attractive to local inhabitants.

Research regarding forest management for NTFPs is in its infancy. Chamberlain (2000) and Chamberlain and others (2002) have examined management of national forests in the Eastern United States for these products. The goal of this research was to broaden understanding of issues affecting management. Only 7 of 32 forest management plans for eastern national forests addressed NTFPs. Of the eastern national forests with management plans for NTFPs, only the National Forests in Florida are located in the South. The management plan for Florida's national forests acknowledged the need for research to develop a system to deal with the increasing demand for gathering products.[8]

[6] Rock, J. 1996. The impact of harvesting ramps (*Allium tricoccum* Ait.) in Great Smoky Mountains National Park. [Not paged]. Unpublished manuscript. On file with: Great Smoky Mountains National Park, 107 Park Headquarters Rd., Gatlinburg, TN 37738.

[7] Personal communication. 1998. J. Jones, Manager, Hammons Products Company, 105 Hammons Drive, Stockton, MO 65785.

[8] U.S. Department of Agriculture. 1985. Land and resource management plan. [Not paged]. On file with: National Forests in Florida, 325 John Knox Road, Suite F-100, Tallahassee, FL 32303.

Chamberlain and others (2002) also examined the attitudes and perspectives of forest managers at several administrative levels to estimate the constraints on improving management of these forest products. Fundamentally, four critical problems impede efforts to improve management. These are (1) lack of knowledge about the biology and ecology of the flora from which these products originate, (2) the diverse nature of the products and their collectors, (3) a severe lack of market knowledge, and (4) insufficient personnel and fiscal resources to assign to management. Until these obstacles are overcome, NTFPs management will remain ad hoc, at best.

Although Chamberlain found a lack of management effort toward NTFPs, there are initiatives underway to better understand these products. Federal Agencies that manage forest lands in North Carolina have initiated projects to examine harvesting impact on galax populations. The office of the National Forests in North Carolina has proposed a study to determine growth and yield of several NTFPs, including galax (Kauffman and others 2001). At this time, no results are available, but informal monitoring has been undertaken. The foundation for the study is recognition that there had been a major increase in the issuance of galax permits over the last 5 years. Because of this, there are concerns that patches of galax are being stripped of large leaves faster than the rate of regeneration. Kauffman and Danley[9] argue that the restricted harvesting season should decrease the trampling of young leaves and provide time for larger leaves to harden off. They recommend annual checks be made in the spring to determine if the season needs to be modified.

The National Park Service has the only study actually underway to examine the impact of harvesting galax leaves. Ulrey[10] established permanent sample plots along the Blue Ridge Parkway. In all, thirty-two 1-m square plots were established in 2001. Locations for these plots were selected based on three criteria: (1) no evidence of collection, (2) some evidence of collection, and (3) well-developed patch. Treatments included removing as many large leaves (> 3 inches) as possible. Harvested leaves were weighed and counted, and remaining leaves were counted. Removal rates were calculated by comparing harvested leaves to the number of leaves retained in each plot. Although insufficient time has passed to provide definitive results, discussions with the principal investigator of this project indicate that the impact of harvesting on populations is insignificant.

PARTING OBSERVATIONS AND POINTS TO PONDER

Recreation Research

Recreation research done in the South by scientists employed in the South has been highly productive. Since 1960 and inspired in part by the ORRRC of that time, a number of highly important and intriguing areas of inquiry have been undertaken. In the beginning, problems of economic development in impoverished areas, use impacts on forest recreation sites, and estimating recreation use were focal areas. Indeed over the years since 1960, research and application have shown that for all three of these problem areas, we pretty much understand the problems and have research-provided tools or knowledge to address them. Forest-based outdoor recreation as an economic development tool to address poverty is not very effective—too seasonal and too leaky for most rural economies. Managing use impacts in forest recreation sites requires site hardening and visitor flow management because planting grasses, shrubs, and other vegetation does not hold up. And, we have tools for estimating recreation use at developed and dispersed areas, if only we had the will and dollars to implement those tools more broadly.

Research has provided a pretty clear picture of who forest recreation visitors are, what they want to have and see, and how satisfied they are under different circumstances. We understand their opinions about fees and how they might react to a variety of use-regulatory measures and information systems. We did enough studies of crowded or environmentally sensitive sites to develop reasonably good principles to guide management within social, physical, and ecological capacities. Indeed, research applied across a broad spectrum of use and activity situations has provided good understanding of the phenomenon of crowding and acceptable or unacceptable encounters with other users.

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[9] Kauffman, G.; Danley, D. 2001. Restriction on galax gathering season. [Not paged]. Unpublished internal report. On file with: National Forests in North Carolina, P.O. Box 2750, Asheville, NC 28802.

[10] Ulrey, C. 2001. Summary of first year (2001) results from galax removal study. 4 p. Unpublished report. On file with: Southern Research Station, 1650 Ramble Road, Blacksburg, VA 24060–6349.

To assist planners, policy analysts, policy setters, and legislators at all levels, including private investors and business managers, research has provided a succession of broad-scale recreation demand and supply and social assessments to help make visible recent and likely future trends. Tools, data, and findings measuring the effectiveness of the spatial distribution of supply, forecasting likely future demand, and examining the social equity aspects of different potential management scenarios have been provided. Long- and short-term trends have been described in laborious detail, as have participation patterns across different parts of the region, and different regions of the country. Access to private lands, as well as to public lands, has been examined and described, as have trends in access.

Methods for and studies estimating the value of sites and site attributes contributing to outdoor recreation also are among the benefits of recreation research in the South. Tradeoff analysis and cost-benefit analysis are the processes in which these values estimates are most appropriately applied. A spinoff benefit of valuation research is the ability to predict effects on visitation of different pricing policies (a hot topic now) and predict who might be impacted most or least by pricing. Another spinoff benefit is being able to predict revenue likely to occur with different pricing policies. Underlying all the above research, which is worthy of far more description and praise than is offered here, is a continuous flow of new and improved methods for doing research. Better and more realistic assumptions, better measurement scales, more sensitive input-output models, and a plethora of other advancements have made recreation research more effective and more credible. But what of the future? Where does recreation research need to go from here? The following are points to ponder as we set sail into the 21st century.

There is a wealth of research-based knowledge on hand concerning a variety of forest recreation topics and problem areas. Not everything that is needed and certainly not all that will be needed to fully address the mass of emerging new problems and complexities will be found in the literature of the past. But, contained between the title on page 1 and the last publication listed in the literature cited section on the last page of a large and rich volume of literature, estimated at roughly 6 to 8 times the number of recreation publications cited in this chapter; i.e., 1,200 to 1,500 journal articles, proceedings articles, book chapters, books, etc., is a huge amount of knowledge. Have we adequately applied this knowledge? Likely, the answer is no. At least we feel we have not. There is a crying need to synthesize, interpret, and make more accessible our research findings. It is a fact that managers, planners, business managers, and others in provider roles will not conduct literature reviews, nor are they likely to read research papers. Let us not kid ourselves. The most likely scenario with most research publications is that three peers read it in the beginning, and since then six graduate students read them for use in dissertations. Overall, maybe a total of 10 ever read the typical research article, including the one that the author sent to mom. A priority for the near future in recreation research, then, is to assemble, organize, study, interpret, and design a delivery system to put our research to work. Dr. Michael Rauscher has developed and is implementing the idea of a research encyclopedia. Look up a concept, such as fees, and via hyperlinks, access relevant research written at a level applicable broadly. As well, research literature should be interpreted collectively to ascertain broadly applicable principles and guidelines.

The existing body of research literature, then, is highly valuable and contemporarily applicable. But forest recreation is not static. New problems arise, the face of the user changes, and the social and economic environment within which everything operates evolves. We see a number of research problem areas needing attention (and funding). These are:

- Democracy and a free country is better than any of the alternatives. However, with this freedom and with free enterprise and resulting differentials of wealth and income can develop inequities in access to forest recreation opportunities, public and private. Associated with access are any number of cultural, legal, or physical barriers that differ in type and degree across southern society. Some of these barriers involve fear, such as women may feel in solo recreation.
- New forms of recreation participation and burgeoning development of new equipment for forest recreation participation feeds conflicts already extant between uses and users. A vivid example is motorized uses of forest roads and trails. Walking, biking, and horseback riding users are not compatible and cannot compete with motorized users. Walkers cannot compete with bikers. Bikers cannot compete with horseback riders. And so on. More use, more

varied forms of use, and greater diversity of users will ensure that this problem of conflict will only heighten in the future.

- Growing use, use in areas where it never used to occur, concentrated use in certain areas, and shrinking places to recreate are among the factors that will contribute to increasing impacts on forest recreation sites. Especially sensitive are wildlife populations at certain times of the year, riparian areas, habitats for threatened and endangered plant and animal species, and fragile or pristine features, such as rock cliffs. Managing use and understanding capacities will continue as a problem begging for research attention.
- A virtual explosion of new outdoor clothing, sports equipment, transport and sport vehicles, means of traversing the landscape, and other technological developments has been occurring in this region and in the Nation. Site designs, management guidelines, information flows, and accommodations often are not well matched to modern needs and expectations.
- One of the needs most often mentioned by recreation users is that of access to better information. Information on hazards, locations of places of interest, interpretation of natural and historical aspects of forest sites, and any number of other aspects of forest areas is high in demand by the recreating public. Especially growing in priority is providing conservation education opportunities offsite, onsite, and in association with recreation visits. Information programs, interpretation, and conservation education need to be integrated, and research is needed to guide that integration.

The population of the South is changing with the times and changing as a result of a tide of immigrants from other cultures. Research regarding public attitudes and values associated with forests, forest management, and forest recreation has not kept pace with these changes. Often managers are left to guess what the public voice would say if it were invited to sit at the management decision table this year, next year, or 10 years down the road.

Recreation seekers come to forested areas and rural places in part, maybe in very large part, to see and experience rural and natural landscapes. Ceaseless development and sometimes insensitive management choices affect the character, sometimes the ecosystem functioning, and sometimes, in the eye of the visitor, the quality of these landscapes. Research can shed light on these impacts and perceptions of them.

The processes of forest recreation planning and decisionmaking can be laborious and highly challenging. This is especially so when it is necessary to step back to conduct comprehensive planning across a broad spectrum of management and policy options. Simplified frameworks and procedures for planning, including accessing and using large demand and supply databases, are needed. A critical aspect of such planning is assurance that the public is heard from and understood at local, subregional, and regional levels.

Exposure to media, entertainment fantasies, international travel, different cultures, and a host of other personality shaping factors ensure that there is an ongoing evolution in the makeup and priorities of forest visitors. Understanding trends in motivations and expectations and linking recreation to improving other aspects of life, e.g., fitness and health, are increasingly important.

As society changes and our knowledge of and association with the land seem to diminish, there are increasing questions about the place of a NWPS for this region, and Nation. Wilderness is much more than a recreation resource. It represents much more than an ecosystem as in the eyes of an ecologist. Needed is better understanding of the value and the social, economic, and welfare aspects of wilderness and trends in these aspects.

In forest recreation, science-based planning and management is much needed—in our view, needed much more than at any previous time. Many charged with recreation planning do not have the background, resources, data, and information to come anywhere near fully accomplishing their charge. Highly focused research with minimal duplication and maximum partnering is needed. And, more and more this research needs to provide turn-key data and information systems for direct application in management, investment, and planning.

NTFPs Research

Research for NTFPs is needed in three main areas. The first relates to the sustainability of forest resources and the communities that depend on those resources. Sustainability cannot be achieved without a concerted effort to improve our scientific knowledge of the ecological dynamics of the plant species being harvested. Second, the long-term maintenance of household and local economies that depend on nontimber products will be in jeopardy unless the true value and impact of harvesting is understood. Third, the social and cultural threads of community fabric that have evolved through generations will be lost if research is not undertaken to find ways to sustain this way of life while improving forest management.

Ecological issues, if not addressed, could result in long-term or permanent decline in biological diversity. The science-based knowledge does not exist to ensure that current harvest levels are ecologically sustainable. Research is needed to examine and determine the effects of harvesting on local plant populations, as well as the impact on associated forest ecosystems. Basic knowledge of the population dynamics of most NTFPs is required. Further, baseline inventory data and regular monitoring of populations are essential in developing sustainable forest management strategies. Standardized protocols for inventory and monitoring for nontimber products is severely lacking. Current supplies, as well as regeneration rates, are key elements in determining sustainable harvest levels, and yet remain unknown. Management decisions will continue to be based on incomplete and perhaps inaccurate information until the science has been done to answer some very fundamental questions.

In general, NTFP economies remain a mystery. Unlike timber, the economic value of NTFPs is not defined nor fully understood. The volumes and values of NTFPs are not reported, documented, or monitored, although the overall value of some sectors, e.g., herbal medicines, is partially documented. Economic and market data are essential for setting fair and equitable rates for collection permits. Knowledge of the value to rural communities and households also is lacking, and yet this information is needed to influence policies for sustainable forest management. Policymakers and decisionmakers need to be knowledgeable about the economic importance of NTFPs to rural communities. Accurate and reliable data on the supply and demand for NTFPs is essential to determine sustainable economic harvest levels.

Traditional ecological knowledge is critical in understanding the fundamentals of NTFP management. Many collectors have a long history and strong cultural ties to these products. Research is needed to document collection methods, techniques, local knowledge on resource accessibility, and other knowledge that could be used to develop socially and ecologically acceptable management approaches.

To improve the science-based knowledge concerning NTFPs to a level where sufficiently reliable information is available to forest managers will require a shift in institutional commitments. This institutional transformation will involve nurturing collaboration between varied disciplines, such as getting botanists, ecologists, foresters, and forest products marketing professionals to work together to determine standardized protocols and management approaches. To ensure that research is grounded in the social fabric and that subsequent protocols and policies are socially acceptable, sound social science and improved institutional arrangements also are needed.

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Chapter 24.

Timber Market Research,

Private Forests, and Policy Rhetoric

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Abstract—The development of the profession and practice of forestry in the United States can be linked to urgent concerns regarding timber shortages in the late 19th century (Williams 1989). These were based largely on perceived failures of forest landowners to protect or invest enough in the productive capacity of their forests (Manthy 1977). The South, as the only major timber-producing region of the United States in which private interests have almost exclusively controlled forests and where unfettered interaction between private buyers and sellers has determined timber prices and harvests, provides the clearest example of the way the private sector manages forests. It provides a setting for evaluating core assumptions regarding markets, market failure, and conservation rhetoric, and for examining the potential role of various policy approaches for attaining conservation goals. We examine the history of research into private timber management and the function of private timber markets in the South. In particular, we examine research that provides insights into the behavior of private forest owners and the structure of private timber supply. We also examine how this body of research has been influenced by and in turn may have influenced policy perspectives regarding forests in the United States. Research on the function and structure of timber markets, especially in the South, has clearly illustrated that the private sector can generate an orderly market for a commodity (timber) with a long production period. Investment responses to scarcity signals in the South demonstrate that timber capital is viewed as a reasonably liquid asset and that market failure with respect to intertemporal allocation does not hold. In an interesting reversal of rhetoric, it appears clear now that timber production from public forests—more strongly influenced by policy shifts and administrative process—is much less reliable or stable than private timber supply. Policy concerns regarding southern timber markets have evolved partially in response to an improved understanding derived from timber market research. Current concerns focus on the ability of forests to provide a broad range of resource values, and improved understanding of how timber markets operate is required for a full understanding of the ultimate sustainability of forests, their functions, and their derivative benefits.

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INTRODUCTION

The workings or failings of timber markets are core issues at the foundation of the conservation movement in the United States. The rhetoric of timber famine, which dates back at least to the 1500s in North America (Hyde 1980), obtained strong public currency in the late 1800s and eventually led to the establishment of Federal forestry programs and creation of the national forests. Regulation of forestry activities by some States also resulted. The profession and practice of forestry in the United States likewise can be linked to these urgent concerns regarding timber shortages in the late 19th century (Williams 1989).

Timber shortages can be viewed as resulting from market failures with several potential causes. Overharvesting—that is, harvesting without adequate provision for future needs—implies either (1) an insecure timber resource or (2) a lack of information regarding overall timber inventories. Without secure property rights, timber owners cannot be certain about future access to their timber, and have a strong incentive to harvest soon. The same outcome would result from timber being harvested from a common property resource. Without information on overall inventories, timber owners cannot anticipate oncoming shortages, and so fail to recognize the potential for additional returns from delaying their harvests. Both cases would lead to departures from the economically optimal allocation of harvesting over time, pushing harvest rates beyond socially optimal levels.

Another related concern regarding timber markets has been a perceived failure of forest landowners to protect or invest enough in the productive capacity of their forests (Manthy 1977). Investment below socially optimal levels could result from several potential causes. One is simply that returns from forest investments are not competitive with those from alternative investments; that is, expected returns from timber fail to justify the investment on financial grounds. In cases where investment is competitive but is not undertaken, the reasons could be (1) a lack of access to investment capital, (2) a lack of information regarding production potential, (3) a lack of market information regarding current or anticipated future prices, (4) a long production period that effectively locks up capital for unreasonable periods of time—sometimes called capital illiquidity, or (5) excessive investment risk. All five of these concerns have been raised as explanations for a perceived underinvestment in forests.

The South is the only major timber-producing region of the United States in which private interests have almost exclusively controlled forests and where unfettered interaction between private buyers and sellers has determined timber prices and harvests throughout the 20th century. Private landowners currently control 89 percent of timberland (productive or potentially productive forest land) in the region (Conner and Hartsell 2002). Twenty percent is held by the forest industry. The South provides the clearest example of the way the private sector manages forests. It provides a setting for evaluating core assumptions regarding markets, market failure, and conservation rhetoric, and for examining the potential role of various policy approaches for attaining conservation goals. In this chapter, we examine the history of research into private timber management and the function of private timber markets in the South. In particular, we examine research that provides insights into the behavior of private forest owners and the structure of private timber supply. We also examine how this body of research has been influenced by and in turn may have influenced policy perspectives regarding forests in the United States.

HISTORICAL PERSPECTIVES ON PRIVATE FORESTS

Patterns of resource utilization across time and space are defined by the intersection of social organization with initial resource reserves, underlying biological productivity, and technological change and adoption. The history of forest use in the United States is an outcome of, among other factors, divestiture of a public domain, establishment of forest reserves, long-sustained economic expansion, and the structure of private property rights. The role of private enterprise, both in supplying and consuming timber, has long been contentious and is often seen as the root of natural resource problems in the United States.

At the turn of the century, perceived abuse and waste of private forests was the primary motivation for the American Conservation Movement in the United States.[2] The rhetoric of timber famine then, and for many decades to follow, was strongly rooted in the belief that private timber owners would fail to sustain the productivity of their forests. The national illusion of timber inexhaustibility began to wane by the late 1800s, and the resulting conservation and wilderness movements of the late 19th and early 20th centuries were based almost exclusively on the argument that private-sector management of forests would lead to destruction of forest lands and emergence of a "timber famine" in the young United States (Pinchot 1947, Williams 1989). A treatise on emerging timber scarcity in 1874 (Hough, as cited by Steen 1976) initially formalized the issue for the Federal Government, attracted the attention of President Grant, and led in 1876 to the establishment of the Division of Forestry within the U.S. Department of Agriculture (Steen 1976). Public ownership of forests in the form of the forest reserves (eventually the national forests) and the formation of the U.S. Department of Agriculture Forest Service (Forest Service) implicitly recognized concerns regarding timber scarcity and the assumption that private ownership was the root cause of resource destruction and eventual shortage.

[2] The related wilderness movement of the day was clearly motivated by other concerns, but both can be viewed as motivated by concerns regarding the loss and destruction of forest lands. Even at this early date, however, the wilderness movement, led by John Muir, was separate from and often at odds with the conservation movement led by forestry advocates (see Nash 1967).

Until the 1960s, forest policy in the United States was driven almost exclusively by this timber scarcity rhetoric,[3] and resulted in efforts to expand the Federal forest estate and Federal programs to support State and private forest management. The latter initiative dates from the Clarke-McNary Act of 1924, which authorized funding for, among other things, forest nurseries and technical advice to woodlot owners to support reforestation, and extended authority to acquire private land for national forests for the purpose of providing timber.

The antipathy toward private ownership had other results. Into the 1940s and especially in the 1930s, conservation leaders, including some Chiefs of the Forest Service, argued for national regulation of timber harvesting and management on private lands (e.g., U.S. Department of Agriculture Forest Service 1941). National private harvest regulation was never approved—the responsibility for forest regulations remaining with the States—and disappeared from the Agency's rhetoric by the late 1940s. Still, private land continued to be viewed as a primary source of resource problems and increasing resource scarcity in the United States.

ECONOMIC PERSPECTIVES ON RESOURCE SCARCITY

The belief that private ownership resulted in timber scarcity was essentially taken as self-evident and remained untested until the 1970s, when research into the limits of growth began to focus broadly on material scarcity. Motivated in large part by concerns regarding oil supplies, a major thrust of resource economics in the 1970s and the 1980s was the study of resource scarcity. This body of work focused especially on how to measure changes and trends in resource scarcity in a way that provided information about the potential for and limits of economic growth.

Economic scarcity is not strictly a physical quantity concept but is influenced by information, technology, and quality. To illustrate, consider that a mineral ore is scarce only if it is needed (demanded) in some form for the production of goods and services. It seems logical that as the ore is extracted and used it would become "more scarce." However, the availability of this ore for human uses is determined not by its total quantity (which is generally not known), but by the known quantity (the information part) that can be extracted by affordable means (the technology-driven cost part).

The available quantity of this ore can actually be increased in two ways. One is through discovery of additional deposits, i.e., by improved information. The other is through technological advances that either allow more efficient use of the ore extracted from existing deposits, i.e., through utilization of lower quality grades, or enable substitution of other materials for the ore in the production of the relevant goods. With a renewable resource such as timber, stocks may also be directly enhanced through investment. Information and technology, therefore, play important roles in defining resource scarcity.

Resource economists use trends in resource prices (rents) or in the marginal costs of extraction to gauge changes in economic scarcity. With good market information, producers will internalize their expectations regarding future returns (based on inventories and technology) and current and anticipated demands into decisions regarding what to produce now vs. what to produce in the future. Therefore, sustained increases in price provide a strong signal that the resource is becoming scarcer as producers withhold material from the market in anticipation of higher future returns. Conversely, a sustained decline in prices signals decreasing scarcity. Erratic price movements or discrete jumps in price paths might indicate that producers were surprised by a change in market conditions impossible to foresee or an information failure.

Analyses of price trends were the first studies to directly challenge the premises of historical scarcity rhetoric. Studies by Libecap and Johnson (1978) and Berck (1979) failed to reject the hypothesis that wood product prices in the late 19th and early 20th centuries increased at rates consistent with the prevailing, risk-free interest rates. This pattern of price growth is predicted by economic theory for the optimal use of an exhaustible resource. That is, these findings offered evidence that refuted the notion that historical timber harvesting had been completely indifferent to future implications.

Evaluation of 20th-century price paths also did not suggest market failure. In the 1960s and 1970s, researchers beginning with Barnett and Morse (1963) evaluated trends in resource rents (*in situ* prices) for various natural resources to look for

[3]A clear exception to this claim is concern and debate regarding the impacts of forest removals on the condition of navigable streams and on potential for flooding that dominated the debate regarding the Weeks Act of 1911. As specified by the Weeks Law and until revised by the Clarke-McNary Act of 1924, property for eastern national forests could only be acquired to protect navigable streams (Steen 1976).

evidence of increasing scarcity. Contrary to popular sentiment, evidence suggested no emerging scarcity for nearly all resources evaluated, even mineral resources. Technological changes coupled with new discoveries were credited with effectively augmenting resource stocks in the 20th century. Throughout these studies, however, the major exception to the trend away from scarcity was timber, which showed an unambiguous increase in scarcity. Rates of increase for timber rents (stumpage prices) were, however, not inconsistent with an optimal depletion pattern.

These results suggest that there has not been an information failure in timber markets; i.e., they do not support the notion that producers failed to account for the future when making harvest decisions even as harvesting shifted from one region of the country to another. However, they do not completely allay concerns regarding conservation of forest resources, even from a strictly timber harvest perspective. Most important, they suggest that timber was not managed as a renewable resource through the early portions of the 20th century. On the contrary, timber price trends appeared consistent with those expected for mining of a nonrenewable resource.

One explanation of why a potentially renewable resource would be utilized as a nonrenewable resource is that old-growth timber and second growth or managed timber are two very different resources. It can be argued that old growth is essentially nonrenewable, since economic conditions do not promote the production of old-growth timber. Second growth is also expensive to produce and is not financially attractive as long as relatively inexpensive old growth is available. The interactions between old-growth harvesting and second-growth management have been explored in a study by Lyon (1981). Using optimal control theory, he found that an orderly timber market would start with a mining phase that would eventually trigger an investment phase in a transition to a sustained, agricultural style of timber production. The trigger mechanism is timber price. Investment in forests commences when the price is high enough to warrant competitive rates of return to second-growth timber production. After transition, landowners anticipate and adjust timber stocks to ameliorate resource scarcity. Timber production and forest management in the United States since the 1970s seem to be consistent with these general prognoses.

Taken together, these studies might suggest that concerns regarding timber famine perhaps were overstated. However, these findings are viewed through a lens of economic theory and data analysis that was unavailable during the early 20th century. In addition, the activities spawned by the American Conservation Movement in the late 19th century may have provided information—scarcity signals—that modified the behavior of timber producers. That is, the rhetoric of the American Conservation Movement may have led to change before policy actions did. Whatever the causal path, it became clear by the 1980s, at least to economists, that timber famine was not a relevant contemporary policy concern. By the 1990s timber scarcity had disappeared from forest policy rhetoric completely. Scarcities of contemporary concern relate to the habitat or ecosystem conditions provided by forests.

The net effect of this research into resource scarcity had important influence on the thinking of resource economists and policy analysts. It (1) rejected the notion that private timber production necessarily proceeded without anticipating future scarcity, (2) left open the question of whether anticipated shifts to renewable agriculture-style production would occur, and (3) illustrated that scarcity can emerge—timber prices can rise—even where no market failure occurs. Overall, this body of work clarified a set of hypotheses for studying the structure and function of timber markets.

SOUTHERN TIMBER MARKET RESEARCH

Research into material scarcity shifted the foundation of forest economics research. Until this time, much research was targeted at understanding the magnitude of assumed market failures. From the 1980s forward, however, the focus shifted to understanding how market behavior could influence forest conditions. For some research, the focus shifted from addressing problems with the intertemporal allocation of timber to understanding how timber management might shape allocative problems with other nonpriced benefits from forests. In other cases, the research focused fully on modeling and forecasting the future evolution of forest production, prices, and forest incentives with increasingly greater precision.

The resource economics research into material scarcity changed the frame of reference for forest economics research but provided only an incomplete understanding of timber markets and private production. These initial analyses were based on highly aggregate data for a very heterogeneous resource, and the findings left several questions regarding market mechanisms unaddressed. For example, Can local "scarcities" appear and drive spatial redistribution of demand? Do prices for some species increase at the risk-free rate of interest until it becomes profitable to shift to a substitute species? How are timber markets related spatially? Why should (or do) timber prices increase in the long run if the timber resource is in its "sustained production" phase? If they do increase over time, is this the result of information failure or market failure? Forest economics research in the South and elsewhere applied multiple approaches to develop a better understanding of the specific working of timber markets in the region, but these questions to some extent remain unanswered.

Economic research generally targets either the behavior of individual agents, e.g., producers or consumers, or the operation of highly aggregate markets, e.g., the interaction between price and quantity on a large scale. Forest economics research has focused both on the behavior of individual forest landowners and on aggregate timber markets, mainly for softwood products. Both approaches have been exploited in the South to develop insights into the ultimate outcomes of forest management on private lands.

ANALYSIS OF HARVEST CHOICES

The central conceptual construct of forest economics is the optimal harvest model. The first correct formulation is credited to Faustmann in 1849 and still serves as a point of departure for research into landowner behavior (Faustmann 1849). Indeed, Newman (1988) identifies more than 85 derivative publications in the modern literature. Extensions of the optimal rotation literature address the influence of nonmarket values (Hartman 1976), spatial configuration (Swallow and Wear 1993), and price dynamics (Brazee and Mendelsohn 1988, Clarke and Reed 1989, Forboseh and others 1996, Gong 1999, Haight and Holmes 1991, Lohmander 1988, Thomson 1992). These studies explore management choices (mainly harvest) that would result from a given set of production functions, objectives, and constraints.

The intertemporal structure of forest production is what defines forest economics as a unique endeavor, and the many variants of optimal harvest models provide the theoretical foundation for nearly all of the work that is forest economics, especially work on individual harvest and management choices. These models have been used to construct normative, simulation approaches for investigating individual behavior and have been the theoretical basis for constructing models for positive statistical analysis of harvest choices. We explore these two approaches in turn below.

NORMATIVE TIMBER MANAGEMENT MODELS

Much early research into forest economics involved comparing actual timber management with the behavioral norms defined by optimal rotation models. "Normative" research approaches prevailed from the 1950s through the 1970s. In the South, this research focused on investment behavior across landowner types to investigate the potential for increasing timber supply from private land.

Research on individual investment behavior has directly addressed whether landowners were pursuing optimal management regimes—as defined by the economist—within their forests. Differences between optimal and actual investment levels were viewed as an untapped potential to produce timber from private lands. These foregone investments were labeled timber investment opportunities (TIO). Suboptimal management was attributed to various market failures, including information failures with respect to technical knowledge of forest management, but more importantly with respect to timber prices and timber price trends, and due to prohibitive upfront costs, failure of markets to reflect the future value of standing timber, and limited access to capital (Adams and others 1982).

The results of TIO analysis were used to argue for various forest policies to address these failures. In particular, TIO results were central arguments for programs that subsidize forest planting, including cost-share programs such as the Forestry Incentives Program and the Agricultural Conservation Program. In effect, these programs were designed to overcome the "front-end loading" of costs that discourages investment in long-run timber production. Assessments of timber markets through the 1980s identified TIOs on private lands as clear evidence that information and capital failures impeded timber supply and as a strong indication that public assistance could leverage additional timber supply from the private lands.

In addition, the gap between actual investment and modeled optimal investment was used as an indication that the lack of a widely available price reporting system was retarding the efficient expansion of timber investment in the South—

an information failure. The demand for price information led eventually to the formation of a price reporting service covering the entire South.

Another element of the nonindustrial private forest (NIPF) market failure discourse addresses risk. Some perceive forest management as a risky investment heavily influenced by physical risk of catastrophic loss caused by insects, disease, fire, ice, or wind. It has been argued that risk reduction through fire prevention and suppression efforts set the stage for forest investment activities in the region. Government-sponsored insurance for timber production was also proposed to address the TIO untapped potential. Insurance policies of this sort have not developed, although some private timber insurance is available today. Subsequent research suggests that risk levels are perhaps not as high as once thought and are effectively mitigated by mixed (geographically and biologically diversified) holdings of forest land. Still, for the risk-averse small landholder with a single holding, the probability of a catastrophic loss, although small, could strongly influence his or her decisions.

The premise of much early forest economics research on individual behavior was that these market failures did occur; analysis was used to measure the implications of market failure. Beginning in the 1970s, however, research began to challenge these premises. The development of individual choice econometric models, coupled with the development of computational speed and capacity, allowed researchers to compare observed landowner choices with economically rational choices. As a result, various hypotheses regarding choices could be tested directly.

POSITIVE HARVEST CHOICE MODELS

Econometric models of individual choices examine the probability of a choice as a function of relevant explanatory variables. The selection of variables, as well as the functional form of the model, can be developed by the theory of producer behavior, modeling landowners as producers seeking to maximize the provision of timber and perhaps other products, or consumer behavior, modeling landowners as individuals maximizing the utility that they derive from forests in the context of a household budget constraint. In both cases, the model structures are based on market behavior. Tests of significance of the relevant variables are construed as tests for consistency with market behavior.

Harvest choice models provide direct insights into the responsiveness of timber owners to signals from timber markets. If landowners were indifferent to scarcity signals in the form of timber prices, then the market would fail to allocate timber efficiently across time. This is one expression of the timber famine hypothesis. This hypothesis has been universally rejected by a collection of harvest choice studies (Binkley 1981, Dennis 1990). All of these studies find a positive correlation between timber prices and the propensity to harvest timber and, therefore, reject the null hypothesis that harvests are not price sensitive. However, these studies did not address the relative efficiency of harvest behavior and, thus, leave unanswered questions regarding the optimality of harvest responses to relative prices.

The econometric harvest choice literature also began to crystallize the idea that rational behavior need not only embrace the provision of timber products. A study by Hyberg and Holthausen (1989) challenged the application of the production theory model to forest landowners. Newman and Wear (1993) found management by nonindustrial private landowners not to be inconsistent with profit-maximizing behavior but rather to reflect the relatively high value such landowners place on holding standing inventory. Also, findings from harvest choice studies consistently showed that certain demographic variables, including age, education, and ownership type, were significant in explaining harvest choices (Binkley 1981, Dennis 1990). This implies that harvest preferences are heterogeneous and may be linked to nontimber goods and services derived from forest holdings. In other words, departures from the expected behavior under a single ownership objective of timber production may not be proof of market failure. Instead, such departures may be the result of rational behavior in a well-functioning market, if other private values are also produced from the forest.

ANALYSIS OF TIMBER MARKETS

Economists also study the behavior of production at aggregate levels. In the case of timber markets, much research has addressed the structure of timber supply at various levels of aggregation, but has focused mainly on the supply response of relatively homogeneous regions. Aggregate analysis provides a framework for evaluating the feedbacks between timber demand and supply in defining the response of the private sector to scarcity signals. Various techniques have been applied to this area of investigation. As with harvest choice modeling, the discussion may be split into two parts dealing with normative and positive approaches.

NORMATIVE TIMBER SUPPLY MODELS

The original applications of normative models to timber supply were simply aggregations of normative harvest choice models. They defined the optimal rotation for each quality class of forests for a given price and then summed the average annual harvest implied for each forest class to define total harvest. By solving the problem for a large number of prices, the aggregate supply relationship could be defined. Such analyses were constructed for the State of Georgia by Montgomery and others (1975), for east Texas by Hickman and Jackson (1981), and for Louisiana by Hotvedt and Thomas (1986). This approach implicitly models the supply that would flow when each forest class has achieved a uniform age distribution between zero and its optimal harvest age (the forester's "normal" forest), an outcome that could result in a long-run static equilibrium for the given price. Accordingly, this approach defines only a long-run supply, because it does not explicitly address the existing age structure of forests. This approach can provide insights into the maximum potential timber output by modeling the output consequences of strict adherence by landowners to maximum profit objectives.

Normative models can, however, provide an extremely rich supply specification and, as shown by Hyde (1980) and Jackson (1980), can provide a tractable approach to examining the market consequences of various forest sector policies; for example, public land management strategies and timber taxes. The detailed supply specification also allows for analysis of market effects of technological or environmental changes. Normative models can also be implemented to address conversion of land from forest use to nonforest uses and vice versa. These strengths derive from the explicit linkage between individual behavior and aggregate outcomes, which can account for heterogeneous forests and forest owners.

Normative supply models provided an important and explicit bridge from stand-level analysis to market-level assessment. They provided the first economically grounded estimates of timber supply and credible measures of maximum supply potential for a region; Vaux (1954) is credited with the first application. In spite of the limitations implicit in any attempt to fully simulate market interactions and short-run behavior, they provided an early mechanism for exploration of the potential welfare implications of various management and policy strategies. These studies, therefore, framed a set of questions that would eventually be addressed by the use of increasingly sophisticated analysis.

Extensions of this mechanistic or engineering approach, especially using linear programming, expanded their usefulness. Dynamic adjustment processes can be modeled to address short-run responses. Quadratic programming can be used to simulate the interaction of supply and demand (Greber and Wisdom 1985, Samuelson 1952). Entropy constraints can be used to simulate the variability of observed market responses (Sallnas and Eriksson 1989). The strength of this modeling approach is its rich supply specification, which allows for analysis of the economic and welfare implications of new technologies and new or hypothetical policy instruments (Wear 2003).

POSITIVE TIMBER MARKET ANALYSIS

Positive analysis of timber markets departs from normative models' focus on supply potential to address expected supply responses. Positive models of timber supply implicitly link the biological model of timber production to a behavioral model of harvest choice and are developed by applying statistical methods to observed behavior. Their strength is the calibration to observed behavior, while the challenges of this modeling approach have been statistical methodologies and access to adequate data. Methodological concerns have largely been resolved; i.e., through the development of simultaneous equation and other estimation techniques and improvements in computational power that allows their application. Data availability and quality can still stand between theoretical development and application.

There are two core motivations for estimating positive timber market models. One is to test hypotheses regarding the structure and function of timber markets and the effects of forest policies. For example, such models provided the first empirical tests for simple price responsiveness of timber supply, i.e., that forest owners harvest more timber when prices rise. More sophisticated approaches have permitted more refined testing which addresses increasingly refined hypotheses regarding investment response, policy effects, market structure, and market extent.

The second, and perhaps the more compelling, motivation for this area of research has been to develop forecasts of market activity. Public and private planners need forecasts of both harvest quantities and timber prices. Initial developments of positive market models in the 1970s took place at a time when there was much concern about underinvestment by NIPF landowners, especially in the South. Price information, including forecasts of future prices, was seen as a necessary condition for the encouragement of optimal investment in forest management. In addition, national forest planning regulations developed in the late 1970s required timber price forecasts, and the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 explicitly required the Forest Service to assess future timber supply and demand.

Several studies focused on southern timber markets or contained a southern market component. McKillop (1967) provided the initial positive analysis of aggregate timber markets. Robinson (1974) examined regional stumpage and lumber markets for the South and the Pacific Northwest for the period 1947 to 1967. His study raised a set of questions regarding the magnitude of the supply response (quantified by the price elasticity of timber supply) that were addressed by subsequent research. As part of their national timber market analysis for RPA, Adams and Haynes (1980) specified southern sawtimber supply functions for two subregions of the South. Daniels and Hyde (1986) applied a regional supply and demand model to the total (hardwood and softwood) wood products sector in North Carolina.

Newman (1987) was the first to model markets for different products in the South concurrently. He used a profit-maximization approach to derive timber demand and supply equations to model the southern pulpwood and solid wood markets in the South. This allowed for the delineation of substitution possibilities by stumpage producers in the region. Newman found solid wood timber to be a weak complement to pulpwood supply as owners jointly produce both goods and, more significantly, this study clarified the important part that the joint production of different timber products may play in determining the structure of timber supply. Prestemon and Wear (2000) further characterized the implications of joint production on timber supply.

These positive timber market models provide the central behavioral construct for developing timber market forecasting models. Timber forecasting models are generally hybrids of both empirical and simulation approaches, constructed by linking empirical estimates of supply response and timber demand to mechanistic models of timber growth, as well as models of land use change and timber investment behavior.

Timber market forecasting models have played critical roles in anticipating change and discussing policy approaches to or implications of forest production. The model developed by Adams and Haynes (1980) is still the centerpiece of national timber market assessments conducted for the RPA (e.g., Adams and Haynes 1996) and has been used to simulate the impacts of various forest sector policies including cost-share programs and international trade scenarios. Regional analysis, which demands a higher degree of spatial specificity than is generally provided by international or national models, is likewise anchored by timber market forecasts. In the South, models developed by Abt and others (2000) have been used for this work (e.g., Prestemon and Abt 2002).

An important area of research that developed through the 1990s involved testing the extent of markets and the linkages between spatially separated markets; in effect, this tests the law of one price. Understanding how shocks and the effects of policies are transmitted across space is essential for characterizing how timber markets respond at the relatively fine spatial scales of regional models. Research on spatial price linkages can also be used to evaluate market efficiency. For example, efficient price transmission between markets allows production in one region to respond immediately to shocks in another region, implying that the effects of policies and market shocks, e.g., hurricane damage, large mill closures, etc., are rapidly shared across regions. Incomplete price transmission, on the other hand, would imply that the consequences of local policy shifts and shocks would be borne locally. Tests of "market integration" have been conducted for various levels of production and at various spatial grains. Analysis of markets for materials at higher stages of production (e.g., finished materials such as lumber) generally supports market integration, even between broad regions (Jung and Doroodian 1994, Murray and Wear 1998, Uri and Boyd 1990). Studies of stumpage markets have not generally supported market integration hypotheses (Bingham and others 2003, Nagubadi and others 2001, Prestemon and Holmes 2000) defining a set of questions regarding not only the structure of stumpage markets, but also the linkages between markets at various stages in the production chain.

ONGOING INITIATIVES

Timber market research continues to address questions regarding the current and future use and conditions of southern forests. However, these questions have shifted away from core behavioral questions and aggregate outcomes and toward understanding the spatial structure and ecological implications of timber market activities. The integration and cointegration line of research continues to investigate the communication of prices between subregions of the South, exploring the spatial extent of markets for various products. In addition, research is beginning to model the supply response of private landowners in spatially explicit fashion.

Increased spatial definition is required to address questions regarding the effects of forest uses on ecological and environmental conditions. Increasingly, concerns are being raised regarding the effects of timber market activity on the structure of forested ecosystems and on the ability of these systems to sustain ecological integrity and a variety of benefits beyond timber products (Wear and Greis 2002). A key concern with respect to the ecological structure of southern forests is the extent, location, and management intensity of pine plantations. These are determined as the outcomes of investment decisions by private landowners. Clearly, the answers to these types of questions require insights into where, within the South, production and investment will respond to expanding demands for southern timber.

Spatially refined forecasting requires aggregate models with the spatial and production detail used to construct normative supply models and individual choice models in the past. Research into supply responses at finer scales has begun to explicitly bridge from the findings of individual choice models to the implications at regional levels. The key to this research is linking harvest behavior to supply responses through a forest inventory. Prestemon and Wear (2000) accomplish this by modeling harvest choices for individual inventory plots, based on a general optimal harvest choice framework, and then estimating supply impacts by applying a harvest probability to the area expansion factor of each plot; this link between a behavioral model and the area frame structure of an inventory was first developed by Hardie and Parks (1991). Pattanayak and others (2002) also use the forest inventory and analysis inventory to model supply responses from partitions of the inventory defined by ownership, location, and quality. Both approaches provide promise for building spatial, ownership, and productivity detail into market forecasting models.

Another aspect of understanding the spatial structure of timber markets is a more comprehensive understanding of individual choices regarding uses of forest land. This requires addressing the linkages among all interrelated decisions regarding land and resources, including land use, investment, and harvest choices. A better understanding of the influence of landowner characteristics on management choices is also needed. This would be required, for example, to forecast how changing demographics could influence the area of forest as well as the supply of timber from forests. For example, the Southern Forest Resource Assessment describes a future in which the area of pine plantations will rapidly expand southwide (Prestemon and Abt 2002). But as the South becomes more populated, the so-called accessibility question regarding timber inventories, i.e., defining how much inventory would be accessible to timber harvesting in the future, becomes more important. Newman and Wear (1993) modeled timber supply and investment in a common analytical framework. However, while several investigators have studied land use, investment, and harvesting separately, none have yet linked all three into a common analysis to address the accessibility question.

CONCLUSIONS

Forest economics research often addresses issues at the core of forest policy debates, and it has had a strong influence on policy rhetoric, perspectives, and, at least indirectly, policy outcomes. Research on the function and structure of timber markets, especially in the South, has clearly illustrated that the private sector can generate an orderly market for a commodity (timber) with a long production period. Investment responses to scarcity signals in the South demonstrate that timber capital is viewed as a reasonably liquid asset and that market failure with respect to intertemporal allocation does not hold. In an interesting reversal of rhetoric, it appears clear now that timber production from public forests—more strongly influenced by policy shifts and administrative process—is much less reliable or stable than private timber supply.

The public and policy concerns regarding whether or not private timber markets will work to provide a sustainable level of timber harvests have been answered. The emphasis has now shifted to understanding how these markets work in attempts to predict how market activity will reshape the extent and structure of forests within the South. This is the crux of understanding how human occupation and utilization of land and resources will influence ecosystem structure and function in the future. Understanding how the private sector will organize timber production is one of the keys to understanding overall forest sustainability that addresses the provision of all desired goods and services derived from forests.

Researchers should not, however, mistake the presence of an orderly private timber market as an indication of a fully efficient market. Indeed, research into industrial organization shows that markets that are not completely competitive can exhibit aggregate behavior that is qualitatively similar to the perfectly competitive case. However, inefficiencies can impose substantive welfare costs on consumers. In the case of timber markets, findings of inefficiency derived from integration studies raise some concerns in this regard. Research into individual landowner choices has not yet fully addressed whether observed investment is suboptimal due to capital constraints, tax structure, risk perspectives, or combinations of these factors. Research into the presence and effects of market power is generally underdeveloped—Murray's (1995) analysis of southern timber market structure is an exception.

Policy concerns regarding southern timber markets have evolved partially in response to an improved understanding derived from timber market research. Current concerns are urgent, and improved understanding of how timber markets operate is required for a full understanding of the ultimate sustainability of forests, their functions, and their derivative benefits in the future.

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Biodiversity

Chapter 25.

Biodiversity
and Southern Forests

Eric T. Linder[1]

Biological diversity encompasses all levels of natural variation and includes molecular, genetic, and species levels. All of these factors contribute to diversity accumulated at the landscape scale. However, biodiversity is not equally dispersed across the landscape, but rather clustered in pockets. The Southeastern United States supports several biodiversity hotspots including the Southern Appalachians, the Panhandle of Florida and Alabama, and the Everglades. As landscapes continue to be modified by habitat fragmentation, loss, degradation, and conversion, many species cannot adapt and will eventually be extirpated. While the Southeast remains relatively forested, much of the region's current forest exists as tree plantations. Some plantations have replaced agricultural land and constitute additional habitat for many forest species. Other plantations have been created from natural forested systems, and this kind of conversion has likely resulted in a less diverse and structurally simplified landscape—one that is less beneficial to most native species. Additionally, changes in the frequency and source of disturbance have severe implications for many southeastern ecosystems. For example, pine forests, pine savannas, and prairies all depend on fire for their persistence, albeit at varying frequencies.

South and Buckner (2004) argue that most of the major landscape changes were a direct result of human population growth over the past 200 years. During that period, the population of the area that is now the United States grew from 6 million to the present estimate of 275 million. Fire and field abandonment have helped maintain stands of yellow pine. However, current silvicultural practices and social attitudes toward fire have resulted in a 65-percent reduction in natural yellow pine stands in the Southeast. Unfortunately, present trends suggest that conservation of such stands, and species associated with them, will be difficult if silvicultural practices and public attitudes do not change.

Gordon (2001) provides an excellent overview of some of the key issues related to forest management and its effects on biodiversity. Gordon highlights four important issues: (1) some details about species dependency in relation to southern forests, (2) the history of forestry in the South and its implications for diversity, (3) what changes have recently occurred in forestry, and (4) what lies ahead in the next century. Furthermore, scientists continue to discuss the relative merits of an intensive production-based or conservation-based approach for future forestry. Agricultural forestry seeks to simplify the landscape in terms of structure, pattern, and product. The benefit of this approach is the intense use of smaller plots of land. The drawback is the reduction of biodiversity in and around those managed stands. Contrast this with the conservation-based approach, which focuses on maintaining a complex landscape and supports a greater diversity of species. Gordon provides examples of each approach and concludes that we need to utilize both approaches in the next century while further investigating how to balance them.

Rather than focus on current research issues, Wigley and others (2001) provide a historical perspective on how research on biodiversity, and particularly wildlife diversity, has evolved in the Southeast. Early research focused on game species, but currently includes threatened and endangered species, nongame species, biodiversity, landscape ecology, and sustainable forestry. Participants in this research include universities, Government agencies, nonprofit organizations, consultants, and industry. Several principles have emerged from this research: stand structure is important; larger spatial scales need to be considered; habitat associations may be complex but must be understood; landscape diversity can increase biodiversity; abiotic factors, e.g., disturbance and site quality, can have profound influences on biodiversity; and silvicultural treatments can be used to enhance habitat quality for a variety of species. Wigley and others suggest that future research needs to continue to

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investigate wildlife-forestry issues, especially on managed forests, but that researchers also need to propose affordable and practical techniques for meeting biological objectives.

Bats (*Myotis* spp.) occupy a unique niche and due to several life-history characteristics, are relatively vulnerable to anthropogenic stressors. Unfortunately, very little is known about the ecology of most bat species and how they respond to forest management (Loeb and Krusac 2001). Research priorities for this group should include: (1) determining distribution and status, (2) determining habitat requirement and associations, (3) determining effects of management practices, (4) determining resource partitioning, and (5) developing effective sampling protocols and techniques. Baseline information for bats is largely lacking, and this makes management for this group potentially haphazard. However, some habitat information does exist, and management should focus on bats' use of snags, large-diameter hollow trees, riparian zones, caves, mines, and bridges.

Carter and others (2001) describe the use of multivariate techniques to identify landtypes in the southern loam hills of south Alabama. Using a combination of vegetation, landform, and soil variables, they identify seven landtypes in this system, each with a unique assemblage of plant species. This approach can be used at the landscape scale to identify specific land units, which can be linked to specific management decisions and used to detect assemblages that may contain rare or endangered species.

Linder and others (2004) propose the use of habitat-based population viability analysis (PVA) to assess management alternatives over relatively large spatial scales, e.g., national forests. These models are constructed in a Geographic Information System, which makes it possible to conduct spatially explicit analyses. Models were constructed using widely available data that cover the extent of the study area. The response variable was presence or absence of the target species, while the explanatory variables included stand age, forest type, and a suite of measurements of the physical characteristics of the area in question, such as elevation. By including forest age and type, Linder and others were able to generate and project virtual forests in the future. In this study, they generated five different virtual forests, based on different levels of timber harvesting and natural disturbances, at 10-year increments over a 60-year period. This approach could be applied to additional species or use diversity measures such as species richness to assess potential impacts of various management strategies.

Rather than using future scenarios to aid in management decisions, Bragg (2001) proposes using a historical reconstruction of forest conditions to aid in the reconstruction of forests and the conservation of biodiversity. He demonstrates this approach by showing how it would be applied to shortleaf (*Pinus echinata* Mill.) and loblolly pine (*P. taeda* L.) stands in southern Arkansas. Using a variety of information sources including lumber operation records, travelers, scientific reports, land surveys, and historical photographs, he delineates reference stand conditions. Early evidence suggests that historical basal area was much lower than previously thought, but with more large trees than now occur in old-growth forests. The spatial heterogeneity was also much more complex in historical forests than contemporary forests, but the understory and litter levels of historical forests resemble those of contemporary forests. The goal of this approach is to determine structural and compositional features of ecosystems to which species were historically adapted, which should aid in the preservation of those species.

Harrington and Edwards (2001) explain in detail how they experimentally restored the abundance and diversity of the herbaceous understory in longleaf pine (*P. palustris* Mill.) plantations. They quantified the consequences of competition for light, water, and nutrients, and then compared these consequences to the potential smothering, mulching, or nutrient cycling effects of pine needle fall. Their results show the value of maintaining low-stocking levels of pines and limiting the encroachment of hardwoods or shrubs. Prescribed fire is also beneficial in reducing the needle-fall accumulation on the forest floor. Experiments like this one can be used to show managers how to restore communities and historical ecosystem conditions.

Sites formerly occupied by longleaf pine stands may also be used by restoration ecologists as seed banks for other rare or threatened species. Walker (2001) examined such sites, since converted to loblolly pine plantations, and existing longleaf stands on the Coastal Plain of North Carolina. She conducted vegetation surveys and used the seedling emergence technique to examine the seed bank. Over 35 species and 1,000 individuals germinated, and the seed banks from both sites contained species not recorded during surveys.

Of the 35 species, many were weedy, but many were also indicative of stable longleaf communities. This study suggests that seed banks remain viable in highly disturbed longleaf pine communities, offering one more tool for the restoration ecologist.

Experiments may provide additional insight into how forest management can affect biodiversity. For example, Rosson and Amundsen (2004) examined the impact of harvest disturbance on tree species diversity at the landscape scale. Timber harvesting has been a major disturbance in the South over the past century, and with recent reductions in harvesting in other regions of the country, more pressure has been put on southern forests. Rosson and Amundsen examined data collected in Mississippi by the Forest Inventory and Analysis Research Work Unit of the U.S. Department of Agriculture Forest Service. Tree species richness in plots where no harvesting occurred was compared with tree species richness for harvested and unharvested plots combined. Tree species richness decreased by 11 percent from 1977 to 1994 for all plots combined, but it increased by 44 percent from 1967 to 1994 on the plots that were not harvested. Other factors have certainly contributed to the decline in species richness across forests in the South, but harvesting is suggested to be a significant factor in this study.

Southeastern forests house a rich herpetofauna, but declines in populations of many species have prompted ecologists to examine how management activities may be affecting this group (Russell and others 2004). Lanham and others (2001) studied the herpetofauna in recently harvested gaps in bottomland hardwood forests in South Carolina. Specifically, they compared herpetofaunal use of ephemeral, skidder-created ponds with use of natural depressional wetlands. Salamanders appeared to be affected negatively by skidder trails and gap creation. Response of frogs was mixed, with hylid abundance greater in gaps but *Rana* spp., *Nerodia* spp., *Chelydra* sp., and *Eurycea* sp. more abundant in skidder-created ponds. Species diversity also appeared to increase along skidder trails. Results suggest that overall abundance did not differ between treatments, but community composition may be changed if habitat suitability for some species is changed.

Baughman and Guynn (2001) studied herpetofauna assemblages in intensively managed loblolly pine plantations in South Carolina. The goal of this study was to assess the baseline herpetofauna assemblages before installation of a complex corridor system. These assemblages were consistent with those on other sites in the Southeast in terms of diversity and relative abundances of the groups under consideration (anurans > salamanders > reptiles > turtles). Despite the apparent consistency between sites, small differences in abundance were found, which could lead to misleading conclusions without pretreatment sampling.

Haskell and others (2001) examined how the avian community varied across habitats on the Cumberland Plateau in southern Tennessee. Species richness was consistently lower in loblolly pine plantations than in oak-hickory (*Quercus* spp.-*Carya* spp.) forests, and abundance was lower in most plantations. Plantations had fewer cavity- and tree-nesting species, and fewer Neotropical migrants, than did oak-hickory forests. Thinned forests seemed to have higher avian species richness, evenness, and abundance than oak-hickory forests had. Haskell and others also studied how avian communities change with respect to human development. They found that residential and rural areas exhibited higher species richness, evenness, beta diversity, and abundance than did oak-hickory forests. Using Partners in Flight priority scores, which were assigned to each species, they quantified and ranked the conservation value of each habitat type considered. This approach appears to support results from direct comparisons, yielding a conservation ranking (from greatest to least) of residential-rural areas, thinned forests, oak-hickory forests, and pine plantations.

Many habitats in the Southeast—and in other parts of the world—are threatened by degradation, fragmentation, conversion, invasion by nonnatives, loss, and other problems. If recent demographic trends continue, more stress will be placed on the habitats and biodiversity of the Southeast. Although there is interest in afforestation (conversion of nonforest land to forest), application of afforestation in the areas where this is most economically suitable may actually reduce regional biodiversity (Matthews and others 2002). Consequently, it is likely that pressure on our forest resources will continue to mount. The scientific community has a responsibility to provide landowners and the public with information that help us to meet demands on our natural resources while maintaining native biodiversity. The creation and refinement of tools used by ecologists, e.g., PVA gap analysis, and is one such contribution. Furthermore, because many of the threats to biodiversity involve ecosystem processes or large spatial scales, it will be necessary to have cooperation between universities, nongovernmental organizations, private landowners, and public land managers.

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Chapter 26.

Population Viability

as a Measure of Forest Sustainability

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Abstract—*Many forest managers work to balance timber production with protection of ecological processes and other nontimber values. The preservation of biodiversity is an important nontimber value. When a suite of management options is being developed, it is difficult to estimate quantitatively the impact of the various scenarios on biodiversity. We suggest population viability analysis (PVA) as a tool for estimating the quantitative impact of landscape modifications on species. Using a habitat-based approach to PVA, we examine the potential effects of five management alternatives on the chestnut-sided warbler (*Dendroica pensylvanica*), a management-indicator species, on the Cherokee National Forest in Tennessee. This analysis shows that population size is positively correlated with disturbance. It also appears that without active management, this species, which is dependent upon early successional forests, may not find enough suitable habitats to maintain viable populations over the next 50 years. Although habitat-based PVA is demonstrated here for a single species, it has been modified to assess large biota. Habitat-based PVA is a useful tool for those who must assess the potential impact of landscape modification on biodiversity.*

INTRODUCTION

During the late 1800s and early 1900s, the forests of the Southern United States were overexploited and mismanaged in ways that resulted in depletion of timber resources, extensive erosion, degradation of water quality, and negative impacts on wildlife habitat and wildlife populations. The latter half of the 20th century saw the emergence of new attitudes regarding land use by private and public landowners. Legislation such as the Multiple-Use Sustained-Yield Act of 1960 and the National Forest Management Act of 1976 requires that national forests be managed for both timber and nontimber values. Today, forest managers are beginning to work to achieve ecological sustainability on both public and private lands (Kohm and Franklin 1997). Pursuit of ecological sustainability includes efforts to maintain ecosystem functions and processes, timber production, and nontimber values. Biological diversity, or biodiversity, is an important nontimber value. Biodiversity is diversity at the genetic, species, landscape, and ecosystem level (Noss and Cooperrider 1994). However, it can be difficult to assess the success of management for biodiversity (Botkin and Talbot 1992). Managing for biodiversity requires the development of strategies for monitoring the flora and fauna of the area in question (Lindenmayer and others 1999). Only a few researchers have described organized approaches to planning for biodiversity as an objective of multiple-use management (Kuusipalo and Kangas 1994, Millar and others 1990, Probst and Crow 1991).

Management to conserve biodiversity or to avoid species extinction is generally addressed at the scale of a species geographic range, which may extend across many political boundaries, ecoregions, or even continents. Species that are widespread and abundant are generally of little management concern, although nonnatives and

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pests are notable exceptions to this rule. Most rare species are of management concern, however, and since most managers work on a spatial scale that is small relative to a species global distribution, preserving biodiversity is really a matter of preserving populations. Small populations are subject to environmental stochasticity and many other uncertainties and are consequently more at risk of extinction. Thus, if populations are to persist, they must be adequately large (Menges 1990, Pimm and others 1988).

It is generally acknowledged that a greater diversity of habitat types is positively correlated with greater biodiversity. Forest management generally affects the composition and spatial arrangement of forest stands at the landscape scale. Different management practices can produce profoundly different habitat conditions. Industrial forest lands, for example, may support large (> 50 ha) even-aged stands of trees of a single species; e.g., loblolly pine (*Pinus taeda* L.). Biodiversity in these managed forests can be enhanced by maintaining a diversity of stand-age classes and stand-size classes across the landscape. Other silvicultural practices that modify forest habitat conditions include thinning and prescribed burning. It can be difficult to predict the consequences when habitat conditions are modified over large areas. For this reason, tools that assess landscape change can be particularly valuable. The use of spatially explicit habitat models is one such tool (Dunning and others 1995).

Population viability analysis (PVA) has been used to predict the likelihood that a population of a single species will persist over a given time period (Boyce 1992, Nunney and Campbell 1993, Soulé 1987). The relative merits of the criteria used in such analyses have been discussed elsewhere (Mace and Lande 1991). Early PVA employed deterministic models that examined the management of endangered species and relied solely on demographic analyses (Miller and Botkin 1974). Later, population models that incorporated demographic and environmental stochasticity were developed (Menges 1990; Shaffer 1981, 1983). Since these models account for a portion of the stochastic events characteristic of small populations, this marked a dramatic improvement in PVA. In 1986, the conceptual framework of PVA was broadened to include a comprehensive examination of factors that can affect the persistence of populations (Gilpin and Soulé 1986). Population persistence is subject to variation arising from several sources, including stochastic, demographic, temporal, spatial, individual, and other processes (White 2000). One challenge associated with the use of PVA is an accurate estimate of the variation induced by such processes. A number of researchers have studied parameter estimation and its influence on model performance (Akcakaya and others 1997, Burgman and others 1993, Conroy and others 1995, Dennis and others 1991, Groom and Pascual 1998, Ludwig 1999, Taylor 1995, White 2000).

One outcome of quantifying population persistence is the concept of the minimum viable population size (MVP) (Harris and others 1987). An MVP is an estimate of the minimum number of individuals required to constitute a population that can persist for a given time period. There has been considerable debate about the characteristics of MVPs (Harris and others 1987, Henriksen 1997, Thomas 1990). Many aspects of species biology must be considered when workers attempt to determine what the MVP is, and these aspects will vary across taxa and with circumstances, e.g., genetic variability, mating system, reproductive power. PVA has continued to evolve as a conservation tool and now includes demographic, genetic, and spatially explicit models (Beissinger and McCullough 2002, Young and Clarke 2000). The various roles played by PVA have been summarized by Burgman and Possingham (2000).

The most common approach to PVA is to model species demography. This usually occurs when species abundance is relatively low, and there are relatively few populations. Demographic PVA has been conducted for dozens of species, and these analyses have ranged from simple population projections to spatially explicit, individual-based models that include heterogeneous landscapes and age-specific demographics (Beissinger and Westphal 1998). One especially interesting aspect of demography is sensitivity analysis (Crouse and others 1987, Mills and others 1999), which can be used to determine which demographic parameter, e.g., juvenile survival, birth rate, has the greatest impact on the population growth rate. Managers can plan their actions in accordance with such analysis, but the use of this method does not guarantee success.

When a single population is under consideration, demographic model development is relatively straightforward but is affected by the type and quantity of data under consideration (Morris and others 1999). When the spatial scale is sufficiently large or when multiple populations are under consideration, a new approach may be useful. For example, one can include a spatial component in the model. This component can be explicit (Lindenmayer and Possingham 1996) or nonexplicit (Hanski and others 1996). Both of these approaches have merits, and both are consistent with the use of PVA to make specific spatial decisions. This makes PVA an extremely valuable conservation and management tool. However, a major drawback of spatially explicit models is that it takes additional data to construct and run them. Also, the use of additional model parameters may negatively impact predictability (Ruckelshaus and others 1997). It is up to the modeler to decide whether a more complex model, which typically represents a more biologically realistic depiction, is preferable to a simpler model that requires less time and effort to construct.

Because count data are easily collected and relatively inexpensive, they are commonly available to land managers. Count data can be used to construct simple time-series models for the projection of population estimates (e.g., Boyce and Miller 1985, Dennis and others 1991). It is important to know whether a population trajectory is based on data for a single population or for several populations. Because a species may be declining in some populations while increasing in others, it can be very helpful to incorporate spatial structure into population models (Stacey and Taper 1992, White 2000). Another factor to be considered is the adequacy of the time span employed. Morris and others (1999) suggest that a minimum of 10 years be used. However, even when a long-term dataset, e.g., 26 years, is employed, conclusions about population persistence can become outdated quickly when populations change abruptly (Boyce 2001, Dennis and others 1991). Finally, although time-series models are useful in determining population trajectories, they offer no insight into the processes driving the population decline.

Another approach to PVA is to examine the ecological factors associated with population decline or population stochasticity. Loss or degradation of habitat is the most significant threat facing species (Pimm and Gilpin 1989, Wilcox and Murphy 1985). Habitat loss is listed as a significant threat for 82 percent of endangered bird species (Temple 1986). Other factors that can reduce the viability of a population include predators, nonnative species, parasites, and disease. However, ecological variables are rarely addressed in PVA because of the difficulty of collecting the necessary data and incorporating them into analyses (Boyce 1992).

In response to criticism surrounding the use of only demographic-based PVA for land management decisions (Harrison 1994, Taylor 1995), researchers attempted to develop a habitat-based approach (Roloff and Haufler 1997, White and others 1997). Two approaches have been developed, and both are based upon concepts rooted in community and population ecology. Community ecologists have developed the concept of minimum area requirements, while population biologists have emphasized minimum population size (Soulé 1987). Both approaches quantify the habitat available in a given landscape and then estimate the sustainable population size. Both assess a landscape's potential (the amount of suitable habitat available for the target species) but differ in their assessment of the detail of data required to conduct risk analysis. White and others (1997) use general habitat relationships to determine habitat suitability, while Roloff and Haufler (1997) use an empirically derived, spatially explicit habitat model. Both approaches utilize presence and absence data, which can be collected with considerably less time and effort than demographic data.

The use of PVA is important in mitigating the negative effects of landscape change on biodiversity (Burgman and others 1993). Habitat loss and fragmentation continue to challenge conservationists. PVA models have evaluated the impacts of habitat fragmentation or loss (Lindenmayer and Possingham 1994, McCarthy and Lindenmayer 1999, Noon and McKelvey 1996), established area requirements (Goldingay and Possingham 1995), and aided in optimizing the design of nature reserves (Burgman and others 1993, Lindenmayer and Possingham 1994). However, PVA has limitations that should be recognized (McCarthy and others 1996, Taylor 1995). The most useful products of a PVA may not be the absolute numbers or statistics generated, but rather the relative values generated under various management scenarios (Boyce 1992). Relative impacts of various management scenarios have been assessed for a handful of species (Drechsler 1998, Haig and others 1993, Lindenmayer and Possingham 1996, Pfab and Witkowski 2000). In the present case study, we use habitat-based PVA to examine the impact of various management scenarios on the viability of forest songbirds.

CASE STUDY

The management of public lands is a central element of national environmental policy in the United States. The management practices employed on public lands today are an outgrowth of past practices, growing awareness of ecosystem importance, and conflicts over various issues, e.g., wilderness vs. timber production. Attempts to resolve these issues can be expensive for all parties concerned. For example, the USDA Forest Service spends over $5 million annually on lawsuits regarding proposed sales of timber on land it manages (U.S. Department of Agriculture, Forest Service 1997). One contentious issue is the role of timber management in the management of our national forests. Impacts on native flora and fauna have been cited as reasons for limiting timber harvests (Harwood 1997). Many studies have examined the impact of forest management on a variety of plant and animal groups. In this study, we focus on impacts on forest songbirds.

Most studies associated with bird communities and timber management examined the impact of a particular treatment on community structure. This is done by examining the bird community before and after harvests. Most such studies have concluded some species are negatively impacted by timber harvesting and that other species benefit from it (Thompson and others 1992). From a management perspective, this suggests that timber harvesting may be a viable option for the management of habitat for some songbirds.

Natural disturbance has always shaped forest communities; anthropogenic disturbance, e.g., silviculture, has had an important role in shaping North American forest communities for the past 200 years (Smith and others 1996). The frequency, intensity, and type of disturbance affect forest structure and composition. Bird communities change dramatically in response to these changes in habitat conditions (Newbold 1996).

We considered two silvicultural methods in this case study: even-aged and uneven-aged timber harvesting. On the Cherokee National Forest (CNF), recent even-aged management consists of relatively small clearcuts averaging 10 ha in area. Clearcutting has been the preferred regeneration system on the CNF for the past 30 years. However, because of public opposition to clearcutting, uneven-aged management may predominate in the future. The CNF uses group-selection cuts that result in a forest that is structurally diverse at the understory, midstory, and canopy levels. This approach results in forests that have structural attributes similar to those of old-growth forests (Annand and Thompson 1997, Thompson 1993). However, uneven-aged harvesting is a relatively recent silvicultural approach and, consequently, few studies have evaluated its potential as a management tool (Annand and Thompson 1997, King and others 2001, Twedt and others 2001). The goals of this case study are to assess the effects of various management alternatives on the viability of the chestnut-sided warbler *(Dendroica pensylvanica)* (CSWA), a forest songbird. To achieve this, we ask three basic questions:

1. Are current harvest levels adequate to support viable populations of CSWAs?
2. What is the impact of natural disturbance in providing habitat for the CSWA?
3. What timber harvesting strategy best promotes the viability of the CSWA on the CNF?

We show how a habitat-based PVA can be used to assess the impact of various management scenarios on CSWA, a species that is typically associated with early succession forests.

METHODS

Point-count data collected in the CNF during the 1992–96 breeding seasons were used to construct a habitat model. Standardized avian census methods were employed (Hamel and others 1996). Habitat variables were derived from the Forest Service's Continuous Inventory of Stand Conditions (CISC) database and the Southern Appalachian Assessment database. Variables included forest type, condition class, stand age, site index, and elevation (table 26.1). Both databases exist in a Geographic Information System, and our analysis was conducted at a pixel resolution of 30 m^2, which is a scale appropriate for our target species. We used stepwise logistic regression (PROC LOGISTIC) (SAS/STAT 1990) with a $P < 0.10$ level to build a habitat model to predict the occurrence of CSWAs. The habitat model was then applied back onto the CNF, creating a probability surface that reflected the likelihood of occurrence of breeding territories ranging from zero to one. To estimate the amount of suitable habitat on the CNF, we multiplied the likelihood of occurrence for each stand by that stand's acreage. The products are similar to the habitat units (HU) in a Habitat Suitability Index model (Schroeder 1983), which for this case study, is equal to 1 ha of suitable habitat. To convert the products into an estimate of the potential to

Table 26.1—Habitat variables and descriptions used to construct chestnut-sided warbler model

Habitat variable	Description	Range
Age (*years*)	Current age of stand	0 – 172
Forest type		
Yellow pine	Yellow pine forest	0 – 1
White pine-hemlock	White pine or hemlock forest	0 – 1
Cove hardwood	Cove hardwood forest	0 – 1
Northern hardwood	Northern hardwood forest	0 – 1
Mixed hardwood-pine	Mixed hardwood and pine forests	0 – 1
Oak-hickory	Oak-hickory forest	0 – 1
Stand-condition class		
Seed	Seedling-sapling	0 – 1
Pole	Poletimber	0 – 1
Saw	Sawtimber	0 – 1
Site index (*feet*)		
Site index 1	Site potential, dominant tree height in 50 years	4 – 130
Site index 2	Site index < 70	0 – 1
Site index 3	70 < site index < 80	0 – 1
Site index 4	80 < site index < 110	0 – 1
Elevation (*m*)		
Elevation 1	Elevation	231 – 1530
Elevation 2	Elevation < 475	0 – 1
Elevation 3	475 < elevation < 872	0 – 1
Elevation 4	Elevation > 872	0 – 1

support a given breeding population, we summed the products across the study area and multiplied the total by the average breeding density of CSWA from Hamel (1992). We used a minimum viable population size of 250 breeding pairs, a very optimistic estimate, as the critical threshold below which the species would not persist. To avoid overestimation of available habitat on the strength of marginal probabilities of occurrence, we stipulated that habitat would not be considered suitable where the probability of occurrence was < 75 percent. Habitat patches that were less than one territory in size were not considered suitable.

In this exercise, we projected figures from CISC databases 60 years into the future. This was accomplished by using a SAS-based forest model to simulate even-aged and uneven-aged timber harvests. The management alternatives developed varied with forest type, total area harvested per 10-year interval, relative proportion of even-aged to uneven-aged harvesting (area basis), group size, and intensity of harvest. Specific variation of intensities and harvesting methods were based on past harvesting practices and expert opinion of the district silviculturists. Since our target species is associated with early succession habitat, we also considered the rate at which forests were restoring themselves naturally. Consequently, we modeled five natural disturbances on the basis of existing literature and historical averages for this region. Natural disturbances included fire, ice, wind, southern pine beetle (*Dendroctonus frontalis* Zimmermann), and hemlock woolly adelgid (*Adelges tsugae* Annand). Each was assigned randomly to forest stands that could be affected by the type of disturbance; e.g., southern pine beetle did not impact northern hardwood stands. For each simulation, virtual forests were updated every 10 years.

Five scenarios were simulated, each with a different intensity of disturbance: no timber harvesting or natural disturbance, no harvesting but natural disturbance, harvesting at expected level (based on recent average harvests on the

CNF), 200 percent of expected harvest, and harvesting at 300-percent expected levels. These scenarios offered a range of disturbance intensities and allowed us to assess the impact of various management practices compared to natural disturbance rates. Using the ArcView Spatial Analyst extension (Environmental Systems Research Institute 1996), we calculated the area of each habitat patch for each simulation. Number of habitat units was calculated for each 10-year interval and so that the habitat potentials for the disturbance scenarios could be compared easily.

We also conducted sensitivity analysis on the habitat variables to test their relative importance. Each forest simulation was run repeatedly, with systematic manipulation of input variables at each harvest level and at levels 30 percent above and below each harvest level. The OPTEX procedure (SAS 1990) was used to identify a subset of variable settings, and this reduced the number of iterations necessary. The response of total HUs to each habitat variable was then tested using the general linear model procedure (PROC GLM) (SAS 1990). Sensitivity analysis quantified the importance of each variable independent of the relative abundance of each forest type. This approach was also used to compare the influence of management alternatives across forest types.

RESULTS

The CSWA is relatively uncommon in our study area, occurring on 14 percent of census points. The CSWA model included positive associations with elevation, seedling and/or sapling condition class, site index, and several forest types (table 26.1). Variation explained (indicated by max-rescaled R-square) was 0.6484. The correct classification percentage (concordance) was 95.6, which is relatively high. The Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 1989) indicated that the fit of the data was acceptable at $P > 0.05$. The CSWA model indicated that preferred habitat consisted of young productive forests at elevations > 1000 m.

Characteristics of high-quality habitat varied across the landscape, with northern hardwoods providing the greatest breeding opportunities (662 HUs), followed by oak-hickory (520 HUs), mixed pine-hardwood (113 HUs), yellow pine (48 HUs), and hemlock-white pine (34 HUs). CSWA habitat was positively associated with most types of disturbance, including (in order of descending importance) area of even-aged harvesting in oak-hickory, area of disturbance by ice and or wind, area of even-aged harvesting in cove hardwoods, area of uneven-aged harvesting in oak-hickory, and area of even-aged harvesting in mixed pine-hardwoods. Disturbance by fire, southern pine beetle, and hemlock woolly adelgid were not related to habitat availability for CSWA. Not surprisingly, the strongest negative association with habitat availability was the association with forest age. Sensitivity analysis indicated that most forms of disturbance were extremely important in generating suitable habitat. Ice and/or wind disturbance was the only natural disturbances that were of much importance, however.

At expected levels of harvesting, the amount of suitable CSWA habitat increased slightly (8 percent) from 1993 to 2053. Based on an average breeding density of 11.9 breeding pairs per 40 ha (Hamel 1992), the initial landscape in 1993 could support approximately 416 breeding pairs. Based on the various disturbance scenarios, the landscapes could support from 250 to 790 breeding pairs in 2053, with suitable habitat being positively correlated with disturbance (fig. 26.1). Thus all disturbance scenarios considered provided adequate habitat to ensure viability (MVP = 250). In the 300-percent harvesting scenario, the number of HUs available increased dramatically the first three decades and declined over the last two decades. The decline in suitable habitat resulted from maturation of trees in the previously harvested areas and a lack of stands suitable for harvesting in the latter years of this simulation.

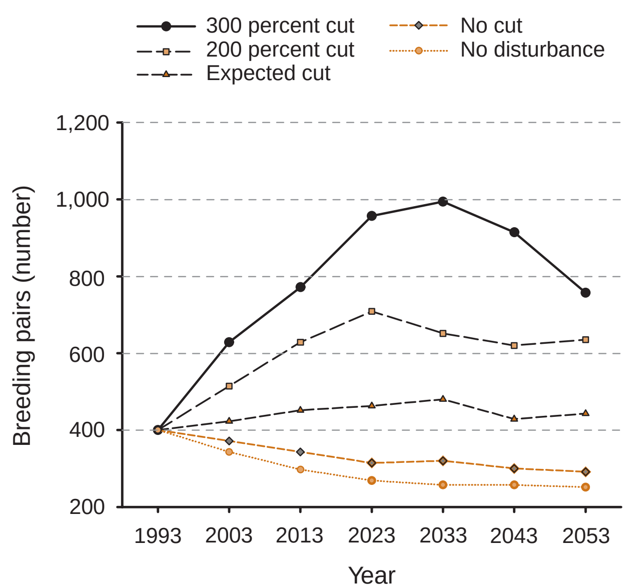

Figure 26.1—Habitat potential for the chestnut-sided warbler on the Cherokee National Forest under five management alternatives over a 60-year time horizon.

DISCUSSION

Disturbance is vital to the maintenance of habitat for CSWA. However, sensitivity analysis suggests that natural disturbance contributes relatively little to the creation of habitat suitable for CSWA on the CNF. If viable populations of CSWA are to be maintained, it may be necessary to create additional suitable habitat by means of active management.

Only habitat variables found in the CISC database were employed in this study. The virtual forests regenerated by timber harvesting were very similar, in terms of CISC variables, to forests regenerated by natural disturbance. For example, simulated clearcuts and wildfires reset condition class and age to identical values. In actual systems, disturbances of these types are likely to produce dissimilar biological results. Schulte and Niemi (1998) found that key habitat characteristics of logged and burned sites differed significantly, and that this resulted in avian richness and abundance. Similarly, there were structural differences between forests that had been disturbed by tornadoes and those that had been clearcut (Newbold 1996). Again there were differences in avian community composition, but diversity did not vary with source of disturbance in this instance. Natural disturbance should be incorporated into habitat models systems in which it can play a significant role.

Habitat for CSWA can easily be created through forest management. It is possible to manage for species associated with late-successional forest by allowing forest stands to age, but it may take decades for high-quality, late-successional habitat to develop. It may be necessary to use silvicultural treatments to promote development of structural characteristics, e.g., snags, cavities, or den trees, important to species dependent on this habitat. The challenge for managers is to provide the balance of habitat types, seral stages, and landscape configurations that is most suitable for the desired diversity of species.

The results of this particular study are relatively clear with respect to CSWAs, as the management alternatives evaluated were distinct and only the intensity of harvesting varied among simulations. Because the approach we employed is spatially explicit, we could have compared the relative effects of several scenarios while maintaining consistent harvest volume. A spatially explicit approach can also be used to assess the effects of several different landscape configurations. Researchers have developed decisionmaking tools for assessing scenario outcomes in studies that yield results that are less clear (Burgman 2000, Drechsler 2000).

Several potentially conflicting ecological, social, and economic factors must be accounted for when planners attempt to formulate the best land use plan for a tract of land. Various pressures are causing researchers, managers, and the general public to devote more attention to the problem of preserving biodiversity (Kuusipalo and Kangas 1994, Lindenmayer and others 1999). The preservation of biodiversity implies the maintenance of viable populations of all species deemed desirable. While PVA is a useful management tool, it is not possible to conduct intensive analyses for each species within the area of interest. It may be necessary to conduct analyses only for indicator species. The use of indicator species is meant to make it possible to estimate the responses of multiple species to a variety of alternatives without addressing the requirements of each species individually. The appropriateness, advantages, and disadvantages of using indicator species in planning for sustainable forestry has been addressed elsewhere (Lindenmayer and others 1999).

There are several criticisms of demographic-based PVAs (Harrison 1994, Taylor 1995). However, a recent retrospective analysis of the predictive accuracy of PVAs clearly demonstrated their value as a management tool (Brook and others 2000). One study that made use of spatially explicit models and specific management plans was conducted by Liu and others (1995) who examined the potential effects of several management practices on Bachman's sparrow (*Aimophila aestivalis*). This species breeds in open, mature pine stands, which are also being managed for the endangered red-cockaded woodpecker [*Picoides borealis* (Vieillot)]. In their analysis, Liu and others (1995) considered several aspects of management, including thinning, burning, and harvesting. Results indicated that certain harvesting practices, such as clustered harvesting, produced a landscape more favorable to juvenile dispersal and subsequent survival. Age-specific thinning and burning of some stands made them suitable as habitat at an earlier age. One of the important findings of this study is that Bachman's sparrow and red-cockaded woodpecker apparently require very different management, although both species are associated with mature pine stands.

In this system, the threat of habitat resulting from stochastic events is relatively high (Dunning and Watts 1991), which increases the likelihood of extinction because population size is small (Shaffer and Samson 1985).

Another excellent analysis of forest management and population viability was Lindenmayer and Possingham's (1996) study of the endangered Leadbeater's possum (*Gymnobelideus leadbeateri*). This species is associated with ash forests (*Eucalyptus*) in Australia and prefers to nest in large trees that are several hundred years old (Lindenmayer and others 1991). The majority of suitable habitat for this species is designated for timber harvesting, which makes future viability of the species quite uncertain. Using ALEX, a computer program for PVA (Possingham and Davies 1995), Lindenmayer and Possingham (1996) attempted to address some of the issues related to the conservation needs of Leadbeater's possum. They increased the usefulness of their PVA model by incorporating a submodel to account for the spatial and temporal variation in habitat quality. Results indicated that spatial arrangement and size of habitat were important factors in extinction risk. Landscapes that contain fewer but larger patches of habitat are often more suitable for species that depend on old-growth forest, but Lindenmayer and Possingham found that landscapes that contain more and smaller habitat patches are more satisfactory for Leadbeater's possum.

A possible objection to the use of habitat models is they are usually developed for a single species. Using some sort of indicator species may alleviate some, but not all, of the concerns associated with the use of a single nonindicator species. One option is to develop these models for a suite of species, thus capturing the diverse ecological requirements of most of the biota in question. White and others (1997) developed a habitat-based approach to risk assessment; they attempted to quantify the risk of landscape change for all terrestrial vertebrates in a particular county. Landscape changes were largely socioeconomic in origin and thus partly subject to control by county-level zoning restrictions. The first steps in determining the potential impact on biodiversity were to estimate area requirements of each individual species and then to determine the quantity of each habitat type. Six possible future landscapes were generated, with varying amounts of each habitat type in each scenario. Because this was done in a spatially explicit framework, patch size could be determined, and this made it possible to estimate carrying capacity of each patch for each species. Species richness was calculated for each landscape plan. Results indicated that some land use plans were considerably more detrimental to biodiversity than others. While this approach lacks the precision of a single-species habitat model, it undoubtedly requires less data than many others, and this can make it a viable option when workers are attempting to assess the effects on the entire biota.

SUMMARY

Our study illustrates the use of PVA to assess the relative merits of various management alternatives, especially when lack of time or money makes it impractical to collect demographic data. If natural disturbance continues at historic rates for the next 50 years, early successional habitat may not be created rapidly enough to sustain a viable population of CSWA. Managers may have to actively disturb the landscape to provide suitable habitat for species that utilize early successional habitat and are less abundant than CSWA. Species associated with late-succession habitat are likely to see available habitat continue to increase unless the frequency and intensity of disturbance increase beyond normal historical levels. Managers must balance the need for additional habitat for early successional species with the need to maintain suitable habitat for late-successional species.

The approach we have outlined is firmly based on established ecological principles and is well suited for meeting management objectives. Two factors that strongly influence population viability are area of suitable habitat (Laurance 1991) and population size (Pimm and others 1988). Demographic models may be too resource intensive for use in assessing the impact of future landscape changes on an entire biota. Habitat-based PVA does require sound habitat models, and thus an appropriate set of habitat variables as well as reliable distribution data on the target species (Roloff and Haufler 1996). Other concerns related to the use of habitat models have been addressed elsewhere (Beutel and others 1999, Karl and others 2000). We advocate the use of habitat-based PVA in management planning where it is applicable.

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Chapter 27.

Responses of Southeastern Amphibians and Reptiles to Forest Management: A Review

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Abstract—*Forest managers in the Southeast increasingly need information about amphibian and reptile responses to silvicultural practices in order to guide sustainable forestry programs. A review of existing literature indicates that effects of silvicultural practices on herpetofauna often are region- and species-specific, with individual taxa responding positively, negatively, or not at all in the short term. Responses of herpetofauna to forestry likely are influenced by adaptations of taxa to historical disturbance regimes. Few studies have evaluated long-term population or landscape-level implications of silvicultural practices for herpetofauna. Furthermore, many existing studies lack pretreatment data, replication, or appropriate reference conditions. We suggest that future research focus on manipulative and retrospective studies designed to identify forestry practices that successfully blend economic objectives with herpetofaunal conservation.*

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INTRODUCTION

Forests of the Southeastern United States support a rich diversity of amphibians and reptiles (herpetofauna). Of the more than 450 species of herpetofauna native to North America, approximately half occur in the Southeast and roughly 20 percent, are endemic. Over 100 species (45 amphibians, 59 reptiles, excluding sea turtles) have been reported from the Coastal Plain of South Carolina alone (Zingmark 1978). Herpetofauna often are the most abundant vertebrates in forest ecosystems (Burton and Likens 1975, Congdon and others 1986); in the Southeast, they comprise up to 45 percent of vertebrate species, excluding fish (Vickers and others 1985).

Several interrelated factors account for this regional herpetofaunal diversity, including tremendous variability in habitats related to a complex matrix of physiography and disturbance regimes (Sharitz and others 1992). Moreover many species of southeastern herpetofauna exhibit biphasic life histories, occupying both terrestrial and aquatic habitats during annual cycles (Gibbons and Semlitsch 1991).

Increasingly, forest managers are challenged to balance production of forest products with maintenance of environmental quality, management of wildlife habitat, and conservation of biodiversity (Moore and Allen 1999, Sharitz and others 1992). Concerns about even-aged management, and particularly clearcutting, have prompted considerable research on effects of timber harvesting on wildlife. Most research has focused on mammals and birds, and other vertebrates such as amphibians and reptiles have received less attention (deMaynadier and Hunter 1995, Gibbons 1988, Moore and Allen 1999).

Despite their presumed role in forest food webs (Burton and Likens 1975, Congdon and others 1986), potential value as indicators of habitat quality (Dunson and others 1992), and controversy about global amphibian declines (e.g., Pechmann and others 1991), herpetofauna often are not fully considered in forest management decisions (deMaynadier and Hunter 1995).

Questions about the compatibility of forestry and conservation of herpetofaunal biodiversity are driven largely by concerns that both terrestrial and aquatic habitats for many species may be degraded or eliminated in intensively managed forests. In particular, the permeable eggs, gills, and skin of amphibians make them potentially sensitive to changes in both aquatic and terrestrial habitats (Dunson and others 1992). To evaluate these concerns, deMaynadier and Hunter (1995) presented a comprehensive review of available literature about effects of forestry on North American amphibians. Several studies suggested that clearcutting and other forest management prescriptions had short-term impacts on some amphibians, especially salamanders. However, other work indicated that many species (1) were relatively insensitive to forest management, (2) recovered more rapidly after harvesting than previously thought, or (3) responded positively to forestry practices (deMaynadier and Hunter 1995). This literature review revealed that amphibian responses to forest management were complex and often specific to taxa or regions (deMaynadier and Hunter 1995).

Since deMaynadier and Hunter's (1995) review, additional studies have provided new insights about southeastern forestry and herpetofauna. Also deMaynadier and Hunter's (1995) review did not address questions about reptiles, perhaps because of the focus on global amphibian declines (Gibbons and others 2000), or the historical perception that forestry impacts on reptiles generally were neutral or positive (Campbell and Christman 1982, Welsh and Lind 1991). Although evolutionary, morphological, behavioral, and ecological differences between amphibians and reptiles are substantial (Gibbons and others 2000), it is likely that these ectothermic tetrapods will continue to be considered collectively from both conservation and management perspectives (Gibbons and Stangel 1999, Gibbons and others 2000). The purpose of this chapter is to provide an up-to-date overview of information available about responses of amphibian and reptile populations to forestry practices in the Southeastern United States.

OVERVIEW OF LITERATURE ON FORESTRY AND SOUTHEASTERN HERPETOFAUNA

Harvesting and Silviculture

Presumably the microclimatic, vegetational, and structural changes that occur after timber harvesting, and clearcutting in particular, create unsuitable conditions for moisture- and temperature-sensitive amphibians. DeMaynadier and Hunter (1995) reviewed potential negative effects of harvesting on microhabitats correlated with amphibian species richness and abundance. Timber harvesting removes forest canopy, and so causes increased light penetration that results in higher soil temperatures and more evaporative loss of water from the soil and understory. Cover, in the form of leaf litter, coarse woody debris (CWD), and understory vegetation may be reduced following clearcutting and associated site preparation activities (Hunter 1990). Clearcut areas also are subject to greater daily fluctuations in temperature and humidity, and to increased soil surface disturbance during intensive harvest activities (deMaynadier and Hunter 1995). However, it has been suggested by several authors (e.g., Campbell and Christman 1982, Greenberg and others 1994, Welsh and Lind 1991) that clearcutting and other harvesting regimes often create favorable habitats for heliothermic reptiles adapted to early successional habitats.

Amphibians—Several studies in hardwood forests of the Southern Appalachians appear to support the contention that changes in microhabitats and climate after clearcutting reduce amphibian diversity and abundance, with negative effects most pronounced on salamanders (Ash 1988, 1997; Buhlmann and others 1988; Ford and others 2002; Harpole and Haas 1999; Knapp and others 2003; Petranka and others 1993, 1994). In northern Georgia, stand age was an important factor explaining the abundance and community composition of plethodontid salamanders, e.g., *Plethodon* and *Desmognathus* spp., in cove hardwood communities (Ford and others 2002). In North Carolina, populations of plethodontid salamanders in recent clearcuts were 40 percent of those in undisturbed forested plots, and by the fourth year after harvesting, no salamanders could be found on clearcut sites (Ash 1988). Similarly Petranka and others (1993, 1994) found that plethodontid salamanders disappeared from Appalachian forests after clearcutting and that recovery to preharvest population levels took up to 60 years at high-elevation sites. Hyde and Simons (2001) also reported that effects of disturbance on the diversity and abundance of plethodontid salamanders in the Great Smoky Mountains National Park were still evident after 60 years. Petranka and others (1993) hypothesized that during the last century, clearcutting reduced plethodontid salamander abundance by 70 percent in western North Carolina alone, with current harvest-related losses approaching 14 million salamanders per year.

Three recent studies have evaluated effects of uneven-aged harvesting techniques on Appalachian salamanders. Harpole and Haas (1999) compared abundance of plethodontid salamanders before and after application of seven treatments (understory removal, group selection, two variants of shelterwood, leave tree, clearcutting, reference) in low-elevation hardwood forests in southwest Virginia. They found that salamander numbers were lower after harvesting on the group selection, leave tree, and clearcut sites, but no postharvest differences were detected during the same period on reference or understory removal sites. However, Ford and others (2000) detected no differences in abundance of plethodontid salamanders among group selection treatments, two-aged timber harvests, and uncut control stands in high-elevation, Southern Appalachian hardwood forests of North Carolina. Bartman (1998) did not find that shelterwood harvesting affected salamander populations in the North Carolina Appalachians.

Although it appears likely that diversity and abundance of plethodontid salamanders would decrease after clearcutting, Ash and Bruce (1994) and other authors (Ash 1997, Johnson and others 1993) argue that available data do not indicate that the long-term losses predicted by Petranka and others (1993, 1994) have occurred. For example, Ash (1997) determined that plethodontid salamander populations on previously clearcut sites in the mountains of western North Carolina returned to 100 percent of those in nearby unharvested forests within 24 years of cutting, rather than the 60 years reported by Petranka and others (1993). Harper and Guynn (1999) also reported that plethodontid salamanders appeared to recover relatively quickly from clearcutting, with salamander densities in stands 13 to 39 years old ($\bar{\chi}$ = 21 years) equal to those in older (≥ 40 years) stands.

Responses of amphibians to forest management in other physiographic regions of the Southeast are more complex, with studies reporting individual species increasing, decreasing, or not changing in abundance after clearcutting (Clawson and others 1997, O'Neill 1995, Pais and others 1988, Perison and others 1997, Russell and others 2002b). Perison and others (1997) reported that the overall abundance of amphibians was lower in clearcuts than in forested stands in the upper Coastal Plain of South Carolina, but they found that certain species, such as green treefrogs (*Hyla cinerea* Schneider) and eastern narrowmouth toads (*Gastrophryne carolinensis* Holbrook), were more abundant on clearcut sites. In Alabama, Clawson and others (1997) found that clearcutting of forested floodplains along blackwater streams had little impact on the total abundance of amphibians, but species evenness changed almost immediately after harvesting. Significant declines of two-lined salamanders (*Eurycea cirrigera* Green) and gray treefrogs (*H. chrysocelis* Cope) on clearcut sites were offset by increases of several species, including southern cricket frogs (*Acris gryllus* LeConte), southern toads (*Bufo terrestris* Bonnaterre), and eastern narrowmouth toads. Abundance and richness of several frogs and toads (anurans) increased at temporary wetlands in Florida (O'Neill 1995) and South Carolina (Russell and others 2002b) after clearcutting of surrounding upland pine plantations. Foley (1994) reported that clearcuts in eastern Texas supported fewer marbled salamanders (*Ambystoma opacum* Gravenhorst) than did unharvested controls, but timber harvesting had no effect on numbers of smallmouth salamanders (*A. texanum* Matthes). In a manipulative experiment, Chazal and Niewiarowski (1998) found no significant differences in the number of captures, body mass and length, or clutch size of pond-breeding mole salamanders (*A. talpoideum* Holbrook) after 6 months exposure to a 4-month-old clearcut and a 40-year-old pine stand (animals were captured at an isolated wetland breeding site and placed in 100-m^2 pens installed after timber harvesting).

Limited evidence suggests that species composition and structure of stands influence diversity and abundance of amphibians in southern forests. Means and others (1996) speculated that conversion of natural longleaf pine (*Pinus palustris* Mill.) stands to slash pine (*P. elliottii* Engelm.) plantations in Florida eliminated populations of flatwoods salamanders (*A. cingulatum* Cope). In the Coastal Plain of South Carolina, Bennett and others (1980) and Hanlin and others (2000) found that the density of amphibians was significantly higher in natural oak-hickory habitats than in previously clearcut even-aged slash pine plantations. Some researchers have speculated that because habitat features which affect the abundance of amphibians, such as soil acidity, leaf litter depth and type, hardwood shrub abundance, and CWD, may be reduced in conifer plantations, these stand types may be inhospitable for many species of amphibians (Bennett and others 1980, deMaynadier and Hunter 1995, Pough and others 1987). However, Hanlin and others (2000) found that pine plantations actually supported higher amphibian diversity than did hardwood stands. Grant and others (1994) also reported relatively high amphibian diversity in Coastal Plain pine plantations, with intermediate-aged (8 years old) intensively managed loblolly pine (*P. taeda* L.) stands having higher amphibian diversity than recently clearcut (1 to 3 years old) and older stands (26 years old). Grant and others (1994) hypothesized that the greater structural and vegetational complexity of intermediate-aged stands, particularly near ground level, could explain differences in species diversity. They suggested that maintenance of stand structural diversity is critical for sustaining herpetofaunal communities in managed forests of the Southeast, but this hypothesis remains to be tested.

We believe that taxonomic differences among amphibians and habitat differences among physiographic regions largely explain the divergence between results of studies conducted in the Southern Appalachians and those conducted elsewhere in the Southeast. Populations of plethodontid salamanders often decline after timber harvesting, but anurans often respond favorably to harvesting in Coastal Plain forests. Plethodontid salamanders are lungless and entirely terrestrial (Duellman and Trueb 1986) and these traits may make them sensitive to changes in microclimate and microhabitats after harvesting (deMaynadier and Hunter 1995). Results of studies from other regions of North America support the supposition that plethodontids may experience greater population declines after timber harvesting than other groups (deMaynadier and Hunter 1995).

Anurans have higher operating and tolerance temperatures than do salamanders, and they have the ability to store and reabsorb large quantities of water in the bladder, e.g., 20 to 30 percent of body mass (Duellman and Trueb 1986). These characteristics may explain their tolerance to warmer conditions found in harvested stands (deMaynadier and Hunter 1995). Unlike plethodontid salamanders inhabiting Appalachian forests shaped by relatively small-scale and low-intensity natural disturbances (Brose and others 2001, Sharitz and others 1992), amphibians in the southeastern Coastal Plain presumably are adapted to the high-intensity natural disturbances, e.g., stand-replacing fires, hurricanes, that characterize this region. In much of the Coastal Plain, elevated water tables, increased soil saturation, and ruts created by tree removal, skidding, and bedding often create standing water in clearcuts (Cromer and others 2002, O'Neill 1995, Perison and others 1997). These fish-free pools, which are often numerous after heavy rains, apparently attract more anurans to clearcuts than are attracted to unharvested stands (Clawson and others 1997, Cromer and others 2002, O'Neill 1995, Perison and others 1997, Russell and others 2002b).

Reptiles—Terrestrial reptiles generally are thought to benefit from the early successional habitats created by forest management (Campbell and Christman 1982, Welsh and Lind 1991), but in reality they do not respond to harvesting as a cohesive assemblage. Studies in Florida sand pine [*P. clausa* (Chapm. ex Engelm.) Vasey ex Sarg.] -scrub habitats have shown that many reptile species respond favorably to even-aged forest management (Campbell and Christman 1982, Greenberg and others 1994), leading these authors to suggest that properly managed clearcutting is sufficiently similar to the effects of historic high-intensity wildfires so that its use can be recommended for maintaining early successional habitats for reptiles. The integrity of these open-scrub reptile communities is diminished by forest maturation, and clearcutting appears to create important microhabitat features such as patches of bare sand (Greenberg and others 1994).

Although numbers of several lizard species increased following clearcutting in eastern Texas, no changes were detected for several other reptiles (Foley 1994). Clearcutting adjacent to bottomland hardwood stands in the upper Coastal Plain of South Carolina generally increased richness and abundance of reptiles relative to richness and abundance in forested stands (Perison and others 1997). However, at least two reptile species, ringneck snakes (*Diadophis punctatus* Linnaeus) and eastern musk turtles (*Sternotherus odoratus* Latreille), were more abundant on unharvested plots (Perison and others 1997). Seldom encountered in habitats lacking cover, ringneck snakes are among those southeastern reptiles associated with deep litter or other surface objects in mesic hardwood or hardwood-pine forests (Gibbons and Semlitsch 1991). Russell and others (2002b) also found that clearcutting adjacent to Coastal Plain isolated wetlands temporarily reduced numbers of several turtle and snake species, including black racers (*Coluber constrictor* Linnaeus), but no effects were evident by 2 years after harvesting. Although black racers are common in early successional habitats, clearcutting temporarily eliminated or disturbed understory vegetation and woody cover that served as refugia and nest sites.

Although effects of forest management on southeastern reptiles have not received the same attention as those on amphibians, available data suggest that reptile responses also are species- and region-specific. The response of an individual reptile species to harvesting is influenced by a variety of factors including the degree of habitat specificity, the spatial scale at which the organism selects its habitat, the morphology and physiology of the organism, and numerous other biotic and abiotic factors. Thus clearcutting may be sufficient to create the open habitats favored by many southeastern reptiles, but insufficient to create habitat suitable for others unless forested patches or CWD are retained.

Roads and Skidder Ruts

Many forestry operations incidentally create aquatic habitats that are used by herpetofauna for reproduction, foraging, and cover. Examples of such habitats include pools along logging roads and machinery ruts within stands. However, these activities can alter hydrological processes and damage natural aquatic habitats (deMaynadier and Hunter 1995). Because the reproductive strategies, e.g., timing, of many amphibian species are adapted to fluctuating hydrology, an increasing concern is that these artificial aquatic habitats may act as population sinks for amphibians if seasonal drying occurs too rapidly (reproductive failure) or not at all (permanent habitat for predators). To date, only two studies have evaluated effects of roads and harvest skidder ruts on southeastern herpetofauna. Adam and Lacki (1993) documented widespread use of forest road-rut ponds for breeding by eight species of salamanders and anurans in Kentucky. Road-rut use was positively associated with surface area, depth, and water clarity, but negatively associated with detrital coverage. More recently, Cromer and others (2002) compared herpetofaunal communities in recently harvested gaps, skidder trails, and undisturbed depressional wetlands to assess effects of group selection harvesting and skidder traffic on herpetofauna in a South Carolina bottomland hardwood forest. Total species richness and abundance were similar among gaps, skidder trails, and undisturbed bottomland depressions. However, salamander abundance, especially for pond breeding *Ambystoma* spp., was negatively correlated with pronounced rutting from skidder trails. The characteristic ephemeral hydrology of bottomland depressions was altered in the harvested gaps and along skidder trails to produce perennially flooded ponds. This created permanent habitat for several aquatic and semiaquatic species of amphibians and reptiles that dispersed from bottomland depressions during periods of drought. However, the skidder-trail ruts also supported fish and invertebrate predators whose populations in the natural depressions typically are controlled by annual droughts.

Although selective harvesting techniques have been recommended as an alternative to clearcutting as a means of protecting forest herpetofauna (deMaynadier and Hunter 1995), these approaches may require repeated stand entries with additional ground disturbance and may create more roads and ruts than do even-aged regeneration methods. The artificial aquatic habitats created by these activities may have significant implications for habitat selection, and effects on reproductive success and survival of herpetofauna should be evaluated.

Site Preparation

Mechanical treatments—As deMaynadier and Hunter (1995) noted, generalizations about the effects of clearcutting on herpetofauna can be misleading because a wide range of site preparation techniques are associated with even-aged management. For example, intensive mechanical site preparation is used extensively in the Coastal Plain to expose seedbeds and remove competing vegetation prior to replanting, but is rarely employed in Appalachian forest management. Unfortunately, few studies have specifically examined effects of postharvest mechanical site preparation on southeastern amphibians and reptiles. The available literature suggests that these activities can, at least temporarily, reduce habitat complexity and affect some herpetofauna negatively. Although direct mortality is likely for selected species (Dodd 1991, Russell and others 2002b), mechanical treatments typically are applied only once during stand initiation, and intensive mechanical treatments, such as raking, harrowing, disking, chopping, bedding, probably do greater harm by removing leaf litter, CWD, herbaceous vegetation, root channels, and other important microhabitats for herpetofauna (Enge and Marion 1986, Whiles and Grubaugh 1993).

Enge and Marion (1986) compared herpetofaunal populations of three pine flatwoods stands in Florida: a 40-year-old pine stand and two clearcuts receiving minimum (roller-drum chop, bed, plant) and maximum (stump removal, burn, windrow, harrow, bed, plant) site preparation treatments. After treatment, the maximum site preparation stand had less leaf litter, CWD, and herbaceous vegetation, and had a greater percentage of exposed soil, than did the minimum-treatment or reference stands. Amphibian richness did not vary significantly among the three stands, but amphibian abundance was lower in both site preparation treatment stands than in the reference stand. Intensive site preparation reduced abundance and richness of most reptile species, with the largest impact on fossorial snakes. The authors attributed lower reptile abundance in the maximum site preparation clearcut to elimination of CWD and other cover objects that served as refugia and nesting sites. However, intensive site preparation appeared to benefit at least one species, the six-lined racerunner (*Cnemidophorus sexlineatus* Linnaeus), a lizard that prefers open sandy areas.

A limitation of Enge and Marion's (1986) study is that effects of site preparation were not isolated from those of harvesting. Russell and others (2002b) found that when compared to clearcut-only and reference stands, mechanical site preparation of sites adjacent to isolated wetlands in the South Carolina Coastal Plain did not appear to negatively influence amphibians breeding at the ponds. In fact, bronze frogs (*Rana clamitans* Latreille) migrated into wetlands from site-prepared stands in higher numbers in the second year after treatment. Snakes, including black racers, were less abundant within the first 6 months after treatment, possibly in response to physical disturbance of nest sites and reductions in ground cover. These effects were short lived, however, and no effects of site preparation on reptiles were detected in the second year after application.

In addition to removing surface cover, mechanical site preparation may destroy burrows and other subsurface refugia of fossorial herpetofauna. Several studies have documented destruction of gopher tortoise (*Gopherus polyphemus* Daudin) burrows by chopping and other mechanical treatments (Diemer and Moler 1982, Landers and Buckner 1981, Marshall and others 1992, Tanner and Terry 1981), although Landers and Buckner (1981) and Diemer and Moler (1982) observed tortoises emerging from destroyed burrows and either reopening them or excavating new sites. Loss of gopher tortoise burrows to site preparation can indirectly affect other species; at least 332 wildlife species are known to use burrows of gopher tortoises, including several rare amphibians and reptiles (Lips 1991). Soil disturbance from site preparation also has been linked to destruction of Red Hills salamander (*Phaeognathus hubrichti* Highton) burrows in Alabama (Dodd 1991).

Prescribed fire—Prescribed burning is used to achieve a variety of silvicultural objectives including controlling heavy fuel accumulation, exposing mineral soil, releasing available nutrients for seedbed preparation, and controlling insects, diseases, and competing vegetation. A detailed literature review of fire effects (and fire exclusion) on southeastern herpetofauna was conducted by Russell and others (1999) and only a brief summary is provided here. Generally, replacing fire-adapted vegetation with fire-intolerant associations, e.g., hardwoods, in the southeastern Coastal Plain leads to concomitant declines in overall herpetofaunal abundance and diversity. However, it may be appropriate to use prescribed fire in combination with other forestry practices to benefit Coastal Plain herpetofauna by restoring an historic mosaic of successional stages, habitat structures, and plant species compositions in both terrestrial and aquatic habitats (citations in Russell and others 1999). For example, in southern Florida, richness and abundance of herpetofauna consistently were higher in slash pine plots subjected to three different burn intervals (1, 2, 7 years) than in a reference plot protected from burning for 20 years (Mushinsky 1985). Based on these results, Mushinsky (1985) recommended a 5- to 7-year prescribed burn cycle to maintain diverse herpetofaunal communities in southern Florida sandhills.

Available evidence suggests that direct mortality of herpetofauna following fire typically is low and presumably outweighed by maintaining desired habitat features (Means and Campbell 1981, Russell and others 1999). Although fire-induced disturbance may temporarily decrease herpetofaunal diversity within a particular stand, a heterogeneous matrix of stand ages and structural conditions should increase diversity on a broader scale (Greenberg 2002, Greenberg and others 1994, Jones and others 2000, Litt and others 2001). Unfortunately, concerns over crop tree productivity, smoke management, air quality standards, and liability have led to fire exclusion policies that may have significant long-term consequences for herpetofauna in Coastal Plain forests and elsewhere (Russell and others 1999).

Even within fire-adapted southern forests some species of herpetofauna may depend on climax vegetation (Greenberg 2002). Means and Campbell (1981) examined herpetofaunal communities in longleaf pine and shortleaf pine (*P. echinata* Mill.) stands in peninsular Florida that had been burned annually for 60 to 70 years and in an unburned forest that had succeeded to a closed-canopy hardwood association. Three species of amphibians [tiger salamander (*A. tigrinum nebulosum* Holowell), oak toad (*Bufo quercicus* Holbrook), ornate chorus frog (*Pseudacris ornata* Holbrook)] and six-lined racerunners were captured predominantly from the burned pine stands, whereas three amphibian species [marbled salamander, mole salamander, and slimy salamander (*Plethodon glutinosus* Green)] were captured almost exclusively in the hardwood forest. The authors suggested that these differences in distribution reflected adaptations (or lack thereof) of individual species to fire (Means and Campbell 1981).

Almost all studies of fire effects on southeastern herpetofauna have been conducted in Coastal Plain forests (Russell and others 1999), and caution must be exercised when extending conclusions to other areas. Until recently, fire was not considered an important or desirable disturbance regime in mixed-hardwood forests of the Appalachian and Piedmont regions (Brose and others 2001). However, it has been hypothesized that periodic, low-intensity surface fires were crucial for perpetuating these oak-dominated forests for millennia and are necessary to restore such forests (Brose and others 2001). To date, only two studies have investigated prescribed fire-herpetofauna relationships in these areas. Ford and others (1999) found that prescribed fires in the Southern Appalachians had little effect on herpetofauna and concluded that concerns about negative effects of prescribed burning on plethodontid salamanders probably were unwarranted. An ongoing study evaluating the use of prescribed fire to restore oak forests in the South Carolina Piedmont also has not found dramatic negative impacts (Floyd and others 2002).

Other topics needing attention include (1) the combined effects of fire frequency, intensity, and seasonality on herpetofauna; (2) the use of herbicides as a substitute for prescribed fire (Litt and others 2001); and (3) the use of prescribed fire to restore and maintain aquatic habitats of herpetofauna threatened by hardwood succession (Russell and others 1999).

Herbicides—In forestry, herbicides are used for site preparation, for release of crop trees from herbaceous and woody plants, for managing species composition and structure, and for timber stand improvement (Miller and Mitchell 1994). Herbicides may be broadcast across a stand, sprayed in bands centered on rows of trees, or applied to individual woody stems. Individual stems usually are treated by directly spraying foliage, applying the herbicide to the tree bole (or to wounds on the bole), or applying a soil-active herbicide to the ground near the tree.

Documented adverse effects of herbicides on some herpetofaunal life stages include mortality, reduced body mass, failure to metamorphose, decreased stimulatory response of neuroepithelial synapses, chromosomal fragmentation, deformities, and DNA profile abnormalities (citations in Pauli and others 2000). It has been suggested that herbicides are among the causative factors explaining global declines of amphibian populations (citations in Fellers and others 2001). However, these effects generally have occurred at exposure levels above those likely to occur in normal forestry operations. Furthermore, several literature reviews have concluded that commonly used forestry herbicides are not acutely toxic to wildlife because they have relatively low mutagenicity, have no or very weak oncogenetic effects, are rapidly eliminated by animals, do not bioaccumulate, and have a short environmental half life (McComb and Hurst 1987, Miller and Witt 1991). Forestry herbicides also are used infrequently, i.e., many even-aged stands receive only one or two applications during a typical rotation, and most herpetofauna likely are shielded from direct exposure, i.e., by being underground or under vegetation, leaf litter, or CWD.

Because herbicides are designed to kill vegetation, they can affect herpetofauna indirectly by altering habitat. Herbicide effects on habitat vary with soils, structure of the pretreatment plant community, herbicide product used, application rates, timing of application, weather conditions, and other factors. However, herbicide application to individual trees in midrotation or maturing stands often promotes canopy gaps and understory biomass production (McComb and Hurst 1987). When broadcast in regenerating stands, herbicides often temporarily reduce biomass production for one to several growing seasons, and shift the dominant understory vegetation from woody to herbaceous plants (Miller and Witt 1991).

Few studies have documented herpetofaunal response to herbicide-induced habitat changes. Results of those studies, and studies for other wildlife taxa, suggest that herpetofaunal responses are species-specific (Howell and others 1996, Lautenschlager 1993, McComb and Hurst 1987), with individual species increasing, decreasing, or not changing in abundance at the stand level (Cole and others 1997, Harpole and Haas 1999, Lautenschlager and others 1998, Yahner and others 2001). Landscape-level responses of herpetofaunal species to herbicide applications probably depend on the productivity and natural disturbance regime of the landscape (Huston 1999), the extent of the area simultaneously treated with herbicides, the vegetation structure of treated stands and the broader landscape, and other factors previously described.

Whether used alone or with other management practices, e.g., prescribed fire, herbicides may be applied to meet selected management objectives for herpetofauna and other wildlife species. For example, Brooks and others (1993) concluded that any of the three herbicide treatments they evaluated (hexazinone, imazapyr, and picloram + triclopyr) were compatible with the goal of maintaining quality habitat for gopher tortoises. Managers can use herbicides to control nonnative plant species; create snags; manipulate the species composition and structure of understory, midstory, and overstory vegetation; manage the spatial and temporal availability of habitat; and for other purposes (Wigley and others 2002).

Riparian Buffers, Isolated Wetlands, and Terrestrial Corridors

Riparian buffers—Retention of streamside management zones (SMZs or buffers) as a means of conserving biodiversity continues to be a widely debated strategy (Harrison and Voller 1998). Some studies conducted in the Pacific Northwest suggest that unharvested riparian buffers are important for protecting stream- and riparian-associated amphibians from effects of timber harvesting (Corn and Bury 1989, Welsh and Lind 1991). Riparian buffers presumably lessen accumulation of fine sediments in stream substrates, limit increases in water temperatures, and mitigate other negative impacts of soil transport and solar radiation on stream habitats (deMaynadier and Hunter 1995). Little information is available, however, about effects of riparian logging on southeastern stream amphibian communities (Pauley and others 2000). In the Southern Appalachians, salamanders were 50 percent more abundant in SMZs than in adjacent harvested areas (Petranka and others 1993). In the western Piedmont of North Carolina, Willson and Dorcas (2003) found that the relative abundance of stream-dwelling salamanders was inversely proportional to the percentage of disturbed habitat at the watershed scale, but they found no relationship between the relative abundance of salamanders and the percentage of disturbed habitat within riparian buffer zones. Stiven and Bruce (1988) speculated that stream-dwelling blackbelly salamanders (*Desmognathus quadramaculatus* Holbrook) were less abundant in recently logged Appalachian watersheds, and that harvesting also might alter genetic diversity of the affected populations.

In eastern Texas, Foley (1994) found that SMZs retained in clearcuts actually supported higher diversity of herpetofauna than did unharvested reference stands. He and others (deMaynadier and Hunter 1995) have suggested that in addition to protecting aquatic amphibians, riparian buffer strips could also provide an intact strip of forested habitat capable of harboring populations for future recolonization of adjacent disturbed areas. Bowers and others (2000) examined herpetofaunal response to different planting regimes in the Pen Branch corridor, which is associated with a third-order stream on the Savannah River Site in South Carolina. This stream received thermal effluents from a nuclear reactor for over 30 years, and this resulted in the destruction of most riparian vegetation in a portion of the stream's floodplain. Subsequent erosion created a braided stream system with a greatly expanded delta, and restoration of the area began with planting of bottomland hardwood species in 1993. Species diversity of herpetofauna in the unaffected riparian zone was significantly higher than on vegetated islands located between stream braids within the impacted floodplain corridor, and there were also significantly more species and individuals within the riparian zone than in the corridor. According to Bowers and others (2000), these results highlight the importance of the unaffected riparian zone in the faunal recovery of the floodplain.

Recommended streamside buffer widths for herpetofauna in other regions of North America range from 30 to over 100 m (McComb and others 1993, Rudolph and Dickson 1990).

It has been recommended that riparian buffer widths be adjusted proportionally with stream width, intensity of adjacent harvest, and slope (deMaynadier and Hunter 1995). However, we agree with Wigley and Melchiors (1993) that we know too little about empirical relationships between forest management effects and riparian habitat functions to justify our recommending specific stream buffer widths for southeastern herpetofauna.

Isolated wetlands—Although little effort has been devoted to research and management of stream-associated herpetofauna in southern forests, protection of isolated wetland habitats in the southeastern Coastal Plain has received increasing attention. Carolina bays, cypress ponds, and other isolated wetlands, i.e., those with no permanent connections to aboveground stream or river systems, are critical habitats for herpetofauna adapted to seasonal hydroperiods and the absence of predatory fish. Of 29 anuran species native to the southeastern Coastal Plain, 20 breed primarily or exclusively in isolated wetlands (Moler and Franz 1987). Several species of salamanders, e.g., *Ambystoma* spp., also migrate to isolated wetlands for mating and egg deposition but return to upland habitats for the remainder of the year (Gibbons and Semlitsch 1991). In contrast, many Coastal Plain turtles and snakes seek food and cover in isolated wetlands or their peripheries but migrate to adjacent uplands for egg laying and hibernation (Gibbons and Semlitsch 1991, Russell and Hanlin 1999).

Most species of herpetofauna associated with isolated wetlands in the Coastal Plain also use adjacent upland forests, and several authors have recommended, on the basis of anecdotal or retrospective data, that closed-canopy forested buffers or complete exclusion of upland forest management activity is necessary to protect these aquatic habitats and maintain landscape connectivity among wetlands (see citations in Russell and others 2002b). For example, Pechmann and others (1991) speculated that the initial absence and then presence of marbled salamanders at an isolated wetland in South Carolina resulted from regeneration of surrounding upland forests that previously were clearcut and burned. Raymond and Hardy (1991) reported that a clearcut 156 m away from a breeding pond in Louisiana appeared to influence the migratory movements and survivorship of the pond's breeding population of mole salamanders. On the strength of data on movements of several salamander species from isolated wetlands to adjacent upland forests, Semlitsch (1998) hypothesized that a buffer zone encompassing 95 percent of the populations using those upland stands would extend approximately 164 m from the wetland's edge. Burke and Gibbons (1995) estimated that an upland buffer 275 m in width would be necessary to protect 100 percent of the nest and hibernation sites of two aquatic turtle species associated with isolated wetlands.

In contrast, Wigley (1999) reported that retention of an adjacent forested buffer was correlated with the presence of only 1 of 40 amphibian species and 37 reptile species sampled from 444 temporary isolated wetlands across the southeastern Coastal Plain—the pine woods treefrog (*Hyla femoralis* Bosc). Russell and others (2002a) also found that 5 small isolated wetlands (0.38 to 1.06 ha) surrounded by 18- to 25-year-old loblolly pine plantations in the Coastal Plain of South Carolina were used by at least 56 species of herpetofauna, suggesting that these aquatic habitats within managed forests are capable of supporting high herpetofaunal diversity. Although retaining forested buffers around isolated wetlands is widely recommended, to date only Russell and others (2002b) have experimentally evaluated management of upland forest buffers on southeastern wetland herpetofauna. They examined immigration and emigration of herpetofauna from isolated wetlands in the South Carolina Coastal Plain before and after clearcutting and mechanical site preparation of adjacent upland forests. Although harvest treatments significantly altered overstory and ground cover characteristics of upland stands, no treatment-related changes in the overall richness, abundance, or community similarity of amphibian and reptile communities at the wetlands were observed. Only short-term negative effects were observed for turtles and snakes. These taxa were less abundant only within the first 6 months after clearcutting and site preparation, possibly in response to physical disturbance of nest sites and temporary changes in ground cover. No amphibian species showed negative responses to treatments, and the number of bronze frogs at the wetlands increased after treatments. The authors noted that although it is premature to suggest that upland forested buffers surrounding southern isolated wetlands are unnecessary, assumptions about effects of forestry operations on isolated wetland herpetofauna, and management based on such assumptions (Semlitsch 1998, 2000), must be tested in the field.

Corridors—Preston (1962) was among the first to suggest possible conservation benefits of upland habitat corridors. Preston speculated that habitat preserves would become isolated, and that the only remedy was to maintain continuous corridors that would link reserves. Most studies of corridors have examined movement patterns of mammals and birds (Bennett 1990, Wegner and Merriam 1979). The function and conservation value of upland corridors is still debated widely (citations in Harrison and Voller 1998, Ford and others 2000). Although use of corridors to manage amphibians has been advocated (Semlitsch 2000), we are aware of only one study of the effects of retaining upland forest corridors for herpetofauna in the Southeast or elsewhere (Baughman 2000). In this study from South Carolina, three sites were randomly selected for retention of a 100-m wide unharvested forest corridor traversing the length of a clearcut, and one site was assigned as an unharvested reference. Baughman (2000) found that mean numbers of herpetofauna captured entering or within corridors did not differ from mean numbers of herpetofauna captured in harvested areas, and that herpetofauna assemblages and movement rates for corridors were similar to those for the stands from which the corridors were created. Although corridors provided a continuous web of closed-canopy forest across the study landscape, Baughman (2000) emphasized that long-term monitoring is needed before potential benefits of terrestrial corridors for herpetofauna in managed forests of the Southeast can be determined.

Demographic Responses to Management

Although short-term measures of richness and abundance may not be affected by forest management, such measures often are not good predictors of habitat quality (Van Horne 1983), and changes in habitats could have longer term consequences for reproductive success, survival, and dispersal of herpetofauna. Few studies have collected demographic data to determine whether responses to forestry practices are age- or sex-specific. Enge and Marion (1986) reported that although there was no difference between overall frog biomass in forested plots, in clearcut plots, fewer juvenile frogs were captured on harvested sites. Raymond and Hardy (1991) suggested that survival of female mole salamanders was lower than survival of males following clearcutting, whereas Ash (1988) reported that sex and age classes of plethodontid salamanders declined at the same rate after clearcutting. Also, without appropriate marking and recapturing techniques, it is difficult to collect data indicative of true population sizes or to monitor movements of herpetofauna in response to forestry practices (Ash and Bruce 1994). For example, estimates by Petranka and others (1993) of plethodontid salamander mortality resulting from clearcutting are based on the assumption that these salamanders exhibit poor dispersal capabilities and strong site fidelity. Bartman (1998) did not observe dispersal of plethodontid salamanders immediately after logging in North Carolina Appalachian forests, but fates (death vs. dispersal) of herpetofauna after clearcutting and other forestry activities remain poorly known (Ash and Bruce 1994, deMaynadier and Hunter 1995).

Landscape-Level Responses

Although characterizing stand-level responses of herpetofauna to forest management is important, perhaps the most pressing questions are at larger scales (Guerry and Hunter 2002). Some recent studies have characterized herpetofaunal communities at the landscape level. Leiden and others (1999) conducted a broad survey of herpetofauna across an industry-managed landscape in South Carolina. The landscape contained stands in various stand structural classes, including pine plantations. Leiden and others (1999) confirmed the presence of 73 of 102 species of amphibians and reptiles potentially occurring in the landscape (based on range maps). This represented the highest recorded richness of amphibians and reptiles in South Carolina, with the exception of the Savannah River Site, where continuous sampling has occurred since the 1950s (Gibbons and others 1997).

Responses of herpetofauna to forest fragmentation have not been studied as often as have responses of other vertebrates, such as birds. However, a limited number of field studies suggest that isolation of forest patches may influence occupancy of terrestrial habitat in such patches by adult amphibians (citations in Guerry and Hunter 2002). Fox and others (2004) and Shipman and others (2004) censused amphibians and reptiles in four forested watersheds (1500 to 4000 ha each) in the Ouachita Mountains that were managed at different intensities, and thus levels of “fragmentation,” ranging from largely unmanaged to intensive even-aged management. Watershed-to-watershed differences in amphibian richness were negligible, and community similarities were high (Fox and others 2004). The watersheds had similar reptile communities, but the least intensively managed watershed had lower per-plot abundance, species richness, and diversity of reptiles than the others (Shipman and others 2004). This was attributed to dominance by two reptile species in the least intensively managed watershed.

Because many aquatic and semiaquatic herpetofauna use adjacent terrestrial habitats for dispersal, foraging, and refuge, both the proximity of wetlands to terrestrial habitat and the area of terrestrial habitat may influence habitat occupancy. If populations of wetland-associated herpetofauna exhibit metapopulation structure, reduced immigration and emigration rates resulting from disconnection of habitat patches may negatively influence viability (Guerry and Hunter 2002, Joyal and others 2001). In Maine, Guerry and Hunter (2002) found species-specific responses of pond-breeding amphibians to area and proximity of adjacent terrestrial forests. Although the presence and abundance of some species were positively related to forest area and pond-forest adjacency, other species exhibited negative or no associations with one or both of these factors. However, we are unaware of any studies that explicitly evaluate effects of forest fragmentation on either terrestrial or aquatic amphibians in the Southeast.

MANAGEMENT IMPLICATIONS OF NATURAL DISTURBANCE REGIMES

Currently available evidence suggests that southeastern herpetofauna respond in a complex manner to changes in climatic, vegetational, and structural features of stands and landscapes after the implementation or exclusion of specific management practices (such as fire suppression). DeMaynadier and Hunter (1995) argue that herpetofauna generally benefit when forest management prescriptions retain sufficient microhabitat and microclimate elements within stands, and ensure a diversity of habitat types across larger areas. They also suggest that identifying and then minimizing differences between forest management practices and historic patterns of natural disturbance, e.g., retention or creation of microhabitats, will improve conservation of herpetofauna in our managed forests.

We suggest this historic context has often been overlooked by those considering the effects of forest management on southeastern herpetofauna. Current forest management regimes are only the latest in a continuum of forest clearing, intensive agriculture, prescribed burning, forest regrowth, and timber harvesting across the Southeast (Sharitz and others 1992). Prior to human influence, natural disturbances, e.g., fire, hurricanes, windthrow, ice storms, occurring at different frequencies, intensities, and extents depending on physiographic region, controlled the character of southern forests and maintained the stand and landscape diversity essential to support the flora and fauna of the region (Brose and others 2001, Myers and Van Lear 1998, Sharitz and others 1992). Unmanaged southern forests were not a homogeneous blanket of “intact” or “continuous” closed-canopy forest, but rather a heterogeneous mixture of stands of different ages and structural types. Many vertebrates in the South, including herpetofauna, have tolerated and adapted to disturbance events throughout much of their evolutionary histories (Campbell and Christman 1982, Greenberg and others 1994, Russell and others 1999). Thus the complexity and regional nature of herpetofaunal responses to forest management should not be surprising. As Means and Campbell (1981) point out, it is illogical to conclude that herpetofauna associated with southeastern forests are not themselves adapted to local patterns of disturbance. We have found, however, that few studies or management recommendations (Semlitsch 2000) involving responses of herpetofauna to forest management have fully considered the spatial and temporal complexity of forest habitats, including disturbance scales and intensities that species and communities are adapted to. It is absolutely necessary that we understand this context if we are to predict how southeastern herpetofauna will respond to forest management, and if we are to develop efficacious and cost-effective conservation strategies. For example, are recommendations for closed-canopy buffers around isolated wetlands consistent with the existence of the exposed and sparsely vegetated nest sites selected by many turtle species (Kolbe and Janzen 2002)? Management and recovery strategies for herpetofauna that do not recognize the dynamic rather than static nature of southern forests, or those that provide one-size-fits-all solutions, are likely to fail.

CONSIDERATIONS FOR FUTURE RESEARCH

Increasingly, researchers and resource managers are recognizing the importance of herpetofauna within the context of forest management (deMaynadier and Hunter 1995, Dunson and others 1992). However, much remains to be learned concerning effects of forestry practices on southeastern herpetofauna. Currently available data suggest that herpetofauna are influenced both positively and negatively (and occasionally not at all) by management of southern forests, and responses are specific to individual regions, taxa, and management prescriptions. The population and community effects of forest management activities on southeastern herpetofauna are still difficult to assess, though, because of methodological limitations and because a variety of study designs have been employed (deMaynadier and Hunter 1995).

The absence of pretreatment data, replication, and true reference conditions in many studies has limited conclusions about impacts of forestry on herpetofauna (Ash and Pollock 1999, deMaynadier and Hunter 1995, Petranka 1999, Russell and others 1999). Most studies have inferred management effects on the strength of retrospective comparisons of herpetofaunal attributes of harvested and unharvested sites. This approach assumes that the herpetofaunal populations of harvested sites once exhibited characteristics, e.g., abundance, identical with those of populations present on forested reference sites. Baseline data on habitat parameters are necessary if we are to assess the comparability of sites and the extent of postharvest changes. Only six studies investigating effects of forest management on southeastern herpetofauna have employed manipulative designs with pretreatment and posttreatment data, treatment replication, or true spatial and temporal references (Ash 1997, Chazal and Niewiarowski 1998, Clawson and others 1997, Harpole and Haas 1999, Knapp and others 2003, Russell and others 2002b). Also needed are longer-term studies that separate immediate population responses to harvesting from long-term effects on fitness.

The challenge for future studies of herpetofauna-forestry relationships has moved beyond simply documenting the range of harvest effects to successfully blending economic and cultural objectives with those for conservation of herpetofauna by identifying silvicultural prescriptions that retain significant natural components of regenerating stands (deMaynadier and Hunter 1995, Grant and others 1994). Although documentation of the magnitude of silvicultural effects on herpetofauna is increasing, the causal factors that shape the distribution and abundance of herpetofauna in southern forests remain poorly understood. Pioneering work by MacArthur and MacArthur (1961) demonstrated the importance of vegetational structural diversity to avian communities. However, quantitative studies that explicitly examine relationships among structural attributes of forests and herpetofaunal populations in the Southeastern United States are lacking (Grant and others 1994). Studies from the Pacific Northwest and Northeast suggest that structural characteristics and components of forests, particularly those at ground level, e.g., CWD, leaf litter depth and moisture, understory vegetation, are important correlates of herpetofaunal abundance and diversity (Aubry 2000, deMaynadier and Hunter 1995, McComb and others 1993, Pough and others 1987).

Although microhabitat variables such as CWD and leaf-litter depth often increase with stand age, there is a great deal of stand-specific variability related to natural and silvicultural disturbance history, climate, soils, elevation, proximity to aquatic habitats, and other influences (Oliver and Larson 1996). For example, intensive site preparation treatments, e.g., bedding or windrowing, may retard development of stand structure by eliminating cull trees, snags, CWD, and understory species, whereas less-intensive applications that only slightly disturb the soil, e.g., roller chopping, or occasional prescribed burning, may increase diversity and biomass of understory species (Hunter 1990). Thus stand age may not be an accurate delimiter of transitions in stand structural development (deMaynadier and Hunter 1995, Hunter 1990, Oliver and Larson 1996), particularly across regions and ownerships with different methods of harvesting or site preparation.

Approximately 90 percent of southeastern forests are privately owned (U.S. Department of Agriculture, Forest Service 1988), and most of these forests will continue to be managed for economic benefit. We think that information obtained by means of retrospective and manipulative studies that elucidate relationships among stand structural diversity, forest management practices, and herpetofaunal communities can be used to integrate management of these forests with the protection and promotion of herpetofaunal biodiversity. This will be accomplished by approximating the range of natural disturbance events that historically shaped the region's forests. One research approach is to inventory the distribution and abundance of herpetofauna in forest stands with variable structural characteristics and management histories within larger landscapes (Gibbons and others 1997, Wigley and others 2000). Then quantitative models can be developed that relate distribution, abundance, and demographic characteristics of species to specific habitat elements found in managed forests, and eventually integrated into sustainable landscape models that would predict herpetofauna responses to different management scenarios (Wigley and others 2001).

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Chapter 28.

Monitoring Tree Species Diversity

over Large Spatial and Temporal Scales

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Abstract—*The prospect of decline in biological diversity has become a central concern in the life sciences, both around the world and across the United States. Anthropogenic disturbance has been identified as a major factor affecting species diversity trends. An increase in the harvesting of naturally diverse timber stands in the South has become an important issue. The ultimate impact of this high, and increasing, level of disturbance on tree species diversity in forests of the Southern United States is uncertain. We offer a brief review of literature related to major points in the development of species diversity concepts over the last 100 years. This is followed by a case study that makes use of periodic U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis (FIA) data from Mississippi. Our interest, for southern forests, is whether tree species richness has declined, increased, or remained essentially stable over the last 35 years. We find that tree species richness has declined by 11 percent across Mississippi since 1977. However, in FIA plots that had no evidence of harvesting, tree species richness increased by 44 percent since 1967. It is difficult to determine what constitutes a healthy level of tree species richness for particular sample designs and large-scale State surveys. Additional analytical complexity comes from the lack of documentation and knowledge concerning various levels of richness dynamics for large spatial and temporal scale studies.*

INTRODUCTION

Questions about, concerns about, and interests in biological diversity have reached high levels of priority with academics, research scientists, resource conservationists, political decisionmakers, civic leaders, and interested members of the general public (particularly those in the environmental community). Though biological diversity has been of interest to ecologists for many decades, broader popular interest in the subject developed in the 1980s in response to the highly publicized exploitation and deforestation of tropical rain forests (Wilson and Peter 1988). This disturbance takes the form of intensive and extensive timber harvesting and land clearing. Heightened public interest in biological diversity and the decline of tropical forests was reflected in the 1986 National Forum on Biodiversity (Wilson and Peter 1988).

Anthropogenic disturbance on forest land in the United States, and its long-term effects on forest biology, has also received considerable attention (Hunter 1999, Kimmins 1997, Kohm and Franklin 1997, Maser 1994, Noss and Cooperrider 1994, Perry 1994, Szaro and Johnston 1996). The types of disturbance range from permanent clearing, as in the conversion of forest land to urban or agricultural use (in this context permanent may mean only a few years to many decades), to intense and repeated harvesting activity. Increases in timber harvesting in the Southern United States has raised concerns about the long-term sustainable (both productive and ecologically sound) use of the forest resource. The concept of sustainable use is different from its predecessor, sustainable yield, in that equal weight is given to biological, social, economic, and political components, whereas sustainable yield matches levels and rates of harvesting with maximum rates of species production. See Campbell (2002) for more background on sustainability.

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Increases in timber harvesting on private land in the Southern United States have resulted primarily from a combination of consumer demands and reductions in the amount of public-lands timber being offered for contract sales. The latter follows from reductions in the allowable sale quantity [the amount of timber offered for sale on national forests by the USDA Forest Service (Forest Service)]. These reductions in timber being offered for sale can be attributed to issues related to habitat protection (as for the spotted owl in the Northwestern United States), reductions in budget and staff, and increases in the amount of time and money expended in litigation (Kohm and Franklin 1997). The result is that less timber is being removed from national forest lands, particularly in the West. The Southern United States is making up much of the shortfall in western timber production by increasing harvests on forest industry and nonindustrial private forest lands. Currently, the Southern United States accounts for 65 percent of all tree volume harvested in the United States (Smith and others 2001). This is a substantial increase since 1992, when the South contributed 55 percent of all harvested volume (Powell and others 1993).

The issues of sustainable forests and sustainable forestry involve both short- and long-term impacts. An example of short-term impacts would be timber supply shortages while long-term impacts reflect the integrity of forest biology. The latter include, but are not limited to, soil deterioration, habitat destruction and alteration, changes in stand structure, successional interruptions, stand fragmentation, declines in old-growth area, age-class imbalance, changes in species composition, and impacts on overall biological diversity. Noss (1996) has identified seven types of biotic impoverishment in forests. These can be thought of as trajectories of change as the dynamics of natural forest processes are shifted by more intense management. The changes are: older stands to younger stands, structurally and compositionally complex stands to simple stands, large continuous forests to smaller fragmented patches, forest stands that are in close proximity to each other (or are continuous with) to increasingly isolated patches, frequent cool fires to fewer hot fires, few roads to many roads, and stable species populations to more endangered species. Any of these factors may occur independently or in combination.

As forest harvesting activity in the Southern United States continues to increase, decisionmakers will need reliable information that tracks the impact of harvesting on forest resource integrity. In order to evaluate the long-term impact of intense timber harvesting, decisionmakers need to know how tree species diversity and overall forest composition may be affected. The effect an increasing area of artificially regenerated forest stands will have on species diversity over a large area, such as a State, is a related concern. For conservation strategies to be effective, reliable information about species diversity trends must be available. Traditional ecological studies have in most cases dealt with smaller areas. However, extrapolations from small-scale, independent, and scattered studies do not provide adequate and reliable information about conditions and processes over large spatial scales.

The study of biological diversity is not new. This chapter presents a brief chronological review of the diversity concept as it has developed in the United States over the last century. We then discuss preliminary findings of a large-scale diversity assessment for an extensive forest area in the Southern United States, along with considerations that are important when applying such assessments over large geographic regions. A case study based on data from recent forest surveys of Mississippi is used to illustrate a method of tracking tree species richness over time.

HISTORICAL OVERVIEW OF THE DIVERSITY CONCEPT IN THE UNITED STATES

Much of the species diversity work after the 1950s was aimed at devising new mathematical methods for quantifying diversity assessments. This review does not cover the broad range of studies devoted exclusively to that subject. Additionally, a general lack of standardization in the terminology may cause some confusion. In this chapter, we use the terms richness and species diversity interchangeably, but we recognize that richness is one type of measurement attribute describing species diversity (Magurran 1988, Pielou 1974). Richness has traditionally been defined as the number of species occurring in a specific area. This area may be small or large. It is important to understand how the richness measure (or any other species diversity measure) is obtained because results obtained from applying different sample designs to the same sample population have differed considerably (Diserud and Aagaard 2002).

Earlier, the concept of species diversity was regarded as a historical phenomenon related to the accumulation of species over time (Fischer

1960, Wallace 1876, Willis 1922). What is now called the study of species diversity was considered as part of the study of species abundance and species populations. Much of the interest and early work in species abundance was by animal ecologists (Kingsland 1985). The early part of the 20th century also saw the beginning of development of techniques for describing plant communities in quantitative terms. Examples include the works of Clements (1905), Gleason (1920), Cain (1932), and Braun (1935). Oosting (1956) described the difference between two approaches to analysis—descriptive (analytical) statistics and qualitative (synthetic) statistics. Descriptive statistics involved measures of individual stands (the actual concrete community that could be visualized on the ground); qualitative statistics were estimates of measures of several stands in aggregate (the abstract community type composed of disjunct stands).

Jaccard (1912) was the first to demonstrate that there was an increase in the number of species with an increase in area (Goodall 1952). This was later expressed mathematically by Arrhenius (1921). Application of the terms "rich" and "poor" is usually credited to Baker (1918), who recorded the number of species on lake bottoms. Thienemann, a limnologist in Europe, identified three important species-abundant principles: (1) the greater the variety of habitats, the larger the number of species; (2) the more that conditions deviate from the normal optima for most species, the smaller is the number of species that occur and the greater the number of individuals that do occur; and (3) the longer a habitat has been in the same condition, the richer and more stable is the community (Goodman 1975, Hynes 1972). The third of these principles is now known as the stability-diversity hypothesis, and is still studied and strongly debated today.

Elton (1927) and others realized that species numbers and diversity were most likely a part of important principles in plant and animal ecology, but Elton observed that it was not clear what these important principles entailed (McIntosh 1985). Publication of Thienemann's first two principles led other workers to conduct a long series of studies involving species-area relations. Cain (1938) and Preston (1948) were early investigators of species-area curves. The early work dealing with mathematical properties of species-area relations has been reviewed by Connor and McCoy (1979). By carefully counting species, several investigators were able to demonstrate that species were organized into predictable compositions (at least at the guild level) and structures (Gleason 1922; Preston 1948; Williams 1944, 1953). Many early works showed that a majority of species were rare and less abundant, and that only a few species were dominant or very abundant. Ecologists soon found it was not possible to conduct a census of an entire biotic community and that patterns of dominance and species abundance would have to be detected by sampling (Golley 1993). Graphing the number of species observed against the number of individuals on a logarithmic scale often produced a straight line. Supposedly, the slope of this line was a measure of the species diversity of the community (Fisher and others 1943). Pielou (1977) states that this approach to species diversity analysis was first introduced by Fisher in 1943. Margalef's later work (1958) was instrumental in the popularization of the phrase "species diversity" among ecologists (Green 1979). Although much work had been done on species diversity up through the 1950s, no ecology textbooks of the 1940s and 1950s, with the exception of Odum's textbook (1959), even mentioned the term "diversity" (Schluter and Ricklefs 1993).

In 1969, the famous Brookhaven Symposia in Biology maintained that the continuity and sustainability of life systems appeared to be associated with the number of species per unit of area (Wolda and others 1969). This meeting also ensured the popularization of the term "diversity." By the late 1960s the study of diversity was expanding, involving not only the number of species but also the proportionate distribution of individuals (evenness) and the consequent development of a myriad of diversity indices. This period also marks the beginning of a significant number of diversity study contributions to the literature. Lloyd and Ghelardi (1964) are credited with introducing use of the term "evenness" in the context of diversity (Krebs 1989).

The beginning of the modern era of quantitative ecology has been attributed to MacArthur (McIntosh 1985). Building on Preston's work (Preston 1948) concerning the canonical distribution of species, MacArthur and Wilson expanded upon Preston's idea as the basis for their seminal book "Theory of Island Biogeography" (1967). Ideas developed in this book essentially set the stage for much of the ecological work over the next two to three decades. Many workers in either plant or animal ecology borrowed and built upon MacArthur's ideas and work related to species-area and species-distribution phenomena.

The literature related to species diversity studies and technique development over the last several decades is voluminous. Many papers in the literature have dealt with the development of new and improved measures of diversity. Several papers and books are considered seminal and helped clarify and resolve certain issues pertaining to the problems of measuring and analyzing species diversity data. Examples are Pielou (1969, 1975), Peet (1974, 1975), and Hurlbert (1961). A comprehensive summary of the diversity literature, prior to 1979, has been prepared by Dennis and others (1979).

Diversity analysis was incorporated into many ecological studies after the 1960s, and increases in tropical forest land clearing and growth of the environmental movement stimulated interest in species diversity along with genetic diversity, habitat diversity, landscape diversity, and ecosystem diversity. In the United States, questions were raised about the management of national forests. One particular concern was the conversion of hardwood stands to pine stands. To address this concern, language identifying the need to preserve natural diversity was written into the National Forest Management Act of 1976. An important workshop addressing this issue was held in 1982 (Cooley and Cooley 1984).

Prominent biologists were quick to address global threats to diversity. This resulted in the National Forum on Biodiversity, which took place in Washington, DC, in September 1986 (Wilson and Peter 1988). The published proceedings of this meeting were distributed widely and quickly brought national and international attention to the potential problem of declining species diversity and the ultimate loss of species through extinction. Since then a followup volume "Biodiversity II" has been published, covering such topics as how scientists study diversity, the status of existing knowledge about life on Earth, and a series of key questions that remain unanswered (Reaka-Kudla and others 1997).

Since the National Forum on Biodiversity, other important conferences have been held. These include the International Symposium of Ecological Perspective of Biodiversity which took place in Kyoto, Japan, in December 1993 (Abe and others 1997); the Symposium on Biodiversity in Managed Landscapes: Theory and Practice, held in Sacramento, CA, in July 1992 (Szaro and Johnston 1996); the Sixth Cary Conference, held in May 1995 at the Institute of Ecosystem Studies, Millbrook, NY (Pickett and other 1997); and the plenary sessions of the 45th annual meeting of the American Institute of Biological Sciences at Knoxville, TN, in August 1994. The last resulted in the publication of a supplementary issue of the journal "Bioscience" (Bioscience 1995). These meetings and published proceedings focused on educating the public about the importance of biodiversity, described the current state of knowledge in particular disciplines, and provided examples of failures and successes in managing ecosystems to preserve biological diversity while maintaining economic viability (Powledge 1998).

Several books about diversity have been published over the last few years. Examples include "Species Diversity in Space and Time" (Rosenzweig 1995), "Species Diversity in Ecological Communities" (Ricklefs and Schluter 1993), "Biological Diversity" (Huston 1994), "Precious Heritage: The Status of Biodiversity in the United States" (Stein and others 2000), "Saving Nature's Legacy: Protecting and Restoring Biodiversity" (Noss and Cooperrider 1994), "Maintaining Biodiversity in Forest Ecosystems" (Hunter 1999), "Ecological Diversity and its Measurement" (Magurran 1988), "The Unified Theory of Biodiversity and Biogeography" (Hubbell 2001), "Global Biodiversity Assessment" (Heywood 1995), "Global Biodiversity: Status of the Earth's Living Resources" (Groombridge 1992), and "Biodiversity: A Biology of Numbers and Difference" (Gaston 1996). All are comprehensive in scope and include sizeable reference sections. Huston's reference section covers 98 pages. The list above is not complete but provides an entrance into the literature.

Although much work has been completed on the theory and concepts of biological diversity, little has been done on the application of this theory to real world problems. The literature is based largely on incidental observations or reports rather than detailed systematic and analytical evaluations. Studies dealing with comparative analysis are valuable and rare (Machlis and Forester 1996).

Most of the studies that have been undertaken were done in small areas that had attracted investigators' attention, mostly because these sites had unusual biotic or abiotic characteristics. The cost in time and money of sampling across areas larger than a few hundred hectares is often prohibitive. Examples of plant patterns and responses to anthropogenic disturbance in forests at a small scale can be found in Grime

(1979), Oliver (1981), and Hunter (1990). Certain workers, such as Sites and Crandall (1997) and Skov (1997), have implemented novel approaches to biodiversity studies. Quantitative studies using systematic and analytical techniques on a large regional scale (an area the size of a State or larger) are lacking (Langer and Flather 1994, LaRoe and others 1995). There have also been requests for the establishment and application of rigorous standardized sampling and analytical techniques for biodiversity assessments (Debinski and Humphrey 1997, Solomon 1979).

Because of the cost and complexity of sampling large continuous geographic areas, very little, and very limited, data (usually addressing only specific resource and conservation issues) are available for large regional studies. Some investigators have taken several local studies and extrapolated the results to a larger area or continental region. One example is a study by Glenn-Lewin (1977) in which richness information data from six temperate forest communities across North America were analyzed for correlations across large spatial scales in species diversity within ecosystem and community structure. Other studies have also followed a similar approach, either by aggregating several local studies scattered across a region or by using abstract information from flora listings by county (Currie 1991, Currie and Paquin 1987, Monk 1967). Although such efforts provide much-needed information, these studies lack rigor because they are based on nonprobability samples and because they have too few plots (from a regional perspective). Additionally, the data come from studies that poorly represent the whole of vegetation conditions and complexes across large areas.

There have been few definitive descriptions of diversity of temperate tree species in relation to disturbance over areas as large as a State. Only one study has attempted to evaluate these relationships over large geographic areas; Stapanian and others (1997) used data from Forest Service Forest Health Monitoring plots, but these data were incomplete because only 14 States were included in the program at the time of the study and because there were fewer than 150 forested plots (on average) for each State. It is questionable whether this small number of initial sample plots is sufficient to represent an area as large and diverse as a State. Additionally, such a small number of plots severely limits any attempt to poststratify the data. Since implementation of the Forest Health Monitoring Program has only recently begun, no adequate historical data are available. Therefore, trend analysis of species diversity is very limited at this time with these datasets.

Beyond the timber supply issue, concerns have been raised about the sustainability of the entire biotic and abiotic forest base. Several recent books have documented the urgent need to alter forest management practices to achieve certain conservation goals (Hunter 1980, Huston 1994, Kohm and Franklin 1997, Noss and Cooperrider 1994, Szaro and Johnson 1996). The Forest Service has adopted and implemented the concept of ecosystem management in order to protect and provide sustainability for all attributes of forests. Foremost in these new approaches to forest management is the concept of managing forests in a way that protects and fosters the establishment of natural biodiversity. With the establishment of the biosphere initiative, the Ecological Society of America has brought the biodiversity problem to the public forum and to the attention of policymakers (Lubchenco and others 1991). Additionally, the dialog has gone beyond the biological aspect of the diversity issue to include and quantify the economic benefits of a diverse natural world (Freeman 1998).

There has been much speculation about the impact of timber harvesting on forest biology, most of it based on studies of small stands. Application of a probability-based sample would provide meaningful insight into the status of any State's forests. Some investigators have concluded that the status of species diversity in U.S. forests has improved dramatically during the last century (Salwasser and others 1992). Others are convinced that the degradation of entire ecosystems is continuing (Noss and others 1994). No studies or rigorous statistics that accurately document the status of biodiversity over large areas in the United States are available (LaRoe and others 1995, Noss and Cooperrider 1994, U.S. Environmental Protection Agency 1990). Therefore, neither claim can be supported rigorously.

Resources for tightly focused large-scale research efforts to evaluate trends in diversity are lacking. Therefore, it seems appropriate to adapt and employ existing large-scale data, particularly if it is rigorously assembled, for the analysis of diversity dynamics. Such data, although originally assembled for use in timber inventory studies and quantitative interpretation, exist in the continuous forest inventory records of the Forest Service, Forest Inventory and Analysis (FIA). These data, which have been collected under conditions that allow their validity to be tested, can be used to demonstrate diversity trends and dynamics over a large spatial scale over a considerable period of time. Below, we analyze such data for the State of Mississippi.

A CASE STUDY OF DIVERSITY TRENDS IN A SOUTHERN FOREST

Data for Mississippi were used as a source of information about changes in tree species diversity over time. The data were from the FIA Program and consisted of field plot data collected over the last 35 years during four survey measurements (1967, 1977, 1987, and 1994). Field plots in which tree harvesting occurred were considered as having undergone experimental manipulation; plots in which there was no harvesting during the four survey measurements were considered the control. This methodology—that of treating natural or anthropogenic disturbance as the manipulation stage of an experiment—is useful in situations in which it is impractical to conduct a true experiment (Hairston 1989, Scheiner 1993).

The study consisted of two phases. In the first phase, all of the plots in the statewide sample were considered without any regard to poststratification criteria. Levels of tree species diversity for the four survey measurements were compared. In the second phase, only sample plots that had not been harvested during the period covered by the four survey measurements were considered. The null hypothesis, that there was no difference in tree species diversity over the four survey measurements made in 1967, 1977, 1987, and 1994, was tested for both the total plot dataset and the undisturbed plot dataset with parametric statistics. The repeated measures analysis-of-variance procedure was used for the tests, with significance established at the 0.05-percent level.

Only trees larger than or equal to 12.7 cm in diameter at breast height were included in the analysis. An overview of the forest survey sample design used in Mississippi has been described by Rosson (2001). The diversity measure used was species richness, defined as the total number of different species occurring on each survey sample unit (field plot). This was a departure from traditional practice, in which the species richness count is typically the sum of different species occurring on all of the sample units. An advantage of analyzing the richness count by sample unit was that this procedure made it possible to utilize parametric statistical tests. Additionally, this methodology reduced the effect of overweighting the loss of one or two species. This was especially important in this study because the low sampling intensity over a large scale means that the forest survey sample design does not adequately sample rare or infrequently occurring species. Preston (1948) has shown how sampling fails to capture the entire spectrum of species. There will always be a percentage of species that occur so infrequently that they will not be detected by sampling. In large-scale assessments it is important that richness measures reflect overall shifts across a State. The occurrence or nonoccurrence of one species on only one sample plot may reflect only a uniqueness of the sample design, and not a biological event.

RESULTS AND DISCUSSION

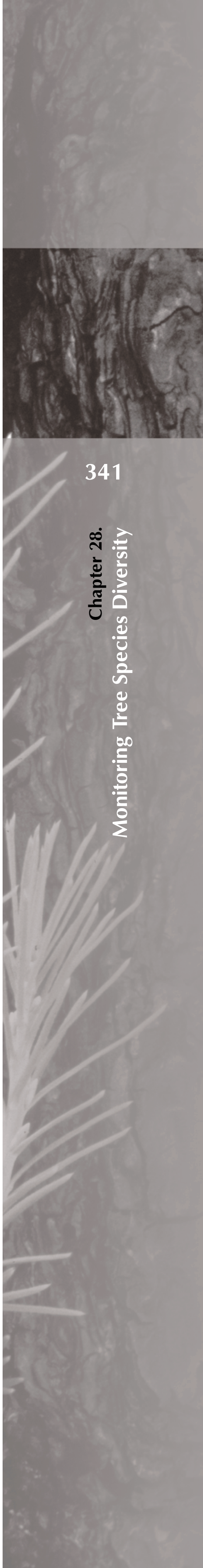
Disturbance Background

Between 1977 and 1994, 4.1 million ha of Mississippi timberland underwent some form of harvesting.[2] A harvest was defined as any harvesting activity in which all, or a high proportion, of the manageable stand was removed, thereby marking the beginning of a new stand rotation. Examples of types of harvests are partial harvests (which would include various selection methods), seed tree, shelterwood, high-grade, and clearcut harvests, as defined by Smith (1962). In addition to these harvested areas, another 0.9 million ha of timberland underwent cutting in an intermediate stand treatment such as thinning or stand improvement.

Of the 4.1 million ha harvested in Mississippi, 1.6 million ha were clearcut (see footnote 2). Clearcutting often has the greatest potential effect on altering tree species diversity. This is because natural stands that are harvested are frequently replaced with monospecific softwood plantations. Management programs typically favor only one species in plantations. In addition, harvest cycles may become shorter and shorter.

The clearcut acreage was spread fairly evenly across Mississippi, with the exception that clearcut acreage was lower in the northwest portion of the State (fig. 28.1) (see footnote 2). Between 1977 and

[2] Rosson, James F., Jr. Current stand characteristics of Mississippi timberland harvested between 1977 and 1994. 21 p. Manuscript in preparation. On file with: Southern Research Station, Forest Inventory and Analysis, 4700 Old Kingston Pike, Knoxville, TN 37919.



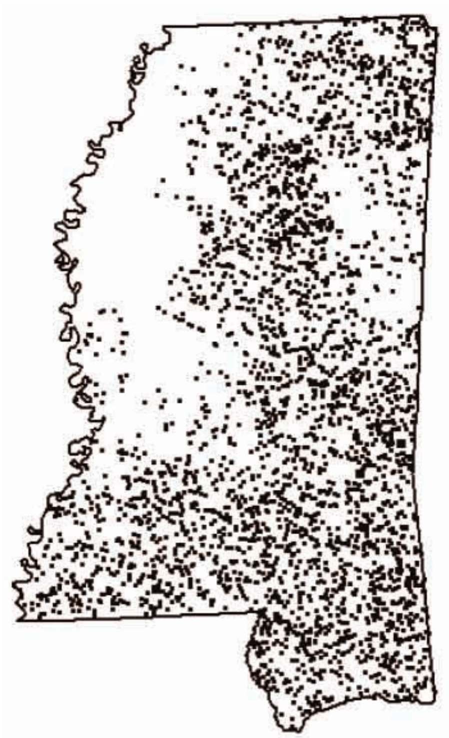


Figure 28.1—Spatial distribution of clearcut timberland in Mississippi. Each dot represents 500 ha of clearcut timberland, harvested between 1977 and 1994. During this period, 1.6 million ha were clearcut.

1987, 0.6 million ha of new softwood plantations were established; another 0.4 million ha were established between 1987 and 1994. Currently, there is a total of 1.7 million ha in softwood plantations throughout Mississippi.[3] The direct effect of these monocultural plantations was to reduce average tree species diversity in the State.

Tree Species Diversity Dynamics

Mean tree species richness estimates, across Mississippi, for all sample units combined were 4.53, 5.02, 4.82, and 4.49 species per sample unit for survey years 1967, 1977, 1987, and 1994, respectively (fig. 28.2). There was not a significant difference between richness in 1967 and richness in 1994 (df = 2,805, $p < 0.0617$). The change in richness from 1977 to 1994 was highly significant (df = 2,805, $p < 0.0001$); note that significant is ($0.05 \geq p > 0.01$); very significant is ($0.01 \geq p > 0.001$), and highly significant is ($p \leq 0.001$) (Sokal and Rohlf 1995).

In contrast, tree species richness means for sample units without any harvesting disturbance were 4.73, 5.86, 6.49, and 6.80 species per sample unit for 1967, 1977, 1987, and 1994, respectively (fig. 28.3). The increase in richness between 1967 and 1994 was highly significant (df = 552, $p < 0.0001$).

Tree species richness for all sample units combined increased between 1967 and 1977. Thereafter, richness declined in every survey

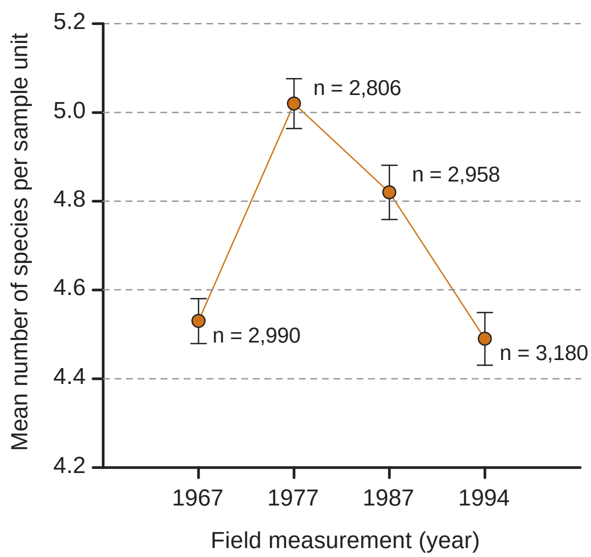


Figure 28.2—Mean species richness per sample unit for Mississippi, by survey year, for all sample units. The error bars represent 2 standard errors of the mean.

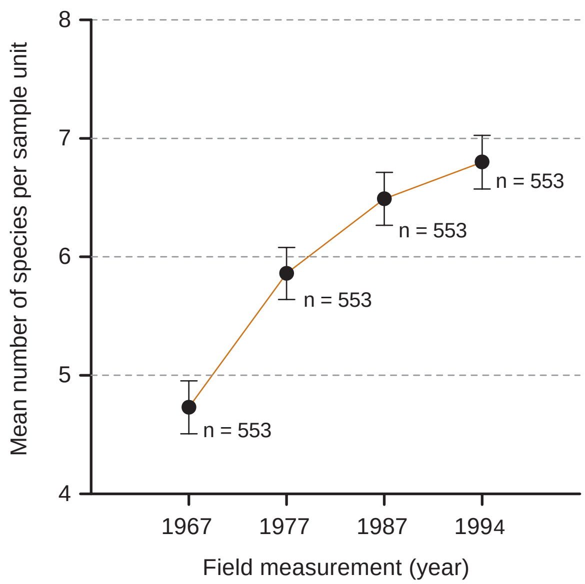


Figure 28.3—Mean species richness per sample unit for Mississippi, by survey year, for sample units that had no evidence of harvesting disturbance during the four survey measurements. The error bars represent 2 standard errors of the mean.

[3] Rosson, James F., Jr. The status of forest plantations in Mississippi, 1994. 30 p. Manuscript in preparation. On file with: Southern Research Station, Forest Inventory and Analysis, 4700 Old Kingston Pike, Knoxville, TN 37919.

measurement. One possible explanation for this was that the forests of Mississippi, within that period, were recovering from the heavy cutting that ended in the 1930s. Species richness had, most likely, been increasing through the decades that followed that cutting. It was during the late 1960s and 1970s that a new wave of timber harvesting began. The peak of more than five species per plot in 1977 (fig. 28.2) may indicate the end of the recovery period and the beginning of a new period of decline in species richness. The analysis is complex because there is no adequate source of baseline data with which to compare results. We do not know what constitutes a normal, healthy level of tree species richness for this particular sample design. The undisturbed sample units were the only applicable benchmark for potential tree species richness in Mississippi, and one should recognize that factors other than harvesting could have affected richness. Examples of such factors might include ownership (and owner objectives), site, and stand history. Moreover, the stage of succession will also affect the number of species per plot. Some forest stands that are in midsuccessional stages may have the highest richness because they contain early, mid, and late-successional species.

Demonstrating a significant difference between means without considering the ecological relevance of the difference may be trivial. Recent literature has emphasized the importance of the distinction between biological and statistical significance (Hilborn and Mangel 1996, Krebs 1989, Scheiner 1993). In our study, we consider the change in tree species richness to be both biologically and statistically significant, based on the following. First, the same sample units were remeasured during each survey year. Second, and most importantly, the sample design remained the same throughout all four measurements. The same sample unit points were remeasured and the same basal-area prism factor was used throughout. It is also very important that the species lists for all the survey periods were the same. This meant grouping some species from the recent, more detailed, surveys to match those of older surveys (when there was less emphasis on tallying species of lesser economic importance). See Rosson (1999) for further details.

Use of remeasured plots helps eliminate much of the variation that is inherent in natural populations. High levels of variation can mask some true biological differences, so reducing this variation as much as possible improves the rigor of the study (Hayek and Buzas 1997, Husch and others 1982). In monitoring studies, the best estimates of variables used to detect change, such as density and basal area, are provided by the use of permanent, remeasured sample units (Bonham 1989). Second, the magnitudes of richness change (usually more than 3 percent), together with the size of the sample and a very low standard error, further support the evidence of real biological shifts in trees species richness. Finally, the comparison of the undisturbed sample units with all the sample units combined empirically supports the overall decline in tree species richness since the 1977 survey measurement.

The fact that tree species richness has increased significantly on sample units without harvesting supports the premise that harvesting disturbance is the major contributing factor in the decline of tree species richness. However, it is important to note that the study did not, nor was it designed to, find a causal agent of decline in richness. The study only points out that tree species richness has declined significantly over time and that concurrent harvesting disturbance is probably a major contributing factor.

There are no established criteria or guidelines for determining what level of tree species richness is too low for an area as large as a State. Also, we do not know the degree to which tree species richness varies naturally. Finally, little is known about the resiliency of mixed forest stands to the disturbances to which they are being exposed. Further work needs to be done in these areas before the results of tree species richness monitoring can be utilized in a rigorous and meaningful manner.

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Chapter 29.

Population Growth and the Decline of Natural Southern Yellow Pine Forests

David B. South and Edward R. Buckner[1]

Abstract—*Population growth has created social and economic pressures that affect the sustainability of naturally regenerated southern yellow pine forests. Major causes of this decline include (1) a shift in public attitudes regarding woods burning (from one favoring it to one that favors fire suppression) and (2) an increase in land values (especially near urban centers). The increase in land values reduces the chance of farmland abandonment, which was common in the first half of the 20th century. Abandoned farmlands provided many of the sites for the naturally regenerated pine stands that are being harvested today. Also, higher land values and higher taxes put pressure on landowners to subdivide their land for development or to establish more profitable tree plantations. These population-related factors and outbreaks of the southern pine bark beetle have resulted in a decline in naturally regenerated southern pines of more than 38 million acres since 1953. As population pressures reduce the incidence of wildfire, prescribed burning, and the abandonment of old fields, the decline in naturally regenerated southern yellow pine will continue. By 2030, only 23 million acres of natural southern yellow pine may remain.*

INTRODUCTION

Population growth is the principal factor placing pressure on forest lands (Barlow and others 1998; Wear and others 1998, 1999). In some cases, the effect is immediate as when naturally regenerated forests are converted to developments, pastureland, rangeland, cropland, plantations, or other uses. In the United States, 11.7 million acres of forests were converted to developed land during the period from 1982 to 1997 (fig. 29.1). Population growth also influences forests in subtle ways that take place over decades. The public generally overlooks gradual changes in species composition, even when millions of acres are affected. Naturally established southern yellow pines[2] are disappearing over Eastern North America. This trend is exacerbated by southern pine bark beetle (*Dendroctonus frontalis* Zimmermann) epidemics.

With the exception of spruce pine (*Pinus glabra* Walt.), southern yellow pines are intolerant of shade, and exposed mineral soil is generally required for their successful establishment. Pines were often the primary tree cover over much of the Southeast when the first historians recorded plant names. However, during the second half of the 20th century, the combined effects of fire

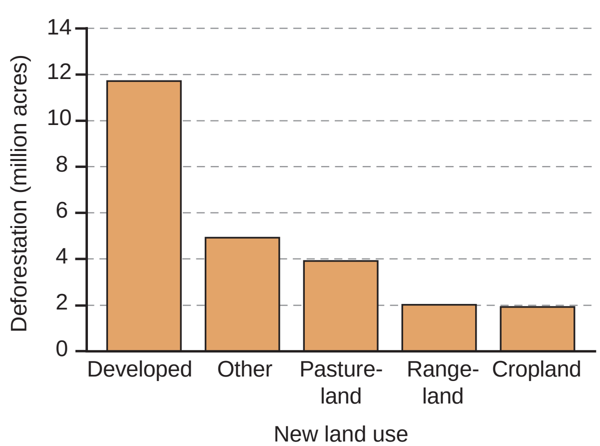

Figure 29.1—The conversion of forested land to other land uses in the United States from 1982 to 1997 (U.S. Department of Agriculture, Forest Service 2001).

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[2] For the purpose of this chapter, the southern yellow pines are defined as eight members of the genus *Pinus* (subsection *Australes* Loud.) plus sand pine and Virginia pine. "Natural" stands of pine are those that are regenerated by seedfall and not by direct seeding or planting.

suppression, increases in naturally regenerated hardwoods, and conversion of old-field pine stands to plantations of loblolly pine (*P. taeda* L.) and slash pine (*P. elliottii* Engelm. var. *elliottii*) have resulted in a decline in natural southern yellow pine timberland[3] from 72 million acres in 1953 to 34 million acres in 1997 (fig. 29.2). In contrast, oak (*Quercus* spp.), hickory (*Carya* spp.), red maple (*Acer rubrum* L.), sweetgum (*Liquidambar styraciflua* L.), and other hardwoods have increased. Oak-pine and oak-hickory stands have increased by more than 25 million acres (fig. 29.3). Pine plantations (many established on former agricultural lands) have also increased by an estimated 30 million acres (table 29.1).

If foresters had not planted pine seedlings and not used herbicides and prescribed burning, we estimate that there would be < 30 million acres of southern yellow pine forests today (instead of 63 million acres). This is because pine plantations are more productive than natural stands. Although plantations represent about 14 percent of the southern forests, they provide more than half of the wood harvested each year.

FIRE AND POPULATION GROWTH

When populations of counties increase, the value of land and timber in those counties increases. Also, the number of houses "in the woods" in the South has increased dramatically since 1950. As property values increase, the need to protect these assets from wildfire increases. The management of fire is related to human population density. South (the author) hypothesizes that the number of wildfire burns of more than 1,000 acres is related to population density. Counties with population densities of < 6 persons per square mile will likely have a higher probability of a regeneration fire than counties with more than 1,000 persons per square mile. In addition, foresters find it harder to conduct prescribed burns as population density increases. The absence of fires discourages natural pine regeneration and allows hardwoods to replace pines.

[3] Natural pine timberland: stands in which 50 percent or more of the volume is composed of naturally regenerated pine and which are capable of producing crops of industrial wood. This does not include pine forests in national parks or other areas that are withdrawn from timber utilization by statute or administrative regulation.

Before Humans

Before humans settled North America, forest fires were started by lightning and occasionally by volcanoes. In the Southeast, southern yellow pines adapted to a variety of fire regimes. Some pines such as pond pine (*P. serotina* Michx.), Ocala sand pine [*P. clausa* var. *clausa* (Chapm. ex Engelm.) Vasey ex Sarg.], Table Mountain pine (*P. pungens* Lamb.), and some pitch pine (*P. rigida* Mill.) genotypes evolved serotinous cones. The chances of successful natural regeneration of these species were strongly tied to fire frequency and intensity. Although the cones of loblolly pine, slash pine, shortleaf pine (*P. echinata* Mill.), longleaf pine (*P. palustris* Mill.), and Virginia pine (*P. virginiana* Mill.) are not serotinous, fires helped to maintain viable populations of these species. Value judgments about species types, stand origin, and timber volumes were not made during this period, as humans were not part of this ecosystem.

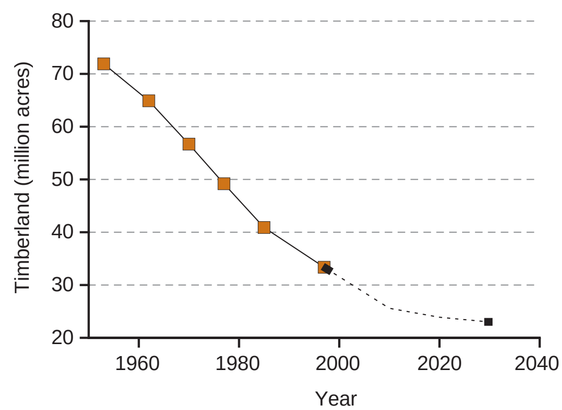

Figure 29.2—Actual and predicted decline of natural southern yellow pine timberland in the South (U.S. Department of Agriculture, Forest Service 1988; Wear and Greis 2002).

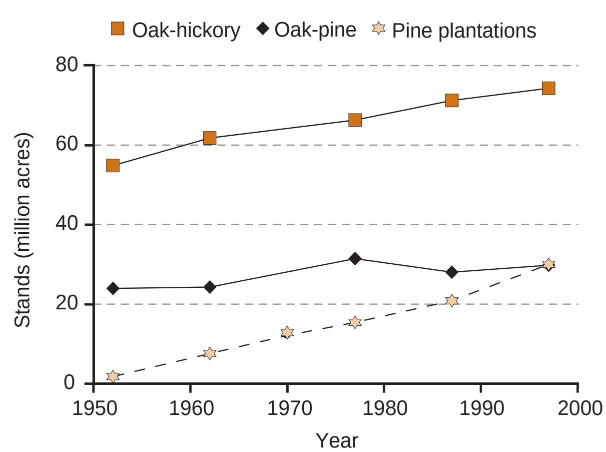

Figure 29.3—Increases in oak-hickory, oak-pine, and pine plantation stands from 1953 to 1997 (U.S. Department of Agriculture, Forest Service 2001).

Table 29.1—Changes in timberland area over a 44-year period for selected species in the United States

Region	Stand type	1953	1997	Change	Change
		- - - - *million acres* - - - -			%
South	Longleaf and slash	26.9	13.1	-13.8	-51
South	Loblolly, shortleaf, and others	51.8	49.7	-2.1	-4
North	Loblolly, pitch, shortleaf, Virginia	3.6	2.3	-1.3	-36
South	Longleaf	12.2	2.8	-9.4	-77
South	Loblolly[a]	35.6	39.1	+3.5	+10
South	Shortleaf[a]	7.8	4.7	-3.1	-40
South	Slash	14.7	10.3	-4.4	-30
South	Virginia, pond, pitch, sand[a]	8.4	5.9	-2.5	-30
South	Southern yellow pine timberland total	78.7	62.8	-15.9	-20
South	Oak-pine	24.0	29.8	+5.8	+24
South	Oak-hickory	54.9	74.3	+19.4	+35
South	Oak-gum-cypress	34.5	28.5	-6.0	-17
South	Oak total	113.4	132.6	+19.2	+10
South	All timberland	204.5	201.0	-3.5	-2

[a] Acreages are estimates made by the authors. Note: Timberland does not include land in national parks or wilderness areas where timber harvesting to produce crops of industrial wood is not allowed due to statute or administrative regulation. The total of forest land and plantations in the South was 226 million acres in 1953 and 214 million acres in 1997 (U.S. Department of Agriculture, Forest Service 2001).
Source: Outcalt and Sheffield (1996); Smith and others (2001); U.S. Department of Agriculture, Forest Service (1988).

Prehistoric Cultural Impacts

As humans moved into North America from Asia 12,000 years ago, they brought fire with them as a cultural tool. They often burned both grasslands and woods. These activities “superimposed a new and extensive fire regime over the existing natural one” (Pyne 1982). Fire was employed to replace forests with grasslands and thereby support grassland browsers as a food source. Fire was also used as an aid to hunting, as a tactical weapon, as a method of weed control, and sometimes in hope of altering weather (Pyne 1982). Blankets were used to extinguish accidental fires in lodges and villages. Backfires were set to keep wildfires from reaching villages. There are no references supporting the idea that early inhabitants of North America suppressed wildfires in forests.

Early European Settlement Fires in the South

European explorers who traveled along the eastern coast of North America frequently saw fires and thick smoke. When Europeans settled along the east coast, most adopted the practice of burning the woods. “Perhaps nowhere else in the country were Indian burning practices more thoroughly adopted and maintained than in the piney woods, in the remote hills, and on the sandy soils . . .” of the South (Pyne 1982). Pyne (1982) further claims that

> Early settlers on the coastal plains learned broadcast burning from local tribes. As they moved inland, crossing some of the premier fire regimes of North America, pioneers carried their fire habits with them. The northern woods might be cleared and settled without fire, but not the southern rough. Skill in broadcast

fire was essential to southern frontier survival: nearly all dimensions of southern agrarian economy relied on it - for landclearing, for hunting and habitat maintenance, and for range improvement. It was employed for fuel reduction in naval stores operations, the antecedent to industrial logging, and it was used by homesteaders to protect themselves from the fires that others were sure to light. Fire protection was even built into the architecture of frontier cabins: the cleared yards around wooden structures acted as firebreaks and as points for igniting protective backfires - doing double duty, as fish ponds did for rural houses in New England. What made the South special, however, was the confluence of economic, social, and historical events that worked to sustain this pattern of frontier economy long after it disappeared elsewhere in the United States, a pattern that created a socioeconomic environment for the continuance of woodsburning.

20th Century Fires in Southern Forests

Even though laws were passed that penalized woods arson, it continued to be a common practice throughout most of the 20th century. With an increase in population, there was an increase in the number of incendiary fires (U.S. Department of Agriculture, Forest Service 1968). The 50-year average (1917–66) for incendiary fires in the South equates to 39 percent of all wildfires. In comparison, the 5-year average (1973–78) for incendiary fires rose to 55 percent (U.S. Department of Agriculture, Forest Service 1980). In 1978, there were 35,850 incendiary fires in the South (U.S. Department of Agriculture, Forest Service 1980). This was far more than occurred in other regions such as the Eastern States (2,589) and the Pacific States (3,135).

As populations grew, the number of people employed to suppress fire also grew. The result was a decline in the total area of woods burned annually. In 1917, 14 million acres were burned on protected areas of the South. By 1999, only about 1 million acres burned annually. Each year, < 0.4 percent of the South's forest land is now burned. The average fire size was about 13 acres in 1978 (U.S. Department of Agriculture, Forest Service 1980).

Over recent decades, public attitudes toward woods burning have changed. As population increased, the acceptability of fire in the environment has decreased. For example, a 1996 survey showed that a majority of respondents disagreed with the statement, "Using fire as a management tool in the national forest is a good idea" (Southern Appalachian Man and the Biosphere 1996). Today, natural and arson fires are rapidly extinguished to protect human investments. Suppression of wildfires has increased to the point that when 7 million acres burn, it is considered a "bad fire year." We certainly do not wish to see our homes and cabins go up in smoke. As a result, few biologists would suggest that forest fires should be allowed to reach a "natural equilibrium."

POPULATION GROWTH AND HARVESTS

The amount of forest land available for timber harvesting in a region is negatively related to the region's population density (Wear and others 1998, 1999). In North Carolina, the percentage of a county in timberland might decline from 70 to 30 percent as the population level increases from 40 to 990 people per square mile (Wear and others 1998). A decline in forest land will reduce both the acreage harvested and the acreage in early stages of natural pine regeneration. In the absence of wildfire and management to obtain natural pine regeneration, a reduction in harvesting will favor succession from pine to hardwoods.

INCREASE IN HARDWOODS

A reduction in the acreage burned results in a decrease in natural regeneration of pines while that of hardwoods increases. Even though relatively few oaks, red maples, or hickories are planted in the South (Boyer and South 1984), there have been large increases in the acreage of upland hardwood stands since 1953 (table 29.1). Since 1953, the increase in oak-hickory and oak-pine stand types totals more than 25 million acres. Ingrowth of hardwoods likely converted 5 million acres of pine stands into oak-pine stands (in which hardwoods make up 50 percent or more of the basal area). Continued aversion to the use of fire and herbicides in pine stands will result in additional conversion of pine stand types to oak-pine or oak-hickory stand types. Currently, the acreage of natural oak-hickory forest type (fig. 29.4) is twice that of all southern yellow pine types combined.

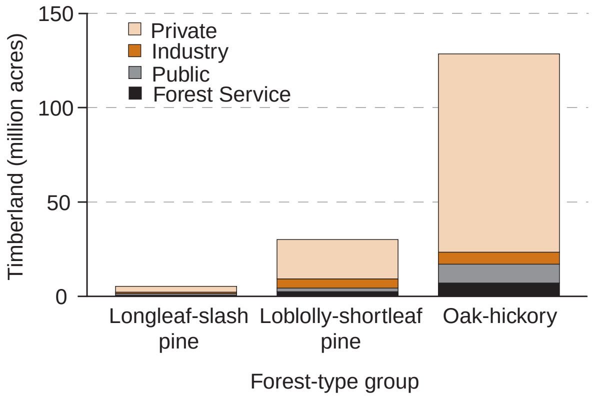

Figure 29.4—Acreage of naturally regenerated longleaf-slash pine, loblolly-shortleaf pine, and oak-hickory forests in the Eastern United States in 1997 by ownership class (U.S. Department of Agriculture, Forest Service 2001).

High-grading is a common harvesting method on private lands. For example, a landowner might remove all of a stand's merchantable pines, leaving 25 percent of the stand's original basal area in low-quality hardwoods. The resulting stand would be reclassified as an oak-hickory forest type. This trend is much greater on lands owned by individuals than on land owned by industry (Alig and others 1986). Since most of the land in the East is owned and managed by private individuals (fig. 29.4), there has been an overall decline in southern yellow pine since 1953 (table 29.1). About 60 percent of the forest acreage harvested annually in the South is harvested by methods other than clearcutting (U.S. Department of Agriculture, Forest Service 2001), but this percentage is higher on privately owned lands. Only about 1 percent of the forest area in the South is clearcut annually (Rudis 1998). Even-aged regeneration harvesting on national forests in the Southern Appalachian region is declining (Southern Appalachian Man and the Biosphere 1996).

Southern pine beetles generally kill pines that are under stress caused by drought or from high-stocking levels or both. Droughts increase the incidence of outbreaks, but overstocking is often the prime factor that weakens the pines (Ku and others 1980). The absence of management practices to control stocking will increase the risk of mortality from southern pine beetles. Recently, thousands of acres of natural pines have been killed throughout the South.

INCREASE IN PLANTATIONS

In 1926, there were only about 3,000 acres of pine plantations in the South. By 1953, pine plantations occupied 2 million acres, and plantation acreage increased to more than 32 million acres by 1999 (Wear and Greis 2002). Today, approximately 17 percent of forest land in the South is in pine plantations. Even though pine plantation acreage has increased by 33 million acres since 1953, pine types have declined by about 16 million acres (table 29.1). This decrease is due largely to the inaction of nonindustrial private landowners (Alig and others 1986) who do not use artificial or managed natural regeneration to maintain their land in pine-dominated ecosystems. Natural regeneration of pines after harvesting can be difficult without fire, herbicides, or mechanical site preparation.

Pine plantations have been established widely on former farmland. The Soil Bank Program was responsible for the stabilization of 1.9 million acres of mostly "worn out" farmland between 1956 and 1961. During the 1980s, the Conservation Reserve Program stimulated widespread establishment of pine plantations. This effort was responsible for the planting of more than 2.6 million acres on farmland. In addition, subsidy programs helped to establish more than 180,000 acres of longleaf pine plantations on farmland. Between 1982 and 1997 more than 22 million acres of afforestation occurred on former pastureland, cropland, and rangeland (fig. 29.5). A large portion of this was from artificial regeneration. Of the 30.3 million acres of pine plantations that existed in 1997, at least 2.7 million acres were afforested through Government incentive programs. We estimate that by 1997, more than 5 million acres of southern

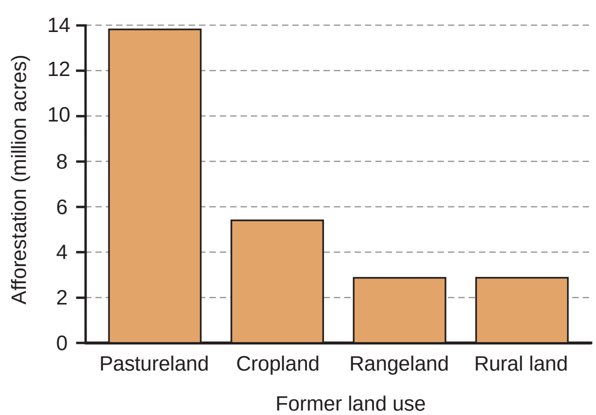

Figure 29.5—The afforestation of nonforested land to timberland in the United States from 1982 to 1997 (U.S. Department of Agriculture, Forest Service 2001).

Table 29.2—Acres of southern yellow pines in the Eastern United States during the 1990s, number of Forest Inventory and Analysis survey plots (data generated from Forest Inventory Mapmaker Version 1.0: run October 15, 2001), and the authors' predicted decline in natural stands for the mid-21st century[a]

Species	Total	Natural stands	Planted or direct-seeded stands	Natural stands	Survey plots	Predicted decline of natural stands
	- - - - - - - - - - - - *acres*	- - - - - - - - - - - -		*percent*	*number*	*percent*
Spruce	39,416	39,416	—	99	7	10
Table Mountain	92,830	92,830	—	100	28	50
Sand	676,321	238,067	438,254	35	276	30
Pitch[b]	854,826	826,462	28,364	97	165	50
Pond	916,474	910,732	5,742	99	361	20
Longleaf	2,819,804	2,346,513	473,290	83	864	45
Virginia	3,424,405	3,163,475	260,931	92	920	50
Shortleaf	5,322,636	4,837,941	484,695	91	1,142	50
Slash	10,722,061	3,335,145	7,386,917	31	3,495	25
Loblolly	39,385,704	17,860,361	21,334,218	45	9,680	35
Total	64,254,477	33,650,942	30,412,411	52	16,938	38

[a] The total decline of natural pine stands is based on predictions by Wear and Greis (2002) and Alig and others (2002).
[b] Assumes no artificially regenerated stands of pitch pine in New Jersey.

yellow pine plantations had been established by afforestation under Government-assisted and nonsubsidized programs. Some predict that an additional 23 million acres of agricultural land will be afforested by the year 2040 (Wear and Greis 2002).

Acreages in plantations and natural stands are listed by species in table 29.2. Loblolly pine accounts for most plantations, and it is also the predominant species in natural stands. In contrast, there are few or no plantations of spruce pine and Table Mountain pine, and their natural stand area is small.

There appears to be a relationship between amount of land supporting a pine species and the amount of young natural regeneration recorded for that species (fig. 29.6). It is often overlooked that pine plantations provide seed trees for regeneration of adjacent areas. For example, although the area supporting natural slash pine stands is about the same as for Virginia pine (table 29.2), there is much more natural regeneration of slash pine. This may simply be due to the existence of about 7 million more acres of slash pine plantations than Virginia pine plantations (table 29.2). Establishing pine plantations on what was previously farmland and on upland hardwood sites increases the chance of subsequent natural regeneration of pines.

The use of prescribed fire is more likely in plantations than in natural stands. During the 1980s, about 54 percent of the yellow pine plantations showed evidence that they had been burned during the past 10 years, while fire effects were evident in only 35 percent of the natural pine stands (Rudis and Skinner 1991). Both

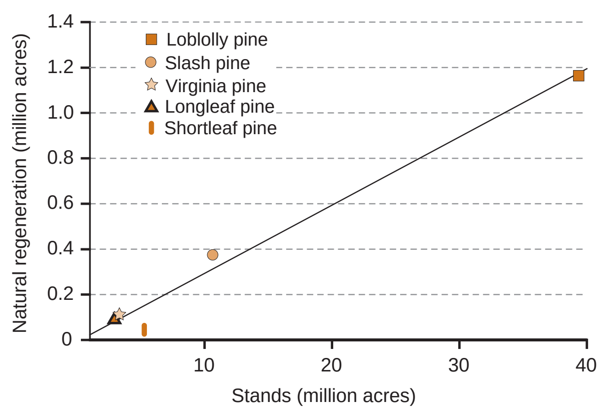

Figure 29.6—The amount of land in pine stands and amount of natural regeneration (age class 1 to 5 years) for five southern yellow pines.

percentages will likely decline as the population of rural counties increases. Public opinion, risk of liability, smoke regulation, and residential developments are important barriers to burning on private lands in the South (Haines and others 2001).

REDUCED PINE REGENERATION

When yellow pine stands remain unburned for about 10 years, hardwoods such as oaks, hickories, and red maple become abundant in the understory (Wahlenberg 1960). Where fire continues to be excluded and no action is taken to reduce the ingrowth of hardwoods, the basal area represented by pines declines as that of hardwoods increases. The area classified as oak-pine (where pine makes up 25 to 50 percent of the stocking) increased by 24 percent between 1953 and 1997 (table 29.1). This accounts for an estimated 5.8 million acres of the decline in natural pine. Approximately 4.5 million acres of pine plantations now have more than 50 percent of their basal area in hardwoods (Rosson 1995).

Since 1953, acreage in oak-hickory stands has increased by almost 20 million acres (table 29.1). Practices that have caused this include (1) fire exclusion, (2) high-grading of pine-hardwood stands, and (3) harvesting of pine stands without replanting pines or implementing successful measures to naturally regenerate pine. In spite of tree planting efforts over the past 44 years, the acreage in loblolly-shortleaf-longleaf-slash pine cover types has declined by more than 15 million acres (table 29.1). Although forest industries plant seedlings to keep their land in pines, practices used by private nonindustrial landowners have favored the conversion of pine stands to hardwoods.

Forest Inventory and Analysis data were used to determine the distribution of stand-age classes for natural stands of several southern yellow pines (fig. 29.7). These data indicate a peak in natural pine regeneration between 1930 and 1950 (equivalent to age classes 40 to 60). A more recent peak during the 1980s can be observed for loblolly pine and slash pine. To some extent it is also evident for longleaf pine. This recent peak may be due to the abandonment of pastureland, and to some extent to the Conservation Reserve Program (which takes cropland out of production). Some of the “natural” regeneration may have occurred on abandoned agricultural fields that were adjacent to loblolly or slash pine plantations.

During the 1990s, the area in natural yellow pine was as follows: 2.3 million acres of longleaf pine, 3.3 million acres of slash pine, 4.6 million acres of shortleaf pine, and 17.8 million acres of loblolly pine (table 29.2). Alig and others (2002) predicted a 38-percent decline for all the southern pines by the mid-21st century. We took their prediction and subdivided it by species (table 29.2).

Spruce Pine

Spruce pine is the rarest southern pine species in terms of total number of trees, total volume, and number of acres. Since supporting data are not readily available, we do not know if the population of spruce pine is increasing or declining. However, the standing volume of spruce pine increased from about 464 million cubic feet in 1963 (Sternitzke and Nelson 1970) to about 587 million cubic feet in 1993. So far, few are concerned about the reproductive success of this species since it is classified as very shade tolerant. In addition, it is highly susceptible to fire and is naturally adapted to areas where fire is infrequent. A small decline in natural spruce pine acreage over the next 50 years could result from development and from utilization of this species as a less expensive source of wood for finishing material.

Table Mountain Pine

Many Table Mountain pines on western and northern exposures have serotinous cones that open only when exposed to high temperatures. Fire exclusion will cause continued decline of this species (Southern Appalachian Man and the Biosphere 1996). Prescribed burning can be conducted to encourage natural regeneration, but only certain types of burns will be effective (Welch and Waldrop 2001). Although prescribed burns may be attempted on public lands where population levels are low, it is doubtful that prescribed burns will be conducted on private lands that are close to residential areas. For these reasons, we believe that this species is the most threatened of the southern yellow pines. Although inventory data suggest that there has been an increase in the numbers of Table Mountain pine (table 29.3), this difference might be related to having a small number of sample plots (28) and the use of sampling methods that do not distinguish between ingrowth and ongrowth. In the absence of major wildfires, a 50-percent decline in Table Mountain pine might occur by 2050.

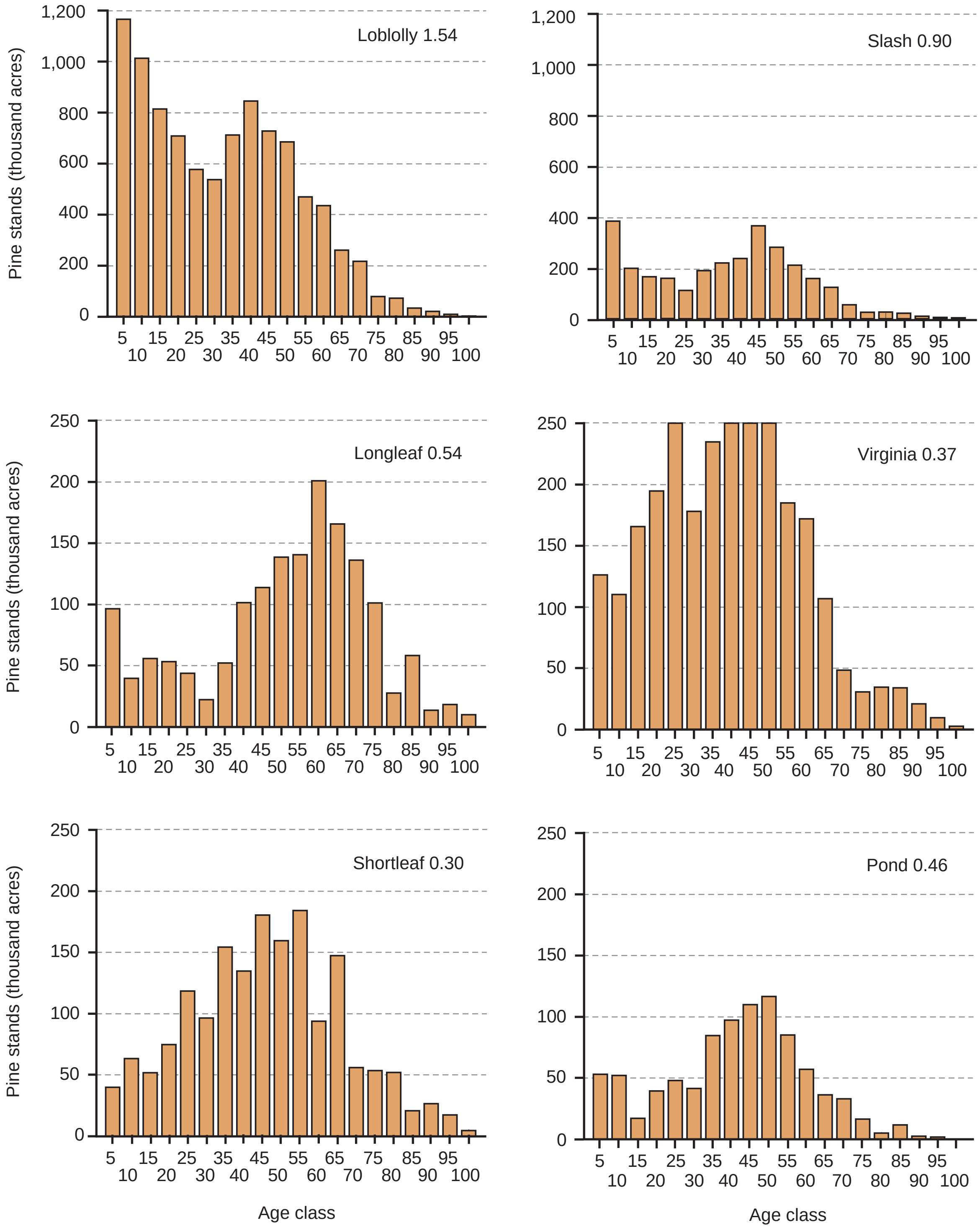

Figure 29.7—Acreage of natural even-aged pine stands by species and 5-year age classes. The number on each graph represents the ratio obtained by dividing the number of acres in the 0- to 10-year age class by the number of acres in age class 41 to 50 years.

Table 29.3—Inventory of Table Mountain pine growing stock by diameter class for two periods

D.b.h. class	About 1977	1989–99
	- - - - - *million trees* - - - - - -	
6	5.6	8.6
8	4.3	5.8
10	2.2	3.7
12	1.4	2.2
14	0.9	1.6
16	0.3	0.4
18	0.08	0.05
20	0.02	0.03

Source: Della-Blanca (1990); 1989–99 data (28 plots) generated from Forest Inventory Mapmaker Version 1.0: run October 15, 2001.

Sand Pine

In central Florida, there are many even-aged stands of Ocala sand pine that regenerated naturally after wildfire. Sand pine was not utilized or planted much before World War II, but planting began around 1956 when 8,000 seedlings were grown at a nursery in Florida (Sampson 1973). Today, more than 60 percent of the stands of sand pine are plantations established mainly by planting. The Choctawhatchee variety occurs in the panhandle of northwest Florida and is rarely planted. Recently, some natural pine stands have been replaced by longleaf pine plantations. Rapid urbanization of the Florida landscape could result in a 30-percent decline in natural sand pine acreage by 2050 (table 29.2).

Pitch Pine

Cones of pitch pine at the north end of its range tend to be serotinous, while this trait disappears in the southern end of the range. In 1978, the National Parks and Recreation Act established 1.1 million acres in New Jersey as the Pinelands National Preserve. Organizations like The Nature Conservancy and the New Jersey Conservation Foundation continue to purchase property within the borders of the preserve while the Pinelands Preservation Alliance alerts the public to developments within the preserve. The New Jersey Forest Fire Service has the task of prescribed burning the Pine Barrens. It will be interesting to learn how effective legislation will be in slowing development and keeping prescribed burning as a tool for managing the Pine Barrens. By 2050, we expect a 50-percent decline in natural pitch pine as a consequence of development.

Pond Pine

Confined to the lower Coastal Plain from Virginia to Florida, pond pine is an ecological enigma. Its serotinous cones and sprouting ability attests to its dependence on fire for regeneration, yet it exists in pocosins and swamps. These traits identify intense fires at long intervals as the primary regeneration vector. The Pond Pine Wilderness Area was established in North Carolina in 1984 and contains 1,685 acres. Because this area is in an isolated location, development will have little effect on new regeneration. However, if intense wildfire is excluded from this region, a gradual decline could occur over the next half century.

Longleaf Pine

Natural longleaf pine has excellent wood properties, and as a result is a preferred species at many sawmills. Good seed crops are infrequent and several years may be required before forest managers achieve successful natural regeneration of longleaf stands. Even when afforestation is attempted on former cropland that has no hardwood competition, success rates are sometimes less than desired. These factors have encouraged landowners who harvest longleaf pine to plant other pine species. As a result, longleaf pine timberland has declined by 77 percent in just 44 years (table 29.1). A Longleaf Pine Alliance has been established to slow the rate of decline. Even though this organization encourages landowners to manage for longleaf pine, we predict that natural longleaf pine will continue to decline as a consequence of fire exclusion and a lack of effort to obtain adequate natural regeneration. We predict a 45-percent decline in acreage of natural stands over the next 50 years (table 29.2).

Virginia Pine

This species was important to the stabilization of badly eroded fields following agricultural abandonment after the Great Depression. Today, many of these naturally regenerated stands are being replaced by hardwoods. Virginia pine will continue to decline over the next several decades, although small groups and individual trees will become established in disturbed areas. Except for use as Christmas trees, planting of this species by landowners is rare. Although there may be over

3 million acres of natural stands today, we predict that fewer than 1.6 million acres will exist by 2050 (table 29.2).

Shortleaf Pine

Shortleaf pine is the most widely naturally distributed southern yellow pine species. Although it is valued as a sawtimber tree, it is rarely planted by forest industry. Also, the planting rate by the U.S. Department of Agriculture Forest Service in Arkansas has been reduced since 1985. Shortleaf pine was often grown at high seedbed densities, and survival of the smaller seedlings after planting tended to be lower than that for larger loblolly pine seedlings. Many areas that supported shortleaf pine have been replanted with loblolly pine after timber harvesting. Although there will continue to be natural regeneration, use of "soft touch" regeneration techniques, such as shelterwood and individual tree selection, will likely result in less natural regeneration of shortleaf than clearcutting and burning. The most recent inventories suggest natural regeneration is about 70 percent less than previously (fig. 29.7). Although individual trees will continue to be found throughout its range, the acreage on which shortleaf pine constitutes more than half of the basal area will continue to decline due to replacement of shortleaf by hardwoods and by loblolly pine plantations.

Slash Pine

Because slash pine has rapid early growth and good wood quality traits, this species has been favored by forest industry in Florida and Georgia, and many plantations can be found outside of its natural range. Many natural stands have been harvested for economic reasons and have been replaced by plantations. Some future stands will develop from seed on areas adjacent to plantations. Although these stands will contain some genes from the genetically improved plantation, future surveys will likely classify these as stands showing no signs of artificial regeneration. While the acreage of natural stands will continue to decline as a result of development, hardwood competition, and conversion to plantations, the rate of decline in acreage of the more common variety of slash pine might be among the lowest of the southern pines. This may be because many new "natural" stands are being established adjacent to existing plantations. However, natural stands of slash pine (var. *densa*) will likely decline due to housing development and low levels of natural regeneration.

Loblolly Pine

It is likely that more seedlings of this species are planted each year than any other tree species in the World. Loblolly does well on a range of site conditions, and trials have shown that at age 20 years, it typically produces more biomass on upland sites in the South than other species with which it has been compared. Into the foreseeable future, it will continue to be the most commonly planted tree in the region. Natural regeneration of loblolly pine appears to be as common now as it was during the 1950s (fig. 29.7), perhaps because loblolly plantations are very widespread (table 29.2).

HERBICIDES IN PLACE OF FIRE

Prescribed burning can keep pine ecosystems viable by suppressing competing hardwoods and preparing seedbeds. The effects of herbicides are not identical with the effects of prescribed fire, but certain herbicides can sometimes substitute for prescribed burning. In some cases, both fire and herbicides are used to manipulate species composition. However, foresters are burning fewer acres each year as population pressures (in the form of clean air regulations, housing developments, and liability suits) are gradually eliminating fire as a management tool. About 4.1 million acres (< 3 percent of our forest land) are prescribed burned in the South each year (Haines and others 2001). Although herbicides could be used to promote natural regeneration of pines, an increase in urban and rural populations will likely limit the use of herbicides around homes, near highways, and even in plantations.

PREDICTIONS

Between 1990 and 2000, the population of Georgia increased by 25 percent. Some predict the population of the 13 Southern States will double between 1996 and 2046, with 70 percent of this increase in urban areas. During this period, the U.S. population is predicted to increase by 67 percent. As the population increases, land values and property taxes will increase, placing additional pressure on pine forests. In some areas annual tax on forest land exceeds $25 per acre. When taxes equal or exceed the revenue landowners get from their natural pine stands, owners will be encouraged to seek ways to make the land more economically productive. Taxation can result in forest fragmentation as forest products companies sell large tracts for residential development

(Flick and Newman 1999). After forest land is transferred to individual private landowners, many will choose not to establish new forests with either natural or artificial regeneration methods.

Population pressures over the South will continue to increase into the foreseeable future. This will result in an increase in forest fragmentation (Rudis 1998). The presence of more houses in forested landscapes will be especially threatening to pine management strategies. Some people living in these new homes will want clean air (no smoke from prescribed burns), no wildfires, no use of herbicides, and no chipping of hardwoods. Some will want to establish forest "preserves," and succession in these preserves will favor hardwoods at the expense of natural pine stands.

Alig and others (1986) reported that natural pine stands in the South decreased at a rate of about 1.2 million acres per year between 1977 and 1985. They predict there will be 20 million acres in natural yellow pine timberland in the South in 2030. This represents a decline of 20 million acres over a 45-year period (or 450,000 acres per year). Others predict a decline of 23 million acres by 2030 (fig. 29.1). The rate of decline is not expected to be as great in the future as it was between 1977 and 1985. Although one computer model suggests the acreage of natural pines might increase by 45 percent by midcentury (Zhou and others 2003), this scenario is based on mathematics and not on the opinions of foresters.

A Longleaf Pine Alliance has been established to help slow the decline in the acreage of longleaf pine. However, we believe that Table Mountain pine is the most threatened of the southern yellow pines. Professor South predicts a "Table Mountain Pine Alliance" will be formed in the future.

We do not expect that important causal factors will change in ways that will favor an increase in the rate of natural pine regeneration. Except for loblolly pine and slash pine, the acreage in new natural pine stands (age class 0 to 10 years) is < 60 percent of that for age class 41 to 50 years (fig. 29.7). This ratio is only 30 percent for shortleaf pine. If these trends continue, there will be significantly fewer natural stands of shortleaf pine, longleaf pine, Virginia pine, and pond pine in the year 2030.

Factors that might contribute to an increase in natural regeneration of pines include large wildfires after droughts, an increase in prescribed burning, an increase in the average rotation age of natural pine stands, a reduction of tree planting after logging of natural pine forests, a reduction in tree planting after wildfires, an increase in the use of herbicides to favor natural pine regeneration, and the abandonment of pastureland or cropland. Pressures from increased urban and rural populations will discourage the implementation of most of these factors. As a result, the loss of natural pine ecosystems will continue at an alarming rate.

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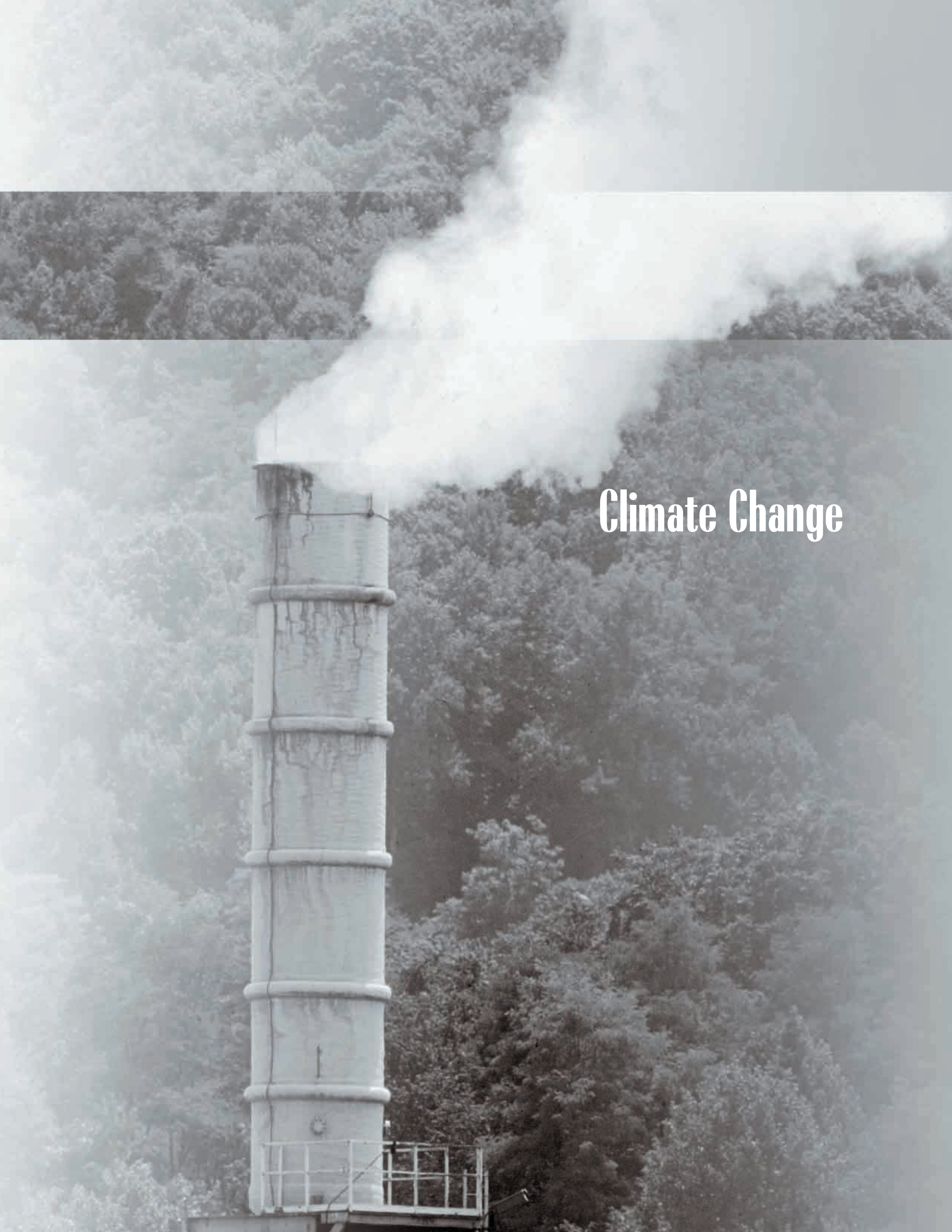

Climate Change

Chapter 30.

Overview of Global Climate Change
and Carbon Sequestration

Kurt Johnsen[1]

The potential influence of global climate change on southern forests is uncertain. Outputs of climate change models differ considerably in their projections for precipitation and other variables that affect forests. Forest responses, particularly effects on competition among species, are difficult to assess. Even the responses of relatively simple ecosystems, such as managed pine plantations, will be affected by complex interactions. Large-scale perturbations, such as rising atmospheric carbon dioxide (CO_2) and changes in precipitation regimes, will interact with site-specific factors such as soil nutrition.

Because making global change predictions is difficult, it may be tempting to ignore the issue entirely and base management and societal planning solely on historical climate and forest responses. However, scientific uncertainty and difficulties in making predictions of system responses are not relegated to this issue alone. Chapters in this book and in the Southern Forest Resource Assessment (Wear and Greis 2002) discuss uncertainties connected with biodiversity, forest productivity, societal demands for forest values, forecasts of future forest type and extent, urbanization, and the relative profit margins of forest vs. agricultural lands. Economic forecasts are particularly uncertain, as responses depend not only on regional supply and demand but also on national and international economic forces that are in great flux. In all these cases, research provides tools to assess past, current, and future system flux so that planning can be based on the best information available. Such planning ranges from the small scale, as when a private landowner considers options for a particular parcel of land, to larger scales, as when States consider regulation of forest-dependent water resources. In almost all cases, science does not provide a definitive answer to a question; rather, it provides probabilities for potential directions and magnitudes of change. In other words, science permits us to assess the spectrum of risks that may be faced.

Clearly, the smaller the scale of inference, the greater will be certainty of predictions, and vice versa. For example, we can have strong confidence how a particular fertilization treatment may impact a stand of trees of a given age, species, and site index, but much less confidence on what effect such a treatment would have on a larger, less refined land base. It is likely the largest uncertainties are associated with issues that may well have the biggest impact on people and ecosystems. Consider some of the major perturbations that have drastically altered the forest landscape of the South over the past century. Chestnut blight {*Cryphonectria parasitica* (Murrill) Barr [formerly *Endothia parasitica* (Murrill) Anderson & Anderson]} rapidly altered the Appalachian forest structure and did so with little warning. Large-scale deforestation [often of longleaf pine (*Pinus palustris* Mill.) or hardwood stands] was followed by intensive agriculture, and in many cases this was followed by natural reforestation to stands largely made up of loblolly pine (*P. taeda* L.). This "introduction" of loblolly pine led to a major forest industry that both owned and with increasing intensity managed forest land and has provided a market for timber and fiber for private landowners. Thus, just over a century ago the forest landscape was one largely dominated by longleaf pine and hardwoods (including chestnut), and loblolly pine was a minor component. Now we have a landscape in which longleaf pine ecosystems occupy 5 percent of their previous acreage (Outcalt and Sheffield 1996) and are the focus of an active restoration effort, a greatly increased proportion of hardwood stands are early to midsuccession, and there are large expanses of pine-hardwood forests and managed pine plantations where loblolly is the most prevalent pine. These examples illustrate two important points. First, southern forest ecosystems can be incredibly resilient to great perturbation. Second, the state of our forests has been and continues to be in rapid flux.

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Global change is predicated due to human-induced increases in greenhouse gases (chiefly CO_2) in the atmosphere. Current increases in atmospheric CO_2 are well documented and are due to the combustion of fossil fuel and other human activities. Atmospheric CO_2 concentrations are currently over 365 parts per million, 35 percent higher than preindustrial values. They are increasing at a rate of about 0.5 percent per year and are predicted to equal or exceed 550 parts per million by the middle of this century (Wigley and others 1996). Thus, the first basic cog in the global change physical machinery is clearly engaged, but the ramifications for potential consequences are in the realm of scientifically derived probabilities. Science, as shown in this book, endeavors to provide systematic methods for evaluating current and anticipated ecosystem function and composition given projected conditions, and to provide information that can guide ecological, economic, and social decisions that are made by landowners, corporations, and governments.

Predictions and discussions of potential global change have existed in both the scientific and political arenas. In the chapter, "Implications of Global Climate Change for Southern Forests: Can We Separate Fact from Fiction?" by Hermann Gucinski, Ron Neilson, and Steve McNulty provide a discussion on discriminating fact from fiction in this polarized debate. They discuss the evidence that global change is currently impacting climate and consider predictions of future climate scenarios. Their major conclusion is that the climate is likely to change given historical climate variation and the possibility that an accelerating greenhouse effect is in progress.

Interestingly, the major greenhouse gas, CO_2, is fundamental to photosynthesis and provides the carbon (C) that constitutes 50 percent of the dry matter of woody tissue. Increasing CO_2 concentration increases photosynthesis, at least in the short run. Most plants, including trees, initially grow faster when CO_2 concentration is increased. Until recently, studies on the growth response of trees were mostly performed using seedlings and saplings, and with only a handful of species, loblolly pine being the most extensively researched (Groninger and others 1999). Recent work indicates that longer-term growth responses of loblolly pine to elevated CO_2 are largely dependent on soil nutrient availability (Oren and others 2001), which also greatly influences belowground C cycling (Butnor and others 2003). Besides research on direct responses to elevated CO_2, forest tree biology knowledge gained through research is being incorporated into models to predict forest responses to changes in environment and/or management.

Because they are major constituents of the landscape, forests can also sequester large quantities of atmospheric C, thus offsetting emissions from fossil fuel burning and thus the rate of increase of CO_2. Again, C sequestration potential has been most evaluated in loblolly pine. Forest C sequestration can be characterized as *in situ* and *ex situ* (Johnsen and others 2001). The former represents C on a forest site in its biomass and soil. Deforestation, reforestation, growth rate, and rotation length can impact *in situ* C sequestration. *Ex situ* C sequestration represents C that remains sequestered in forest products. Various product types (paper, lumber, etc.) have various lifespans before their C returns to the atmosphere via combustion or decomposition.

Forest C sequestration can provide a short- to medium-term offset for atmospheric CO_2 emissions, while potential additional C sinks are filled. Additionally, utilization of woody biomass for bioenergy production can provide long-term offsets, as these partly supplant fossil fuel combustion.

As result of concern about the potential impacts of global change, international policies have been established to reduce total C emissions to a predetermined baseline (Kyoto Protocol) (Oberthür and Ott 1999). Carbon emissions are the algebraic sum of total emissions and C sequestered, again relative to the baseline. Forests are recognized as one of the important avenues for biologically sequestering C. Thus, the concept of C credits has been born. Although the United States has not signed the Kyoto Treaty, industry is still interested in working with C emissions and sequestration as a commodity. In the early to mid-1990s some companies, particularly energy companies, established programs to promote forest C sequestration on private land. They did this so that they could apply these offsets against their own plant emissions. Nongovernment organizations such as The Nature Conservancy have established large forest C sequestration programs throughout the world with a major emphasis on managing for and quantifying C sequestration. Very recently, a large-scale C commodity exchange has been established for the first time in the United States.

Large-scale policy (regional, national, global) requires large-scale analyses. In the chapter, "Forest Carbon Trends in the Southern United States," by Robert A. Mickler, James E. Smith, and Linda S. Heath provides an analysis of aboveground C stocks by forest types in the Southern United States, and the change in composition and extent of these stocks since 1957. This work is based on Forest Inventory and Analysis data and a process model. Mickler and others estimated that approximately 29 percent of the aboveground forest C in the United States occurs in the South. Their analyses indicate that aboveground forest C has increased at the rate of 42 megatons per year from 1957 through 1997. Their analyses also indicate that acreage in private pineland decreased by 18 percent from 1957 to 1997. However, C stocks on this landownership type are estimated to have decreased by only 2 percent. These estimates only hint at the tremendous increase in productivity that has accompanied the continued development of pine plantation forestry over recent decades. Pine forestry has continued to develop and use management tools such as site preparation, fertilization, weed control, and the use of genetically improved material, and the result has been a steady increase in productivity on managed pinelands.

Thus, managed pinelands represent a major opportunity for increasing C sequestration in the South. However, it is clear that any system of C credits will require simple but reliable methods for quantifying C sequestration. As the major industrial forest species in the world, loblolly pine has been the subject of a large body of research, research that has steadily advanced to make possible increased productivity in forest stands. The same body of research, and the fact that pine plantations are relatively simple ecosystems, make loblolly pine plantations a prime target for the implementation of C credits. In the chapter, "Carbon Sequestration in Loblolly Pine Plantations: Methods, Limitations, and Research Needs for Estimating Storage Pools" by Kurt Johnsen, Bob Teskey, Lisa Samuelson, John Butnor, David Sampson, Felipe Sanchez, Chris Maier, and Steve McKeand detail the methodologies and tools required to quantify C on a stand basis, and they identify areas in which important work is still required to improve and reduce the cost of quantifying forest C.

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Chapter 31.

Implications of Global Climate Change for Southern Forests: Can We Separate Fact from Fiction?

Hermann Gucinski, Ron Neilson, and Steve McNulty[1]

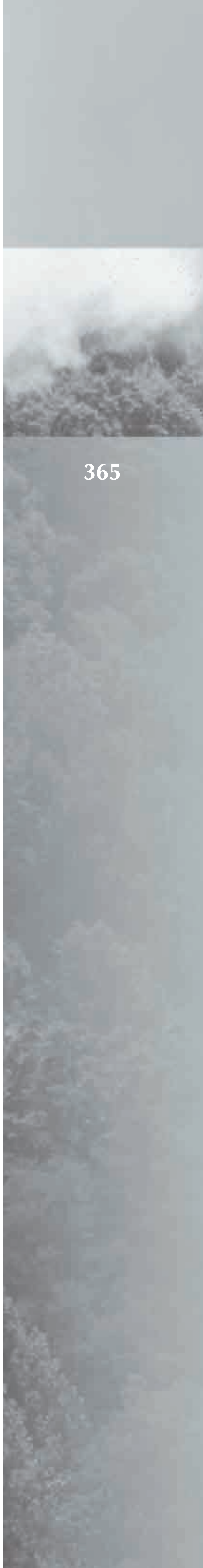
Abstract—*There is no scientific dispute regarding the existence of a greenhouse effect. There is no doubt that water vapor, carbon dioxide (CO_2), and methane concentrations are greenhouse gases. The data showing increases in CO_2 in the atmosphere are incontrovertible. Uncertainties arise when the Earth's biological responses to climate change are to be quantified. Such uncertainties can be compounded when the responses of ecosystems, especially forests, are to be delineated. Complex interactions among effects of climate change, disturbance, competition, invasive species, management intervention, land use change, and other actions must be clarified by modeling. Model development has improved greatly, but evaluation and validation remain difficult. Model outputs for the South show a fairly wide range of potential changes under scenarios developed from different climate models, suggesting that the assumption of steady-state conditions has little likelihood of occurrence. This implies that we should rethink management approaches, design research to include new ecosystem variables, and seek integrated ecosystem knowledge on scales heretofore rarely treated.*

INTRODUCTION

There is persistent skepticism about the evidence that greenhouse warming may be occurring, and this skepticism requires consideration. This chapter is a semitechnical discussion of the issues, and is designed to shed light on the question of climate change without attempting to present new research information or make new interpretations of the research findings.

There is no scientific dispute regarding the existence of a greenhouse effect in planetary atmospheres such as ours (Raval and Ramanathan 1989). Nor is there any doubt that water vapor, carbon dioxide (CO_2), and methane are greenhouse gases (Ledley and others 1999). Moreover, the data showing increases in atmospheric concentration of CO_2 are incontrovertible (Keeling and Whorf 1999, Keeling and others 1989). Lastly, it is clear that the rise in atmospheric CO_2 is largely attributable to the burning of fossil fuels (Andres and others 2000, Carbon Dioxide Information Analysis Center 2000). Does this prove that there will be climate change in the form of global warming? It strongly suggests a change in the Earth's energy balance, but there is no simple yes or no answer to the question about global warming, because the variables that affect the outcome are many, and the interactions between Earth system processes have not been delineated as fully as one might wish.

It is possible to make probabilistic estimates of likely outcomes, and these have been made (Harvey and others 1990, 1997). The Inter-governmental Panel on Climate Change (IPCC) is thought to be the most authoritative scientific body that has assembled such estimates. The acceptance of the IPCC estimates has not been total. Uncertainties remain, and skepticism persists. Because these estimates have vast policy implications, the debate has spilled from the purely scientific area into the arena of public



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debate and governmental policy. The controversy has led august scientific bodies to make strong statements regarding the status of climate change science. In this case a group of National Science Academies, representing 16 countries, say the following (excerpted from http://www.royalsoc.ac.uk/files/statfiles/document-138.pdf):

> The . . . IPCC represents the consensus of the international scientific community on climate change science . . . and we endorse its method of achieving this consensus. Despite increasing consensus on the science . . . doubts have been expressed . . . . We do not consider such doubts justified . . . . We support the IPCC's conclusion that it is at least 90 percent certain that temperatures will continue to rise, with average global surface temperature projected to increase by between 1.4 and 5.8 °C above 1990 levels by 2100 . . . . The balance of the scientific evidence demands effective steps now to avert damaging changes to the earth's climate.

This statement has since been endorsed by the National Academy of Sciences. Figure 31.1 shows the reconstructed temperature record for the past millennium and the recent temperature rise coincident with the era of industrial development.

CLIMATE CHANGE SKEPTICS

Despite the growing scientific consensus, skepticism continues, both in the strictly technical areas, where it is part of the scientific process, and also in the arena of policy development. It is useful to examine the scientific validity of the claims made by the skeptics. These claims have appeared in Web sites [2] [3] and in a book by Lomborg (1999) and can be summarized as follows:

- The present uncertainties in Earth processes overwhelm any confidence in predictions of future climate. The uncertainties might include modeling deficiencies, skewing of temperature records due to "heat island" effects, or the swamping of the small increases in CO_2 derived from fossil fuel compared to the large-scale exchange of CO_2 between the atmosphere and the oceans and land
- Factors other than increases in greenhouse gases are responsible for warming trends; e.g., Milankovich cycle, changes in the sun's energy output
- Radiometric data from satellites and high-altitude devices show no warming

Arguments made on scientific grounds are testable hypotheses, subject to confirmation or rejection. We also see arguments made on policy grounds, or derived from various logical positions, or, at times, logical fallacies. Examples of the latter include the use of the fallacy of "condemning the origin," e.g., climate change arguments are made only by "greens" or radical environmentalists; ergo, the argument must be false, or by discrediting the process ("the IPCC is a United Nations body, hence subject to political conspiracies"). Policy perspectives are not subject to scientific review, but can be examined in the light of precedents, and by examining the assumptions upon which they rest. For example, the argument has been made that expending national resources on mitigating potential climate change is unwise because of present uncertainties. One can investigate the underlying assumptions using Bayesian formal decision theory. Thus, it may be even more likely that the "no regrets" option, i.e., the avoidance of investments to mitigate climate change that will prove costly if no climate change occurs, is not the least expensive, given the risks. Of course, positions derived from self-interest, i.e., having a "personal" stake in the outcome, are not subject to scientific debate, because they bear no relation to the scientific process.

Consider the issue of scientific uncertainties. The IPCC contends that improvements in data collection and processing, model developments, process-level understanding, and improved large-scale consistency of models with observations give a confidence level of better than 90 percent for the statement that 20th-century global temperature increases are the highest of the last 1,000 years. Moreover, the likelihood that temperature increases of the 20th century are not due to climate variability is now estimated at the 99 percent level (Houghton and others 2001). Such convergence of the analysis demands a better scientific response than simple rejection of the climate change hypothesis on the grounds of uncertainty. Hence it is important to distinguish

[2] George C. Marshall Institute. 2002. Homepage. http://www.marshall.org. [Date accessed unknown].

[3] Heartland Institute. 2002. http://www.heartland.org. [Date accessed unknown].

between scientific debate about the implications of the remaining uncertainty, and categorical assertions that uncertainties are large. Moreover, improvements in process-level understanding have largely overcome the difficulty of calculating small differences between large numbers, and signals can be observed despite the large flux of CO_2 between atmosphere, oceans, and the land (Houghton and others 2001).

Factors other than increasing greenhouse gas concentrations in the atmosphere are affecting the total radiative energy reaching the Earth's envelope. Some factors work on cyclical scales far longer than any relevant to the postindustrial emissions era, while others, such as 11-year sunspot cycles, are too short to influence climate change but do confuse the signal (Houghton and others 1994, Lean and Rind 1996). Hansen (1998) asserts that the existing record of solar radiance observation shows variation on the order of 0.1 percent, which translates into a forcing of a few tenths of watts/m^2, whereas the forcing from CO_2 increase over preindustrial levels alone is about 1.4 watts/m^2 (Hansen 1998). The relevant observation is that secular changes are additive to the human-caused fossil fuel-derived effects, and that the total picture needs to be analyzed.

Local anomalies, such as the heat island effect, have been taken into account in the analysis of global surface temperature data. For example,

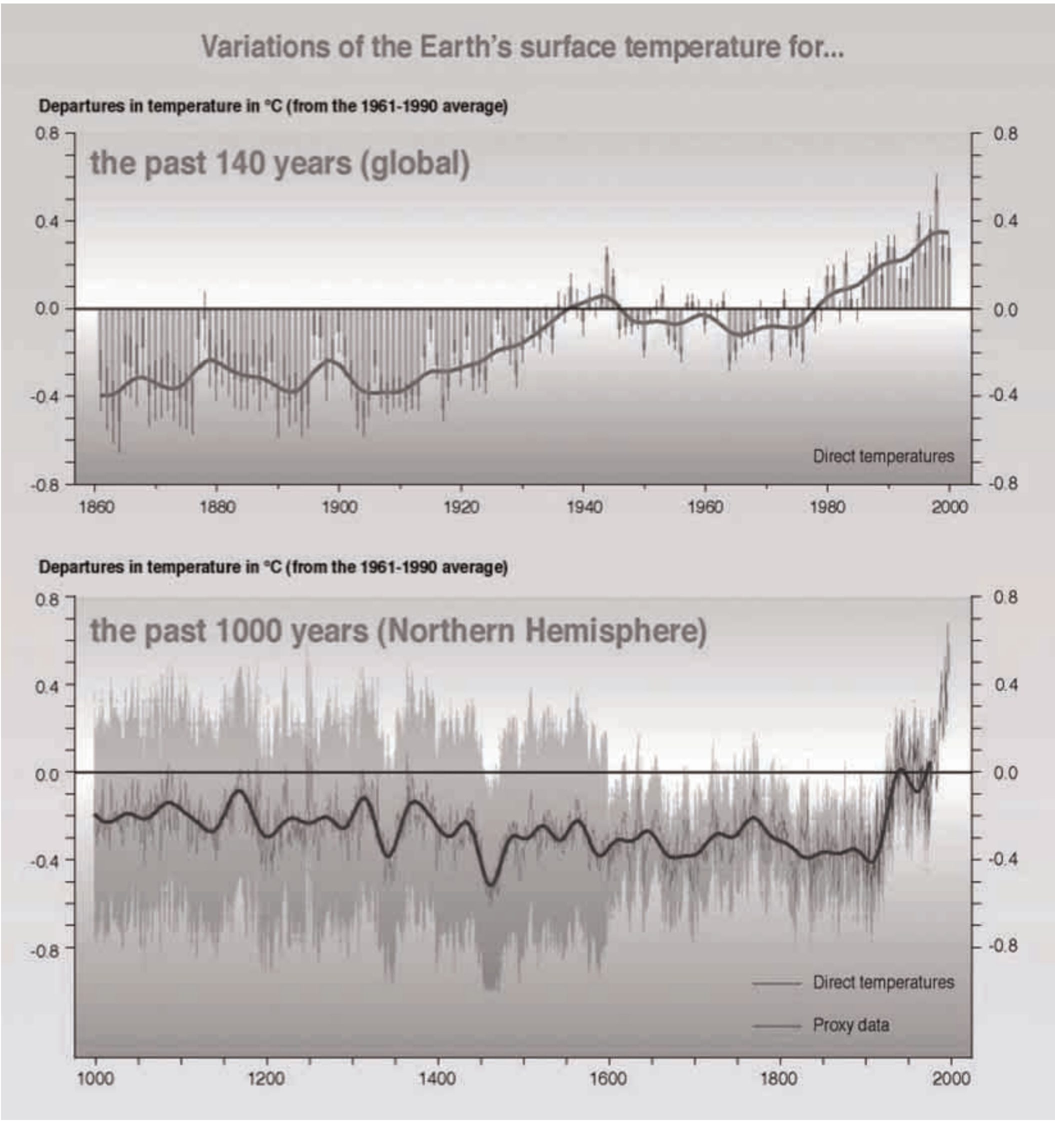

Figure 31.1—The reconstructed Earth surface air temperature record for the past millennium (http://www.ipcc.ch/present/graphics/2001syr/ppt/05.16.ppt).

Hansen and others (2002) point out that observed warming is greatest at high latitudes, especially in Northern Canada, Alaska, and parts of the Antarctic Continent. By comparison, the heat-island effect occurs primarily at middle latitudes where the greatest numbers of cities are located. Space-based observations see no stratospheric warming. This is consistent with thermodynamic principles, stratospheric cooling due to ozone depletion, and effects of sulfate aerosols (National Academy of Sciences 2001) and does not contradict ground-based observations (Houghton and others 2001).

The magnitude of uncertainties concerning the heat island effects and the scale of the corrections applied do not invalidate the record of recent rise in global surface temperature, but affect the absolute magnitude and its standard error. Similarly, upper air temperature measurements from balloons and aircraft do not invalidate present assessments. The argument is advanced that the greenhouse forcing from CO_2 increases is negligible compared to the exchange of this gas in the seasonal uptake and release from plant photosynthesis and respiration. This argument ignores both the physics of greenhouse gases and the principle of superposition. The latter that says as a first-order approximation the effects of multiple processes are additive; hence, the additional atmospheric loading of increasing CO_2 will be cumulative regardless of the magnitude of the annual exchanges.

It is important, therefore, to distinguish skepticism stemming from bad science or preconceived conclusion from scientific skepticism that seeks to ensure the knowledge derived is complete, accurate, and inclusive of all the important variables that are driving the system trajectory. Not all uncertainties have been eliminated, nor is the potential of unexpected future results negligible. This is particularly true when one attempts to map the responses of terrestrial vegetation to probable external forcing, and even more so when one wants to examine effects at local to regional scales.

IMPLICATIONS FOR SOUTHERN FORESTS

What, then, are the implications of global climate change for the Southern United States in general, and for its forests in particular?

The most important inference is that the continuation of the present climate is no longer the only tenable scenario. Instead we are faced with a range of scenarios that may have differing probabilities attached to them but cannot be dismissed out of hand. These scenarios arise principally from two processes. One derives from the uncertainties regarding future CO_2 and other greenhouse gas emissions, and the other from differences in the climate models themselves, which have been evolving to incorporate a greater number of variables and feedback loops over time. Models have been built that map potential vegetation based on climate drivers including temperature, such as growing degree days and winter temperature minimums, water (precipitation and soil moisture holding capacity), and photosynthetic radiation. These can use the outputs of general circulation models (GCM) to drive the vegetation both in equilibrium phase, i.e., after atmospheric CO_2 has doubled and equilibrium is attained, and in dynamic phase, mapping the vegetation response to gradually changing climate (e.g., Bachelet and others 2001, VEMAP members 1995). Building in the responses of the terrestrial ecosystems via their biogeochemical cycles is still a developing area (National Academy of Sciences 2001).

As a result, major GCMs exhibit a range of possible climate change outcomes, especially at the regional scale, where the remaining uncertainties are perhaps greatest. It is instructive to consider the worst-case scenarios along with the benign or even desirable outcomes.

A scenario that might pose particular difficulty, because it might convey a false sense of security, is one in which climate change would initially be favorable, i.e., one with initial warming and steady or increasing precipitation, followed by the development of unfavorable conditions, i.e., continued warming accompanied by increasing aridity. A hypothesis that may apply for the Southern United States is the expansion of the subtropical high-pressure fields, including the Bermuda High (Bachelet and others 2001, Doherty and Mearns 1999). Such expansion would shift portions of the jet stream northward, which might unfavorably alter the precipitation and water regime. Southeastern forests would presumably decline, and catastrophic fire could well be the change agent for this decline.

For the Southern United States, ramifications of such scenarios go beyond forest responses, and include changes in water availability among other hydrologic effects. One may use the global climate models to calculate ground-water balance and river discharge, which together can describe water availability. Figure 31.2 is a depiction of the water availability under the scenario of a drier South onto which population growth rates have been superimposed. The figure shows water stress as the ratio of changed availability divided by changed growth rates. This is only one possible outcome of several, selected to show a worst-case situation. There are benign and even promising scenarios in which forest expansion is a strong possibility. Unfortunately, there are no reliable data at this time on the probability of occurrence for any of these scenarios (see discussion in Smith and others 2002).

The foregoing implies that our management strategies with respect to climate change must be structured to function in the context of uncertainty and incomplete information. This is not shocking and not unprecedented; a similar situation exists with respect to other phenomena, such as market fluctuations or exposure to risk from hurricanes and floods. It simply means that decision theory approaches developed elsewhere may be applied here and that risk assessment and risk management approaches apply in this arena as they do in others (Gucinski and McKelvey 1992).

Risk assessment must address two elements, the probability of the occurrence of an event, such as future drought, and significance (or "value" or "utility" in economics parlance) of the event when it does occur. For large-scale events with costly or even catastrophic outcomes, it has been customary to take a "risk-averse" stance over a "risk-neutral" one, but even that can be problematic in terms of required action. The "zero-infinity" paradox, in which the probability of the occurrence of an event is vanishingly small, but the consequences simply catastrophic, such as unprecedented wildfire, or a massive earthquake in an urban area, requires preparatory action regardless of likelihood.

What are the implications of potential climate change for risk management?

The study of disturbance processes, and their lessening or accentuation by changing climate, is still relatively young. Wildfire frequency and intensity is being modeled as a response to the effects of climate change on forest ecosystems (Lenihan and others 1998). McNulty (2002) has described effects of hurricane on southern forests. Management strategies for resistance to hurricanes include planting (or encouraged regeneration) of deeper rooted and salt-tolerant species, and denser forest stocking (or lower thinning levels). On the other hand, management strategies for southern forest response to fire include removal of understory, planting (or encouraged regeneration) of species that are more fire resistant, and lower stocking—or higher thinning levels. It appears that improved forest management and better policy is also needed to improve postfire and posthurricane salvage.

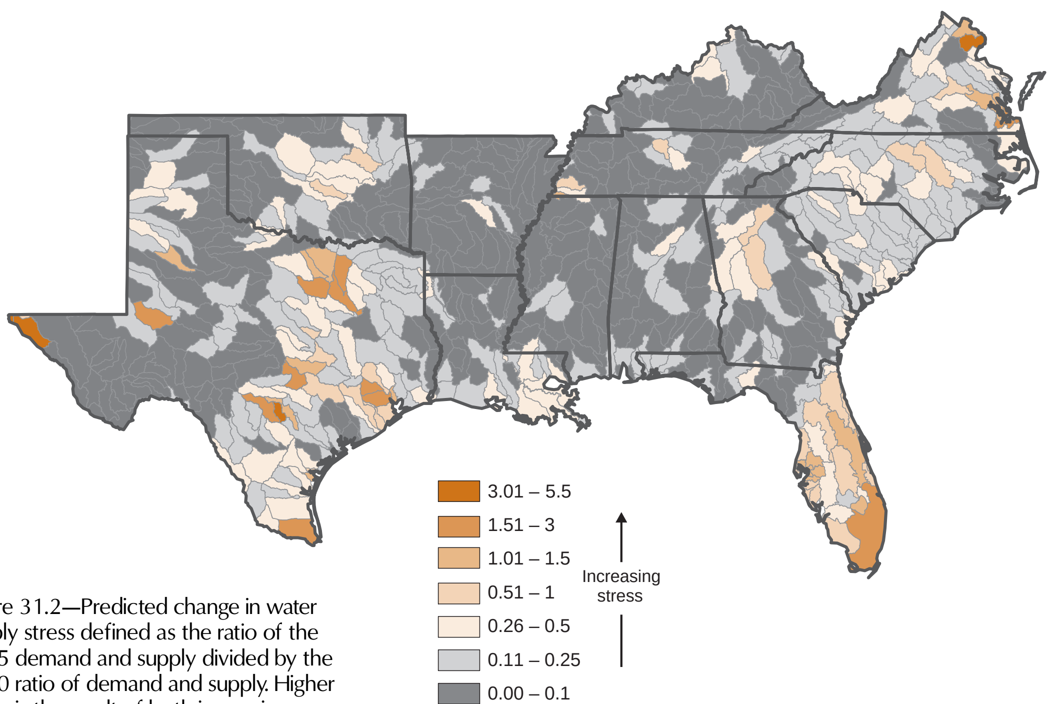

Figure 31.2—Predicted change in water supply stress defined as the ratio of the 2025 demand and supply divided by the 1990 ratio of demand and supply. Higher stress is the result of both increasing demand (population pressure) and the changed supply (climate driven) (McNulty and others 2004).

However, increased stocking needed for improved hurricane resistance increases fuel loads and is detrimental to fire suppression.

Potential effects of climate change on opportunistic species, especially invasives, are being studied, as are fragmentation-related barriers to plant migration, limits on seed, disruption of pollinators, and other potential problems. The better we understand the many facets of the possible responses to potential climate change, the better our position to weigh courses of action that remain open.

We believe that the following may serve as useful starting points for further exploration of possible options for mitigating negative climate change impacts on Southern U.S. forests:

- Manage forests for low-probability climate scenarios that have large-scale consequences. In this case, diversity may bring resiliency, and ultimately sustainability. This strategy may be especially appropriate for the Southern United States, where the rotation period for reaching harvest potential is relatively short
- Weigh the risks of omission against those of commission. Sometimes the risks incurred through inaction are greater than by implementing active approaches early, especially when these approaches would be beneficial regardless of the effects of impending climate change
- Analyze the potential cost of delaying action in the hope of obtaining better information when the delay may eliminate viable options. This is the argument advanced by the National Academies in endorsing the IPCC findings. Delaying action until there is greater certainty about the potential effects of climate change may have its own costs. Of course, this does mean that additional information should not be sought or consulted
- Be aware that risk assessment is influenced by both objective and subjective elements, and that consistency in assessment approaches will improve our chances of meeting our objectives

CONCLUSIONS

Approaches in which potential global climate change is treated as a set of future risks have often been ignored, and certainly have not been used adequately to assess possible impacts in the Southern United States. The existence of decision-theory frameworks, and their use in other sectors, makes this a viable option for managers, who can also benefit from additional research in the science community. If by improving our understanding of the risk spectrum now and applying the insights gained in the planning process, we may have many more options in the near term. Future climate change constraints may limit the choices for climate change mitigation considerably.

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Chapter 32.

Carbon Sequestration

in Loblolly Pine Plantations: Methods, Limitations, and Research Needs for Estimating Storage Pools

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Abstract—*Globally, the species most widely used for plantation forestry is loblolly pine (*Pinus taeda *L.). Because loblolly pine plantations are so extensive and grow so rapidly, they provide a great potential for sequestering atmospheric carbon (C). Because loblolly pine plantations are relatively simple ecosystems and because such a great volume of knowledge has been gained about the species, the quantification of C dynamics of loblolly pine stands will be relatively easy. Here, we evaluate the state of science that relates to quantifying standing C pools in managed loblolly pine stands. We consider the accuracy and precision with which aboveground and belowground pools can be estimated, the portability of these tools across different stand types, and the intensity and efficacy of the measurement techniques. We emphasize the need to develop standard and relatively inexpensive measurement protocols.*

INTRODUCTION

The Southern United States is now the most intensive and extensively managed forested area in the World. The tree species most widely employed in plantation forestry is loblolly pine (*Pinus taeda* L.). Because loblolly pine has great commercial and economic importance, its culture and management has been studied in great detail (Schultz 1997).

Although much practical knowledge has been gained about loblolly pine, the research has typically been aimed at providing information needed for commercial wood and fiber production. Such research has produced growth-and-yield models, artificial regeneration methodology, stand amelioration methodology (and especially that relating to fertilizer use), and information about forest genetics and tree improvement.

There is growing interest in quantifying the ability of forest trees to sequester atmospheric carbon (C). This interest stems from observed rapid increases in atmospheric carbon dioxide, an important greenhouse gas, and their potential for changing the Earth's climate. Because loblolly pine plantations are so extensive and grow so rapidly, they have great potential for sequestering atmospheric C (Johnsen and others 2001c). And because loblolly pine plantations are relatively simple ecosystems and because such a great volume of knowledge has been gained about the species, the quantification of C dynamics of loblolly pine stands will be relatively easy.

The quantification of C pools in loblolly pine stands is necessary for two main reasons. One benefit will be in developing and validating process models (Johnsen and others 2001a, 2001b). Conventional growth-and-yield models have been practical tools for managing loblolly pine stands, both naturally regenerated and plantation, over the past century. These models are based on empirical data about past performance and utilize site index to characterize stand quality

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and productive potential. Growth-and-yield models have been effective because the growth of the stands they are used for has typically been similar to the stands growth-and-yield tables were based on. However, with intensive forest management increasing, this assumption is no longer valid. Loblolly pine is being grown at unprecedented rates (Albaugh and others 1998, Samuelson and others 2001). Process models, which incorporate mechanistic information of tree and stand function, will hopefully provide tools for predicting stand performance under novel conditions. C, as a basic and major constituent of cellulose, lignin, starch, and sugars provides a valuable “currency” for models to be based on.

Process models are needed for more than managing stands of pine. Policy and planning with respect to the uncertainty of future climate and large-scale land management issues requires modeling tools that can provide useful forecasts. These efforts form the basis of the U.S. Department of Agriculture Forest Service, Southern Global Change Program. Clearly, information and tools developed to inventory stand C and model C dynamics at the managed pine stand level should be utilized to improve the performance of larger scale regional, national, and international modeling efforts.

Quantifying pine stand C pools will also provide a basis for “carbon credits.” Although no system of C credits exists yet in the Southern United States, they are in serious consideration in Europe. It is clear that if C credits are to become a practical reality, standardized, dependable, but relatively simple protocols for quantifying C pools will be needed to accurately evaluate C sequestration over time.

In what follows, we evaluate the state of science that relates to quantifying standing C pools in managed loblolly pine stands. We consider the accuracy and precision with which aboveground and belowground C pools can be estimated, the degree to which estimation tools are applicable across different stand types, and the intensity of the measurement technique. We emphasize the need to develop standard and relatively inexpensive measurement protocols.

PARTITIONING CARBON AMONG TREE ORGANS

A tree’s total biomass resides within its stem, branches, leaves, reproductive organs, and root system. Biomass is allocated differentially among the aboveground and belowground components, and the proportions of biomass in different tissue components change during the course of stand development. For example, foliage can constitute up to 50 percent of a seedling’s dry mass, but this proportion decreases greatly in older trees (fig. 32.1A). Figure 32.1A shows standing biomass components of fertilized trees at the Southeast Tree Research and Education Site (SETRES) (Albaugh and others 1998). Schultz (1997) stated that approximately 20 to 25 percent of standing biomass is present in root systems of mature trees, consistent with results from SETRES. In 1995, these stands had been fertilized for 3 years, and differential allocation among organs in terms of standing biomass was not strongly evident. However, figure 32.1B shows yearly production that indicates a much greater proportion of new growth allocated to both foliage and roots; fertilization reduced allocation to fine roots (data not shown). Both foliage and fine roots represent ephemeral organs. Thus, the proportions of standing biomass cannot be simply considered analogous to partitioning of total C gain.

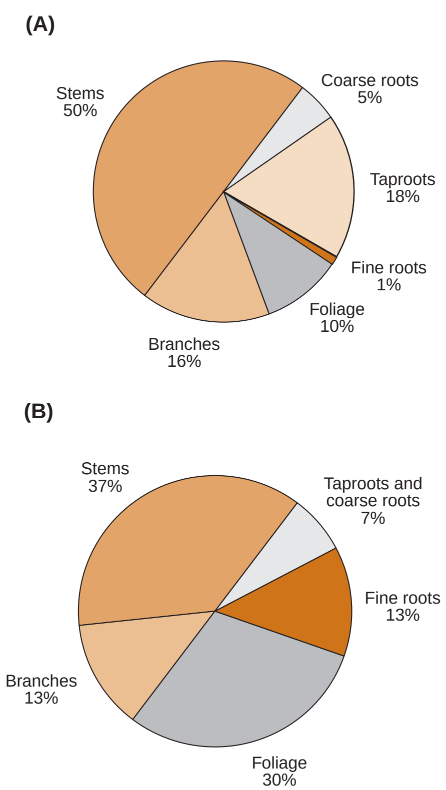

Figure 32.1—(A) standing biomass and (B) annual biomass production for fertilized trees from the Southeast Tree Research and Education Site located in North Carolina. The stand was established in 1985 and data are from 1995, 3 years after fertilization commenced.

BIOMASS ESTIMATION

In several investigations, aboveground and belowground organs of trees have been harvested and the biomass of loblolly pine stands has been estimated, typically in a plantation setting. Often, relationships have been developed between simple metrics [diameter at breast height (d.b.h.) and height] and biomass components, and these relationships can be used to estimate site C. Although these studies can provide simple tools for estimating C pools, they are largely site, age, and/or tree size specific. In the following sections, we discuss the estimation of C for aboveground and belowground components using formulas available in the literature and other methods.

Aboveground Standing Carbon

Stems—Figure 32.2 compares stem biomass estimates from six independently derived biomass equations at two tree size/age classes [only Baldwin (1987) uses age as a predictor]. Note that except for Van Lear and others (1984) and Naidu and others (1998), the larger size class examined in figure 32.2 represents a tree size larger than the sample trees examined in the studies. The larger size class was examined, though, because it represents a tree size frequently occurring during a full rotation. Except for Baldwin (1987), there is reasonable congruency among the estimates. However, confidence intervals are still large, and selecting the right equation to use for any particular site remains problematic. More such investigations are needed across a wider range of sites and tree sizes so that a stronger rationale can be developed for model selection. On a positive note, two sites that received extremely intensive management treatments (Albaugh and others 1998; Samuelson and others, in press) do not appear as outliers relative to the other sites that had less intensive management.

As boards and fiber are mostly contained in the boles of trees, many growth-and-yield tables for bole volume are available. For any given site, there are multiple growth-and-yield models to choose from. Again, we use SETRES as an example. Figure 32.3 shows the volume estimates provided by two growth-and-yield models: one from Goebel and Warner (1969) and one from Shelton and others (1984). Under all treatments, the Shelton and others model predicts approximately 50 percent higher volume than Goebel and Warner. The Goebel and Warner equation gives wood volume not total volume, i.e., no bark. The Shelton and others equation estimates volume outside bark. These are not trivial differences, especially for young trees, and probably account for a large part of the differences in volume estimates.

As with biomass equations, a systematic and nonsubjective method is needed for choosing the right growth-and-yield model for application to a particular stand. This will require a detailed evaluation and integration of the many models in the literature, as well as further research, particularly on intensive forestry systems. Landowners will need to provide nonsubjective simple biometrics such as height, d.b.h., and

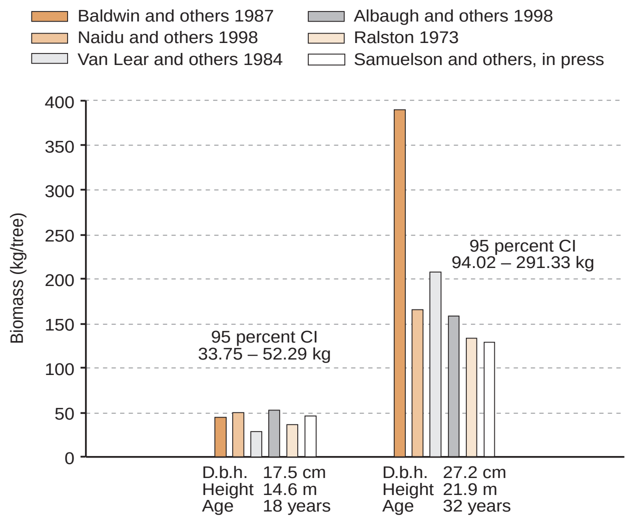

Figure 32.2—Stem biomass estimates obtained by applying six independently derived biomass equations for two tree size or tree age classes. Confidence intervals (CI) of 95 percent are shown for each size class.

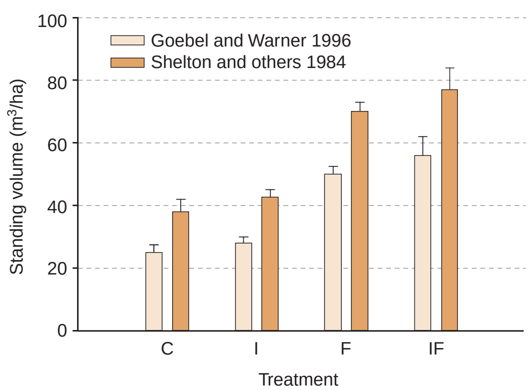

Figure 32.3—Standing volume estimates, using two growth-and-yield equations, for 10-year-old loblolly pine stand trees grown for the last 5 years under four treatments: control (C), irrigation (I), fertilization (F), and irrigation plus fertilization (IF). Treatments are described in Albaugh and others (1988).

stocking to a decision-support system that will use the appropriate growth-and-yield table (or biomass equation) and produce volume estimates.

Volume of stemwood, expressed as m^3/ha, is converted to Mg C/ha in the following way. First, multiply volume in m^3/ha by a value for the specific gravity of pinewood. Schultz (1997) suggests 0.5 is a good average to use. Then, because pine biomass is approximately one-half C, multiply the result by 0.5 to obtain an estimate of stemwood in Mg C/ha.

Zobel and others (1972) and Tauer and Loo-Dinkins (1990) demonstrated increasing specific gravity with tree age, and decreasing specific gravity with tree height, respectively, for loblolly pine. Concentrations of C vary among tree organs, ranging from 50 percent for branches to 42 percent for fine roots (Sampson and others 2001). In reality, specific gravity of wood as well as C concentrations of tree organs may vary with tree growth rate as influenced by management, and so both areas require further research and/or literature review to provide good estimates for application to a particular stand.

Branches—Branch biomass typically accounts for 10 to 20 percent of biomass (Shultz 1997). However, relatively little effort has gone into predicting stand branch biomass (Baldwin and others 1997). Branch biomass is strongly influenced by stand age and site quality (Hepp and Brister 1982). Again, the equations used to produce figure 32.2 also provide estimates for branch biomass, but stocking and productivity influences limit the portability of these relationships across sites.

Foliage—After planting, the quantity of foliage accretes over time until it reaches a semiplateau. Both the initial growth rate and the plateau reached are functions of site limitations. Therefore, in early stages of stand development, strong relationships are exhibited between metrics such as d.b.h. and height on the one hand, and leaf area or mass on the other hand. Once tree canopies close and a plateau in leaf mass is reached, such simple relationships may no longer exist. For larger trees, relationships between sapwood area and leaf area or mass will probably be more useful (Mencuccini and Grace 1995).

For midrotation stands like those at SETRES, the standing biomass of foliage of trees past the sapling phase is approximately 10 percent of total stand biomass. However, production of foliage biomass is much greater and at SETRES is approximately 30 percent of yearly biomass production. However, leaves represent the photosynthetic capital of a tree, and leaf biomass, or leaf area, is a major determinant of stand productivity. Leaf area dynamics are critically important in loblolly pine because the species maintains each cohort of leaves for two growing seasons so peak leaf area in late summer is approximately twice that in midwinter leaf area. Thus leaves are an important component of stand biomass, and yearly leaf area dynamics must be understood and modeled properly if stand productivity is to be modeled satisfactorily.

Leaf biomass can be determined from estimates of leaf area index (LAI), and vice versa, if estimates for specific leaf area (g/m^2) are also available. There are three common approaches to estimating leaf biomass and LAI. These include destructive biomass harvesting, litterfall techniques, and "instantaneous" techniques that employ measures of relative light flux density. Destructive harvesting is expensive and time consuming, and produces results that may be site-specific. Estimating LAI from littertrap data requires a waiting period, the length of which depends on both the number and longevity of individual annual foliage cohorts.

Instantaneous methods, such as using the LI-COR LAI-2000 Plant Canopy Analyzer (PCA), are rapid and much less expensive, and permit estimation of seasonal patterns in LAI when LAI varies monthly. However, the PCA underestimates LAI by 10 to 30 percent in pine stands (Sampson and Allen 1994), and corrections as shown in figure 32.4 are required. Estimation of

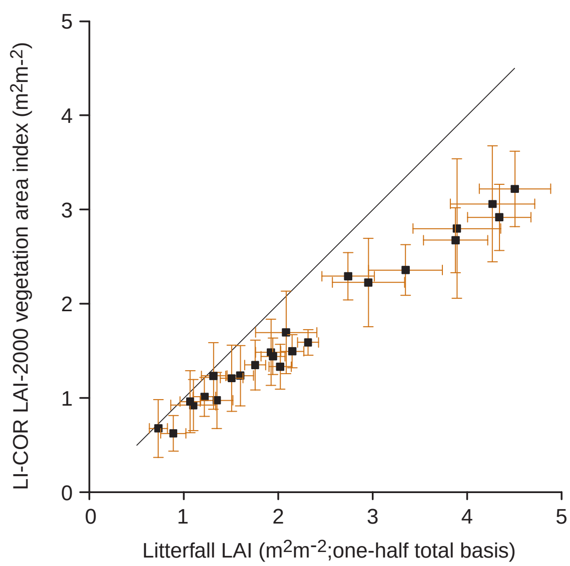

Figure 32.4—Relationship between litterfall, estimated leaf area index (LAI), and nondestructive measures using a LI-COR LAI-2000 from the Southeast Tree Research and Education Site.

seasonal foliage biomass or LAI using PCA will still require sequential measurements over time. In an attempt to minimize the sampling frequency, Sampson and others (in press) developed equations for estimating seasonal LAI from a single measurement. While this work utilized plots that varied greatly in productivity and stand structure, the general applicability of such an approach still needs to be tested.

Belowground Standing Carbon

Roots—Taproots represent an important sink of C; intensive destructive sampling at SETRES showed that they constituted 15 to 18 percent of total tree biomass. Taproot excavation is extremely labor intensive. Heavy machinery can be utilized, but losses due to ripping and imprecision in the volume of soil sampled increase sampling error considerably. In the future, it will be necessary to develop inventories of stand taproot C on the basis of relationships between taproot C and simple measures such as d.b.h. and height, which will also be used to estimate aboveground biomass. Taproot morphology can vary tremendously within a stand. The four taproots shown in figure 32.5 came from trees on the same site in South Carolina and range from a single carrot-shaped root to a complex series of large sink roots stemming from a buttressed stem. Thus estimating total coarse root biomass removes the subjectivity involved in deciding exactly what constitutes the taproot.

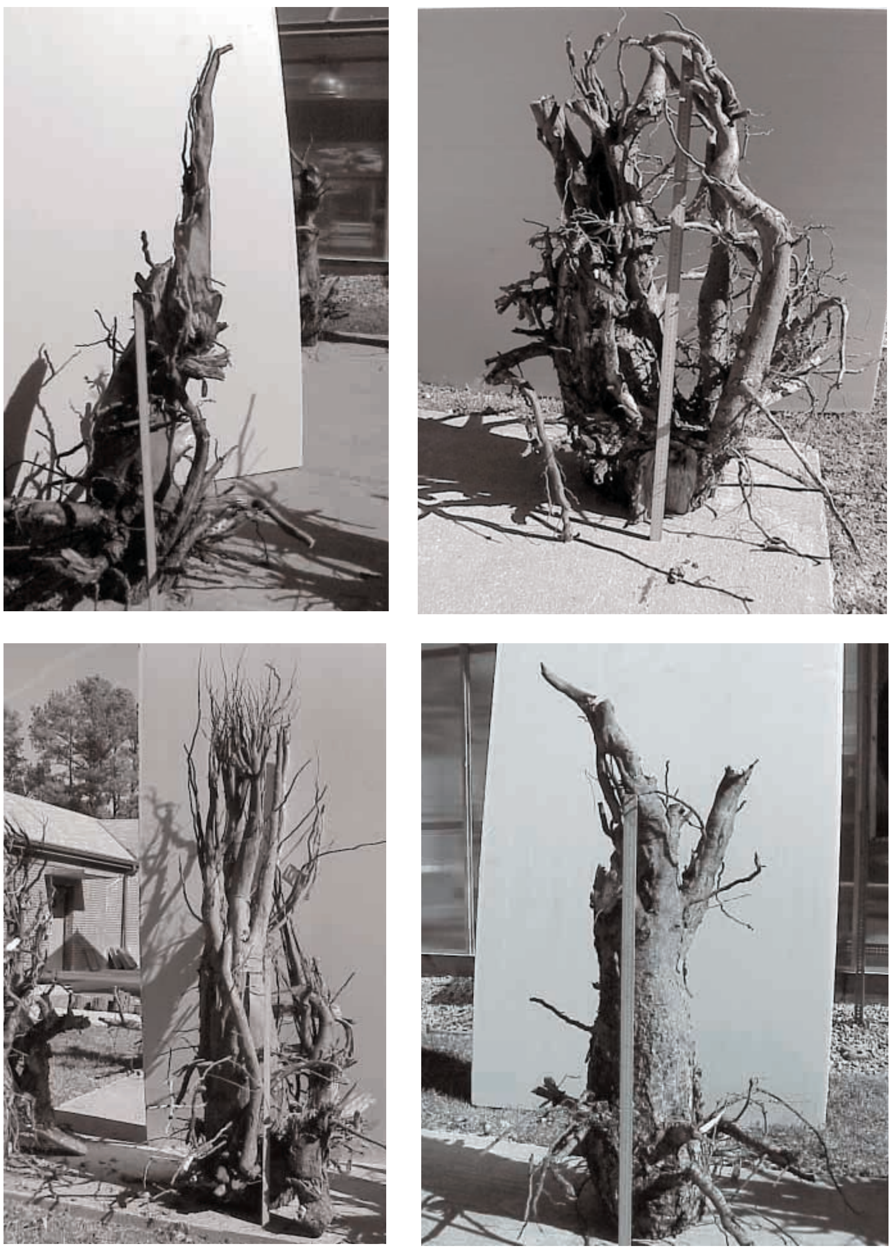

Figure 32.5—Taproots excavated from a 20-year-old plantation in South Carolina, showing the variation in root morphology. Photos by Lance Kress.

Figure 32.6 illustrates the relationship between coarse root biomass and total aboveground biomass for combinations of site and stand age. The figure shows total coarse root biomass because of the morphological differences discussed above. Log-log regression analyses of the data in figure 32.6 indicate that the allometric constant is approximately 0.20, which means that the ratio of coarse root biomass to aboveground biomass declines with stand development. Therefore, simple coarse root biomass:aboveground biomass ratios will not suffice. Note that these sites represent a large range in soil permeability (deep sand, clay, and loam), and so the fact that one relationship holds between coarse root biomass and aboveground biomass for all these sites is surprising. Relationships will likely have to be constructed for different site types. For example, a water table that is high or fluctuating or both may well reduce vertical taproot development.

Depending on soil and moisture conditions, taproots can penetrate below 3 m. Thus taproots reside in an environment that is not as conducive to rapid decomposition as finer root components and may be important in sequestering C belowground. Ludovici and others (2002) examined *in situ* decomposition of loblolly pine taproots

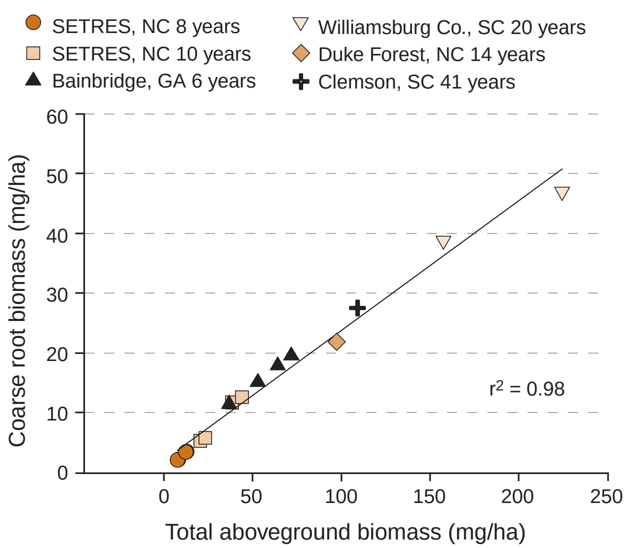

Figure 32.6—Relationship between aboveground biomass and coarse root biomass across sites. Note: All estimates are via biomass sampling except those for the Williamsburg site, where stem volumes were estimated using a volume equation and converted to carbon values as described in text and value was adjusted to add branch and leaf carbon using Baldwin and others (1997). Southeast Tree Research and Education Site (SETRES) estimates are via Albaugh and others (1998); Bainbridge, GA, from Samuelson and others (in press); Williamsburg, Co., SC; Duke Forest, NC, from Ralston (1973); and Clemson, SC, from Van Lear and others (1984, 1995).

grown on a Piedmont site across a 60-year chronosequence. Ten years following cutting, approximately 45 percent of taproot biomass persisted, and a small fraction was still recoverable after 60 years. These trees were of a size and age well beyond typical loblolly management standards for many areas of the South, and so taproot decomposition of more typical stands still needs to be assessed.

The characterization of nontaproots into size classes is subjective. Often, fine roots are defined as being < 2 mm in diameter. As with leaves, fine roots represent an ephemeral tissue type. Thus the contribution of fine roots to total standing biomass can be low (fig. 32.1A). However, the contribution of fine roots to yearly production can be high (fig. 32.1B). Fine root production and biomass are affected by environmental conditions. For example, fertilization can greatly reduce fine root biomass production. Fine root biomass is often estimated by means of soil coring, which often requires high sample sizes as within-plot special variation can be extremely high. High-intensity root core sampling at a 20-year-old loblolly pine experiment in South Carolina demonstrated the great variation in root biomass and showed that the variation increases with profile depth as fine roots become scarcer (table 32.1A).

However, fine roots are much more homogeneously distributed than are coarser roots. Coarse root estimates derived via soil coring may in fact have little value in themselves. We have recently begun using an "air knife" that displaces soil by means of compressed air. Root systems can be excavated in a chosen area to a chosen depth around a sample tree; roots over 2 mm in diameter are left intact. This method appears to be superior to coring for estimating coarse root biomass.

As the sample size requirements in table 32.1A indicate, making precise estimates of root biomass is extremely difficult. Alternative methodologies need to be devised. Recently Butnor and others (2001, 2003) have explored the use of ground penetrating radar (GPR) to estimate root biomass. Because it provides an integrated measure, variability is actually lower in GPR estimates than in estimates obtained by coring. The use of GPR still requires that some coring be done so that GPR images can be calibrated. However, in 4 hours, the equivalent of over 2,000 cores' worth of data can be collected using GPR, so sampling intensity can be increased greatly. Although GPR has shown promise on coarse-textured soils, much more work needs to be done so that it can

Table 32.1—Site mean, mean square error, and estimated sample size needed, by soil profile depth, to detect 10-percent differences between treatment means for root biomass (A) and percent soil carbon (B)[a]

Depth	Mean root mass	MSE	Sample size
cm	*g/core*		*10% difference*
A			
0–20	16.88	15.91	679
20–40	0.62	1.85	7,296
40–60	0.57	1.18	3,336
	Mean % carbon		
B			
0–20	2.09	0.96	176
20–40	0.28	0.28	167
40–60	0.24	0.24	276

MSE = mean square error.
[a] Data is from a sample of 240 10-cm diameter soil cores collected from a 20-year-old North Carolina State Forest Nutrition Cooperative Regionwide 7 trial in Williamsburg Co., SC.

be applied across more soil types. However, both antennae optimization and rapid improvements in data processing make it likely that GPR will provide a very powerful and useful tool for estimating root biomass.

Soil Carbon—Soil C often is the largest component of a stand's total C stock. Soil C is typically sampled by coring, often in combination with root sampling. As with roots, soil C decreases with depth (table 32.1). Soil C is more homogeneous than root biomass, however, and this is reflected in the lower coefficients of variation and sample size requirements for soil C (table 32.1). However, sampling intensity needs to be high, and sampling therefore can be very costly.

If one is to take cores for soil C analyses, one must decide whether to core by horizon or by standard depths. Coring by horizon is more difficult as it requires locating the horizon depths for each sample, but it can reduce variation among samples and thus decrease sample sizes. Coring by depth is more rapid, but as soil profiles will often change within a depth increment, variation among samples will be higher. The tradeoffs between the two protocols need to be established before one chooses a sampling scheme.

If large cores with a known soil volume are used, then data can simply be scaled to the stand level volumetrically. Where small soil augers are used, soil bulk density must be assessed so that soil C data can be scaled up. Although soil C concentrations typically decrease with depth, soil bulk density increases also, and so values of both characteristics must be determined to properly scale the data to the stand level.

In managed stands, soil C can display large temporal variation. After clearcutting, root biomass soon becomes necromass and decomposes over time, resulting in a large temporary increase in soil C. This phenomenon is clearly shown in figure 32.7, which displays soil C results of a long-term site productivity study in the Croatan National Forest in North Carolina. During year zero, the old stand was cut and replanted. After only 1 year, soil C increased, probably as a result of the decomposition of the least recalcitrant fine roots from the harvested stand. By year five, soil C peaked as larger root classes decomposed. By year ten, the strong pulse of organic matter was largely lost due to soil respiration. However, soil C concentrations were still higher than at year zero. If C sequestered in the soil is to be quantified properly, these fluctuations over time must be taken into account. Although the soil C pulse is ephemeral, it still results in a net exclusion of C from the atmosphere.

Again, the variability among soil C measurements is large and indicates that new methodologies must be devised. Currently workers are exploring the possibility of using advanced Raman/SERS fiberoptic-based devices (Wullschleger and others 2001), Laser-Induced Breakdown Spectroscopy (Ebinger and

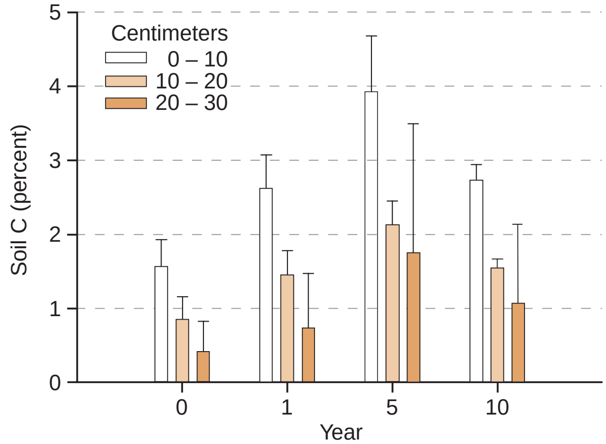

Figure 32.7—Percent soil carbon (C), by soil profile depth, over time, for stands from the long-term site productivity experiment located in the Croatan National Forest in coastal North Carolina. The previous stand was harvested and the new stand planted in year zero.

others 2001), and inelastic neutron scattering (Wielopolski and others 2000) to analyze and characterize C concentration in soil.

CONCLUSIONS

Clearly land will rarely if ever be managed solely for sequestering atmospheric C. However, C sequestration can provide a cobenefit, and the possibility of receiving income provided for C credits would often affect land management decisions about management intensity and rotation length.

Obviously sampling, site, and temporal variation is associated with measuring each of the stand components discussed above. We have indicated where we think further research is needed both to improve the precision of estimates and to make estimation easier. Increased collaboration among researchers in the Southern United States will produce great gains.

True quantification of C sequestered by managed forests will require assessing the temporal variation of the various C pools, integrating each curve, summing the integrated values, and then dividing the sum by rotation length. Models can be developed so that integrated values can be estimated from measurements made at critical times in a plantation's development. Alternatively, landowners could be credited for C on a site each year, relative to some standard base level. However, in the latter method, C deficits following stand harvesting and planting would require that a landowner actually pay for negative C credits until accreted C again reaches the baseline C level. This manner of executing C credits would obviously be extremely difficult and expensive.

We envision at least two tiers of precision in estimates of standing C for the purposes of documentation for C credits. At the coarser level, the landowner might provide only basic stand information such as d.b.h., height, and stocking. All conversion factors, as well as soil C values, would then be obtained from the literature and might be stratified to provide different estimates for different regions, soil types, and management intensity. This level of precision would likely be suitable for most small private landowners.

At finer and more precise levels, the landowner would provide more specific stand data. These could include direct estimates of soil C, root biomass, specific gravity, C concentration of tree tissue, and leaf area. These levels of precision would more likely be used by forest industries, and especially those with strong internal research programs or cooperative research programs with agencies and universities.

The value of C credits would then likely increase as the direct inputs into estimates increase. The financial gain made by providing more direct information for stands will determine the willingness of landowners to collect and provide more data. It is possible that consulting companies will proliferate. These consultants would be geared up to use state-of-the-art tools, and would incorporate field data into state-of-the-art models to provide C sequestration estimates. In any case, all estimates provided for C credit documentation will need to be certified for authenticity.

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Chapter 33.

Forest Carbon Trends
in the Southern United States

Robert A. Mickler, James E. Smith, and Linda S. Heath[1]

Abstract—*Forest, agricultural, rangeland, wetland, and urban landscapes have different rates of carbon (C) sequestration and total C sequestration potential under alternative management options. Future changes in the proportion and spatial distribution of land use could increase or decrease the capacity of areas to sequester C in terrestrial ecosystems. As the ecosystems within a landscape change as a result of natural or anthropogenic processes, they may go from being C sinks to being C sources or vice versa. We used periodic forest inventory data from the U.S. Department of Agriculture Forest Service's Forest Inventory and Analysis Program and Landsat Thematic Mapper data to obtain estimates of forest area and type. A simulation model for estimating and predicting C budgets (FORCARB) and a physiologically based forest productivity model (PnET) were used to generate estimates of historic, current, and future C storage for southeastern forests.*

INTRODUCTION

If the United States is to meet the challenge of future carbon dioxide (CO_2) emission and sequestration goals, the Southeastern region will play a critical role in increasing carbon (C) sequestration potential through conversion of nonforest land to forest land and through the management of forest lands. Terrestrial C fluxes caused by changes in land use and landcover must be quantified so that C sources and sinks in the United States can be identified. International treaties on greenhouse gas reduction require that current C emissions and sequestration potential of forest lands be determined so that baselines can be established for current and future forest C stocks. Changes due to afforestation (establishment of forest on land that is not now in forest use), deforestation (conversion of forest land to nonforest use), and reforestation (regeneration of forest after clearcut or significant partial-cut harvesting) are being used to derive estimates of forest C stocks for an historical baseline and future projections. Additional gains in C sequestration may be realized by increasing photosynthetic C fixation by plants, reducing decomposition of soil organic matter, reversing land use changes that contribute to global emissions, and creating energy offsets through the use of trees in urban environments.

The Southeastern United States can play an important role in a national program for reducing greenhouse gas emissions. The conversion of nonforest land to forest land results in an increase in aboveground and belowground sequestered C. The present-day conversion of abandoned farmlands to naturally regenerated forests and commercial forest plantations is contributing to an increase in the region's terrestrial C sink. In this chapter, we present historic, current, and future projections of forest C as simulated by an empirical simulation model used to estimate and predict C budgets (FORCARB) and a physiologically based forest productivity model (PnET).

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MODELING HISTORIC AND CURRENT ESTIMATES OF FOREST CARBON

Ecosystem C pools for the aboveground portion of southern forest ecosystems were estimated using an inventory and modeling approach. Similar approaches have been employed by Plantinga and Birdsey (1993), Heath and Birdsey (1993), Birdsey and Heath (1995), Turner and others (1995), Intergovernmental Panel on Climate Change (1997), and Houghton and others (1999). Forest inventory data were obtained from the U.S. Department of Agriculture Forest Service (Forest Service), Forest Inventory and Analysis Program (FIA) (Miles and others 2001, Smith and others 2001). One can estimate regional C stocks by multiplying forest area by C per unit area. If a second survey is conducted at a later time, then the rate of change in the C stocks can be calculated as the change in C mass divided by the time between inventories in years. Traditional forest inventories provide the data required for calculating C mass. Approximately 50 percent of live tree biomass, or dry weight, is C.

Since the early 1950s, forests in the United States have been surveyed periodically on a Statewide basis. The inventories have been conducted more intensively on the more productive forest land known as timberland. Timberland is defined as land capable of producing in excess of 20 cubic feet per acre per year of industrial wood products and not designated as reserved. Approximately 94 percent of southern forests are timberlands. Significant areas of less productive or reserved forest lands that have not been inventoried in the past exist in Texas, Oklahoma, and Florida. FIA surveys were designed for estimating forest area and merchantable timber volume. Tree volume can be converted to C mass by means of basic models or conversion factors. C in other forest components can be estimated similarly on the basis of forest attributes. Forest C is often assessed separately for a number of pools. For the purposes of this chapter, we partition the forest into five components: (1) aboveground live trees, (2) aboveground standing dead trees, (3) down dead wood (including stumps), (4) understory vegetation, and (5) the forest floor. We focus on aboveground pools in this chapter because of the uncertainty in belowground C estimates, and because there are accounting difficulties relating to the transfer of large blocks of soil C as a consequence of land use change (Heath and others 2003).

Another important aspect of forest C budgets in the United States is the fate of C in harvested wood. The categories used to describe harvested wood products in C budgets are (1) C in wood products in use, (2) C in landfills, (3) C emissions from wood burned to produce energy, and (4) C emissions from wood either decaying or burned without producing energy. Release of C emissions may result from burning of wood for energy at the mill, from other burning of fuel wood, or from burning of biofuels made from wood. The sum of the four categories of wood products is equal to the total amount of C harvested. Estimates of C in harvested wood products are based on national estimates from Skog and Nicholson (1998), partitioned by State on the basis of the ratio of statewide removals to national removals (Smith and others 2001).

Forest Carbon Estimates from Past Inventories

Forest inventory data are available for the last half of the 20th century. The data were compiled for years 1953, 1963, 1977, 1987, 1992, and 1997. The Forest Service has a detailed plot-level database for the forest inventory data compiled for the years 1987, 1992, and 1997. For the other years, only forest statistics aggregated across the landscape are available (Smith and others 2001).

Our estimates of historical tree C mass are based on (1) generalized tree biomass equations (Jenkins and others 2003); (2) tables of volume distributed among diameter classes and forest areas (Smith and others 2001) aggregated across the landscape; (3) effects of ownership and forest type on C content from the databases associated with the 1987 and 1997 U.S. forest statistics (Smith and others 2001, Waddell and others 1989); and (4) the equations of Smith and others (2003). C density of forest growing stock was estimated from average tree volumes, diameter distributions, and biomass equations. Estimates of C in nongrowing stock and standing dead trees were based on similar relationships and data in the detailed 1987 and 1997 databases. The other nonstanding-tree C pools were estimated based on relationships for live-tree C pools from the 1987 and 1997 data, and on forest floor equations in Smith and Heath (2002), and understory vegetation information in Birdsey (1992, 1996).

MODELING CURRENT AND FUTURE ESTIMATES OF FOREST CARBON

The physical and chemical environments of forest ecosystems are changing at rates unprecedented in recent geologic time. The Mauna Loa record shows a 16.9-percent increase in the mean annual concentration of atmospheric CO_2 from 315.98 parts per million by volume (ppmv) of dry air in 1959 to 369.40 ppmv in 2000. The 2.87-ppmv increase in CO_2 concentration in 1997–98 is the largest single yearly increase since the Mauna Loa record began in 1958 (http://cdiac.esd.ornl.gov/ndps/ndp001.html). If emissions continue to increase at this rate and there are no measures taken to slow the growth of CO_2 concentrations, a doubling of atmospheric CO_2 is possible by 2100 (Houghton and others 1996). In addition to elevated atmospheric CO_2, climate change resulting from the production or use of greenhouse gases and sulfate aerosols has increased over the last century. Air temperatures have increased on average by 1 °F across the United States during this period. In the Hadley model scenario, the Eastern United States has temperature increases of 3 to 5 °F by 2100, with larger increases for other regions (National Assessment Synthesis Team 2000). The physiological responses of southern forest ecosystems to elevated CO_2 and climate change have been the subject of hundreds of publications. A detailed review of the literature on this topic for southern forests is presented in Mickler and Fox (1997).

In this section, we present the responses of southeastern forest to elevated CO_2 and climate change. The objective of the research described here is to utilize remotely sensed forest cover data linked to a productivity model to determine, evaluate, project, and map forest productivity in the Southeastern United States from the present to 2100. We hope eventually to integrate existing climate, soil, and remotely sensed landcover data, and the Hadley2Sul climate scenario for the Southeastern United States as input to forest process models to predict, validate, and project forest growth and forest biomass. This section will describe methods for linking Landsat Thematic Mapper (TM) landcover information and a PnET to estimate and display forest productivity.

Remotely Sensed Forest Classification

Forest cover mapping using spaceborne sensors has been a goal of forest managers since the launch of Landsat-1 in 1972. The enhanced spatial, spectral, and radiometric resolution available with the launch of Landsat-4 and subsequent Landsat satellites has improved the application of the TM sensor for discerning forest cover classification at Anderson Level II and III classification precisions at a pixel spatial resolution of 30 m. One of the projects sponsored by the Multi-Resolution Land Characteristics (MRLC) Consortium was production of landcover data for the conterminous United States. Landcover was mapped using general landcover classes. For example, forest is classified as deciduous, evergreen, mixed, and woody wetlands. Landcover classification was based on MRLC's Landsat-5 TM satellite data archive and a host of ancillary sources.

The Landsat TM data used for this project were preprocessed following the procedures described by MRLC for the National Land Cover Data (NLCD) set. The NLCD-selected TM scenes consist of data acquired between 1990 and 1994. Image processing for the NLCD set is described by Vogelmann and others (1998, 2001). Spectral information from leaf-on and leaf-off datasets was used to derive the landcover classification products. First-order classification products were developed using predominantly the leaf-off mosaics as a baseline and refined with the spectral data from the other season and ancillary spatial information. Further refinements in the classification were made using decision trees and visual inspection. Landsat TM and ancillary data in the NLCD set were acquired for the 13 Southeastern States from MRLC (http://www.epa.gov/mrlc/nlcd.html). Individual State flat landcover files were imported into ERDAS IMAGINE®. Image data were projected to Albers projection, NAD83 datum, GRS1980 spheroid, and units of meters. Individual State images were used to produce one regional mosaic image. Forest area was displayed and summarized for three NLCD landcover classes: (1) deciduous forest (class 41), (2) evergreen forest (class 42), and (3) mixed forest (class 43). The deciduous forest class was supplemented with the woody wetland class (class 91) to create a reclassified deciduous forest class. The accuracy of the landcover classification has been described by Yang and others (2001).

Land Use Change

Forest land and agricultural land account for 90 percent of the South's total land use. Historically conversion of forest land to agricultural use, and vice versa, has been driven primarily by changes in economic conditions (Adams and others 1996). Smith and others (2001), who analyzed Forest Service FIA survey data, reported that total forest in the South decreased from 91 471 000 ha in 1953 to 86 646 000 ha in 1997, a 5.3-percent decline. Murray and others (2001), who examined Natural Resources Inventory survey data, determined that the forest area of the region declined by 687 981 ha, or 1.1 percent, between 1982 and 1997. They then assessed the future effects of global climate change on forest and agricultural rents. Climate projections using the Hadley base scenario with a 2 °F (1 °C) and 4 °F (2 °C) warming combined with a 20-percent reduction in precipitation were applied to a model of land allocation for the Southeastern U.S. forest area decline by ~4 000 000 ha [2 °F (1 °C) warming] and ~8 000 000 ha [4 °F (2 °C) warming] by 2040. Given the uncertainty associated with any projection of change in forest area under global climate scenarios and the historical trend for the last 50 years showing only a slight decrease in forest area in the region, the present study is based on the assumption that forest area will remain constant to 2100. We report the effects of climate change on the future productivity of the region's forests with the knowledge that changes in forest and agricultural returns may change forest area in the future.

Forest Productivity Modeling

We utilized the physiologically based, monthly time-step process model PnET to predict forest productivity and hydrology across a range of climates and site conditions. PnET predictions of forest productivity have been correlated with average annual growth in site basal area measured across the Eastern United States (Aber and Federer 1992), and predictions of forest biomass from PnET have been correlated with average annual growth in basal area measured at sites across the Southeastern United States (McNulty and others 1998). Forest biomass predictions for 2000, 2050, and 2100 were estimated using a decadal mean of net primary production (NPP) from the PnET model. Input data required by PnET include monthly climate parameters, soil water-holding capacity (WHC), and species- or forest-type specific vegetation parameters. PnET output is dependent on the spatial resolution of input data and includes forest growth, evapotranspiration, drainage, and soil water stress over time.

Monthly climate variables required by PnET include minimum and maximum air temperature, total precipitation, and solar radiation. The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) provides these variables for the period 1895–1993 across the continental United States at a 0.5° by 0.5° resolution (Kittel and others 1997) (http://www.cgd.ucar.edu/vemap/datasets.html). VEMAP also provides transient climate scenarios that include the same monthly climate variables for 1994–2100, based on general circulation models developed at the Hadley Centre and the Canadian Climate Centre (http://www.met-office.gov.uk/research/hadleycentre/index.html). These climate scenarios, Had2CMSul and CGC1, include temperature and precipitation effects related to increasing atmospheric CO_2 and sulfate aerosols. These datasets have been used to compare time-dependent ecological responses of biogeochemical and coupled biogeochemical-biogeographical models to historical time series and projected scenarios of climate, atmospheric CO_2, and nitrogen deposition. This dataset has the finest spatial resolution available with this level of temporal and spatial consistency, and hence, other input data are modified to match the 0.5° by 0.5° resolution for the model.

Soil WHC is derived from the CONUS-Soil dataset, which was developed by the Pennsylvania State University Earth System Science Center. The State Soil Geographic Data Base (STATSGO) Program was developed by the U.S. Department of Agriculture, Natural Resources Conservation Service to store and distribute soil survey information for U.S. lands. STATSGO maps were compiled from more detailed soil survey maps and present soil associations at a scale (1:250,000) more appropriate for regional analysis. Soil WHC information derived from the CONUS-Soil dataset (Miller and White 1998) was adapted to the 0.5° by 0.5° grid by area-weighted averaging of the CONUS soil series WHC polygons.

PnET vegetation variables include foliar nitrogen concentration, light extinction coefficient, and other physiological coefficients or constants derived from field measurements and published literature (Aber and Federer 1992). Based on the climate, soil, and vegetation input data, PnET calculates the maximum amount of foliage or leaf area that can be supported. NPP equals total gross photosynthesis minus growth and maintenance respiration for leaves, wood, and roots. Respiration is calculated as a function of the current and previous month's minimum and maximum air temperatures. Changes in water availability and plant water demand place limitations on leaf area produced; as vapor pressure deficit and air temperature increase above optimal photosynthetic levels, total leaf area decreases. Reduced leaf area decreases total C fixation and alters ecosystem hydrology. Transpiration is calculated from a maximum potential transpiration modified by plant water demand that is a function of gross photosynthesis and water use efficiency. Interception loss is a function of total leaf area and total precipitation. Evapotranspiration is equal to transpiration and interception loss. Drainage is calculated as precipitation in excess of evapotranspiration and WHC. Maximum water storage capacity is equated to WHC to a depth of 100 cm. Monthly evapotranspiration is a function of leaf area, plant water demand, and climate; i.e., air temperature, vapor pressure deficit.

We report PnET predictions of NPP for evergreen, deciduous, and mixed forests. The PnET model runs were performed for evergreen and deciduous forest types. NPP for mixed forest types was assumed to be a 50:50 mix of deciduous and evergreen NPP. Estimates of NPP were output at the 0.5° by 0.5° resolution, and then Anderson Level II forest-cover type pixels were assigned NPP values within each 0.5° by 0.5° cell. The resulting estimates of forest productivity across the Southeastern United States are stored at a 30-m spatial resolution and include information about attributes for specific forest types. Forest biomass predictions for 2000, 2050, and 2100 were estimated using decadal means of NPP from the PnET model.

RESULTS AND DISCUSSION

Estimates of Carbon Stocks in Southern Forests

Southern forests presently contain 5810 Mt of aboveground C on 87 million ha. Forests of the conterminous United States contain 20 340 Mt of aboveground C on 250 million ha. Thus the South accounts for approximately 29 percent of aboveground forest C stock in the conterminous United States. Allocation of this stock among forest ecosystem pools is shown in table 33.1. The sum of standing C in live and dead trees is provided in table 33.2 by forest type and ownership. The majority of C is in privately owned forests and in hardwood forest types.

Countywide estimates of mean aboveground forest C density are shown in figure 33.1. Aboveground C includes that in live and dead trees, understory vegetation, down dead wood, and the forest floor. Values for each county represent the mean for forest land within the county. Only counties with at least 5 percent of area classified as forest are included. Mean net annual growth for the period 1987–97 is shown in figure 33.2. The C pool represented in this figure includes the aboveground portion of all live trees having diameter at breast height greater than 2.5 cm. Net annual growth is essentially the net annual change in live tree C stock, a definition consistent with the use of the term in summary forest statistics of the United States (Smith and others 2001).

Estimates of Forest Carbon Stocks 1953–97

In the Southern States, aboveground forest C stocks generally accumulated steadily between 1953 and 1997 (fig. 33.3). The mean annual change in tree C stocks between 1953 and 1997 (table 33.2, column 2) is calculated as the difference between C stocks in the 2 years divided by the interval in years (44 years). A positive value represents an average increase in C stock, as in the case of oak-hickory forests, while a negative value indicates an average decrease, as in the case of privately owned longleaf-slash pine forests. Because these are total C estimates, the differences could result from changes in the area of forest, or in C density, or both. Between 1953 and 1997, total area of

Table 33.1—Mean aboveground carbon density of productive southern forests (timberlands) by forest type and carbon pool, 1997

	Forest type		
Carbon pool	Softwood	Mixed	Hardwood
	Mg carbon/ha		
Live trees	37.7	55.4	56.0
Standing dead trees	1.7	3.0	3.1
Understory vegetation	2.9	2.2	2.9
Down dead wood	3.3	7.4	7.5
Forest floor	9.3	7.6	5.7

Table 33.2—Mean aboveground tree carbon mass of southern forests by forest type and ownership classifications, 1997[a]

Forest type	Mean annual carbon change 1953–97	Total tree carbon	Carbon density	Forest area
	Mt carbon per year	*Mt carbon*	*Mg carbon/ha*	*1 000 ha*
		Privately owned forests		
Miscellaneous conifer	0.1	14	74.1	193
Longleaf-slash pine	-1.8	148	33.2	4 468
Loblolly-shortleaf pine	0.8	721	39.4	18 286
Oak-pine	6.0	486	45.1	10 767
Oak-hickory	23.4	1 686	59.3	28 445
Oak-gum-cypress	6.4	734	70.8	10 356
Elm-ash-cottonwood	0.3	52	61.5	851
Maple-beech-birch	0.3	28	71.5	397
Other Eastern types (including nonstocked)	0.4	23	8.9	2 541
Total	35.8	3 892	51.0	76 303
		Publicly owned forests		
Miscellaneous conifer	0.1	6	66.7	86
Longleaf-slash pine	0.2	34	38.8	883
Loblolly-shortleaf pine	0.3	97	48.8	1 988
Oak-pine	1.1	75	52.9	1 418
Oak-hickory	3.8	229	71.6	3 198
Oak-gum-cypress	1.0	113	71.9	1 572
Elm-ash-cottonwood	0.1	8	74.9	102
Maple-beech-birch	0.1	6	83.7	72
Other Eastern types (including nonstocked)	< 0.1	6	5.8	1 025
Total	6.6	574	55.5	10 343
Total South	42.4	4 466	51.5	86 646

[a] The carbon pool includes aboveground portions of live and standing dead trees. Mean annual carbon change between 1953 and 1997 is calculated as the net change in carbon stock divided by the number of years.

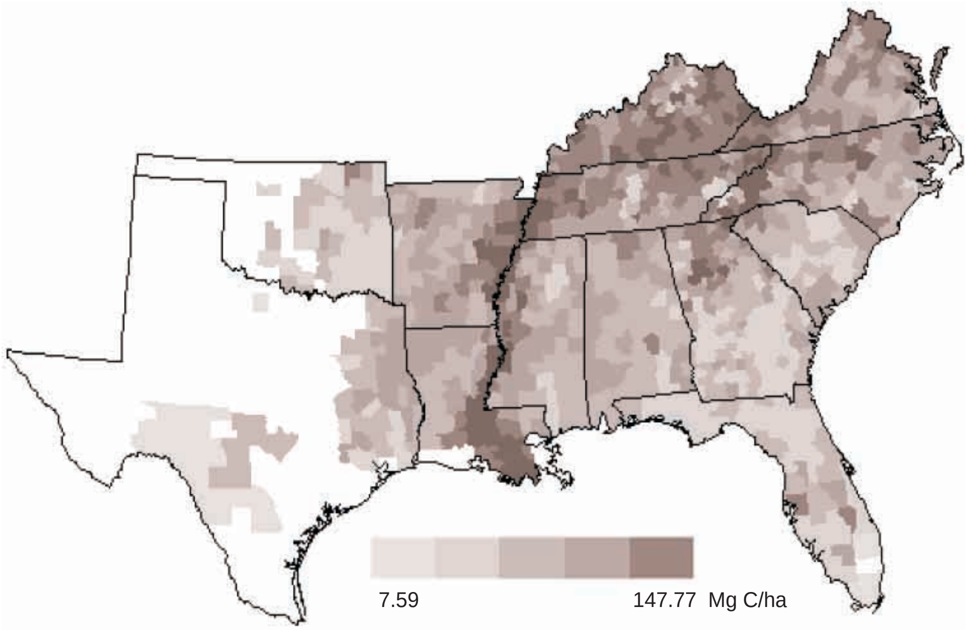

Figure 33.1—Aboveground carbon (C) density (Mg C/ha) for forested lands in 1997 in the Southern United States.

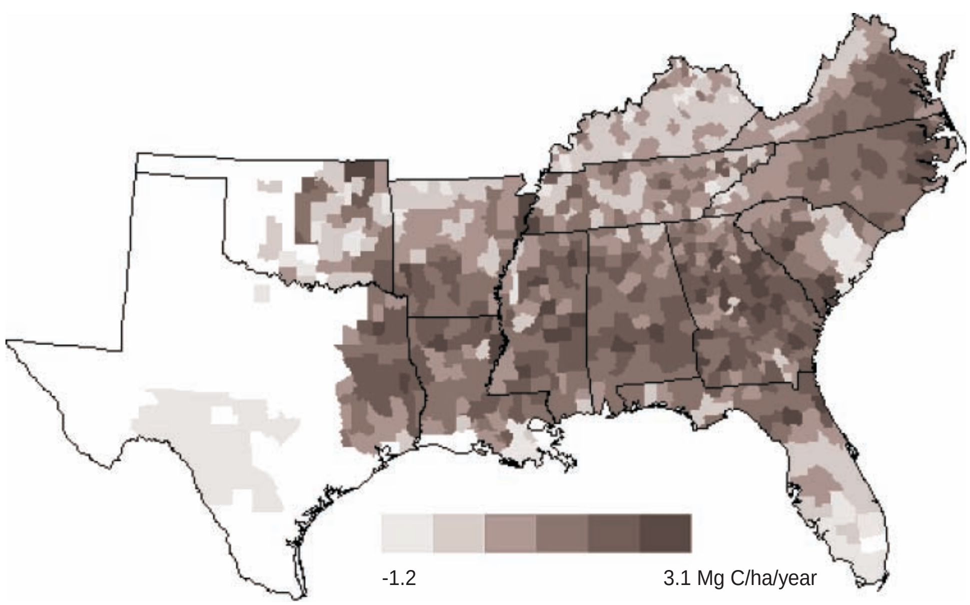

Figure 33.2—Mean net annual tree growth 1953–97 in terms of carbon (C) density (Mg C/ha/year) for forested lands in the Southern United States.

privately owned pine forest in the South decreased by 18 percent, but total C in trees decreased by only about 2 percent (see table 33.2). During this interval, the proportion of planted pine to all pines increased from about 2 percent to about 50 percent.

An estimate of the annual forest contribution of C for each Southern State is presented in figure 33.4. Estimates of C in harvested wood products are given in figure 33.5. All States have increased C in forests over the period. A number of States have sequestered 5 to 6 Mt C per year in forest ecosystems. Many States have also sequestered an additional 2 to 3 Mt C per year in products in use and landfills, with an additional amount of C in wood burned for energy.

Estimates of Forest Carbon Stocks 2000–2100

One can only speculate about the effects of global climate change and socioeconomic responses to the change on the future composition of forest ecosystems. The analysis reported here provides an estimate of potential forest production for 2000, 2050, and 2100 for the Southeastern United States. This analysis is based on an uncalibrated model of forest C balance, a warmer and wetter climate projected under the Hadley2Sul scenario, and forest cover from Landsat TM data (table 33.3). The trend in total forest C stocks between 2000 and 2050 was generally steady C accumulation throughout the period for States in the northern portion of the region and decreased C accumulation in

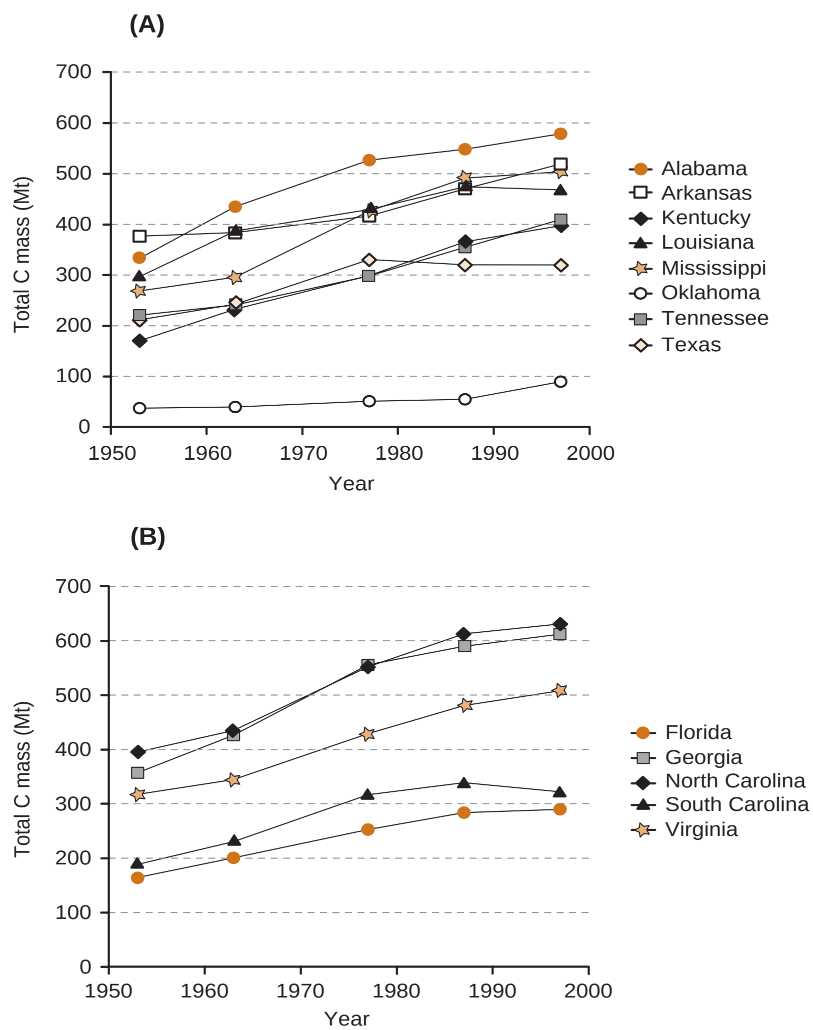

Figure 33.3—Estimated total aboveground forest carbon (C) stock for (A) Southcentral and (B) Southeastern States 1953–97. Total C mass (Mt) is for all productive forest land within each State. Aboveground C includes that in live and dead trees, understory vegetation, down dead wood, and the forest floor.

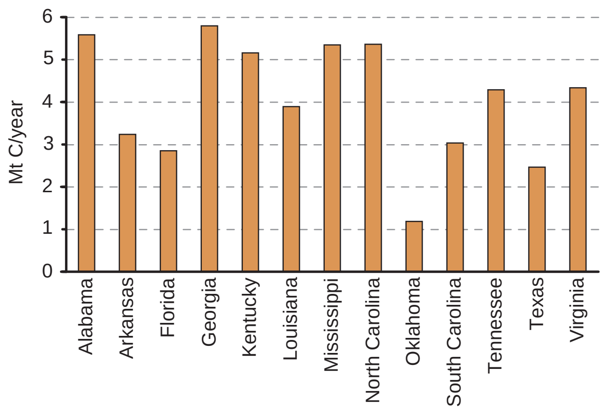

Figure 33.4—Estimated mean annual change in aboveground forest carbon stock 1953–97. Estimates are for productive forest land.

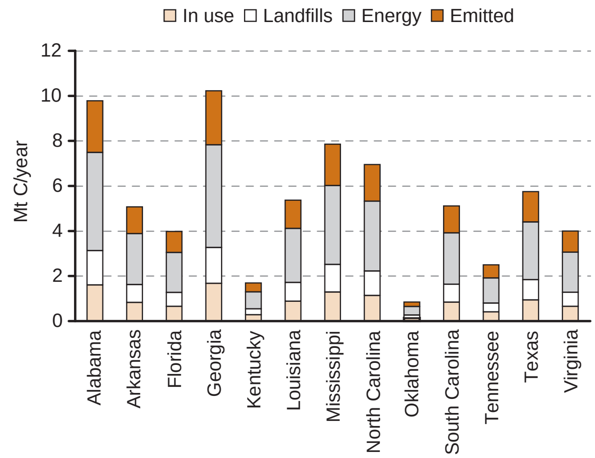

Figure 33.5—Estimated mean annual change of carbon in the harvested products categories 1953–97.

Table 33.3—Hadley 2000, 2050, and 2100 minimum, maximum, and average net primary production for all forest types

	Hadley 2000			Hadley 2050			Hadley 2100		
State	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
	g carbon/m²/year								
Alabama	1064.2	2320.7	1313.9	1080.6	2158.0	1338.3	674.5	1761.8	1197.4
Arkansas	885.6	1464.4	1151.0	822.9	1480.3	1117.4	744.5	1534.7	1158.1
Florida	1172.8	2320.7	1554.6	1020.9	2191.6	1430.5	391.2	1806.0	1088.4
Georgia	1049.9	2019.8	1298.1	1004.4	1954.7	1323.5	360.2	2026.3	1127.4
Kentucky	997.3	1544.2	1213.2	1017.9	1702.7	1344.8	1006.2	1633.1	1328.5
Louisiana	1037.5	2331.2	1506.9	893.3	2171.1	1363.1	805.8	1755.7	1225.4
Mississippi	1078.1	2086.4	1367.4	999.0	2013.9	1310.2	884.9	1629.6	1210.0
North Carolina	1078.5	2135.5	1424.4	1269.9	2280.3	1627.4	1152.8	2222.0	1488.3
Oklahoma	892.5	1357.3	1107.6	800.1	1224.7	1015.3	546.5	1390.4	1006.0
South Carolina	1060.3	1900.4	1339.2	1184.8	2174.0	1462.1	600.7	2222.0	1344.7
Tennessee	1034.3	1595.2	1286.7	1019.2	1899.3	1402.4	1013.0	1926.5	1371.9
Texas	871.6	2079.4	1202.0	721.9	1933.6	1055.1	597.9	1628.3	1015.1
Virginia	646.8	1936.4	1242.2	785.8	2173.1	1437.5	801.9	1910.3	1359.0
Regional	646.8	2331.2	1313.5	721.9	2280.3	1354.3	360.2	2222.0	1250.7

the Southern States (figs. 33.6A and 33.6B). There is a projected decreasing trend in total forest C stocks between 2050 and 2100 for all States in the region (figs. 33.6B and 33.6C). Future trends in climate suggest increasing air temperature that will affect woody tissue respiration, evapotranspiration, and the development of diurnal and seasonal water stress. Air temperature will likely be a contributing factor in lowering future forest productivity, especially along the Gulf Coastal Plains.

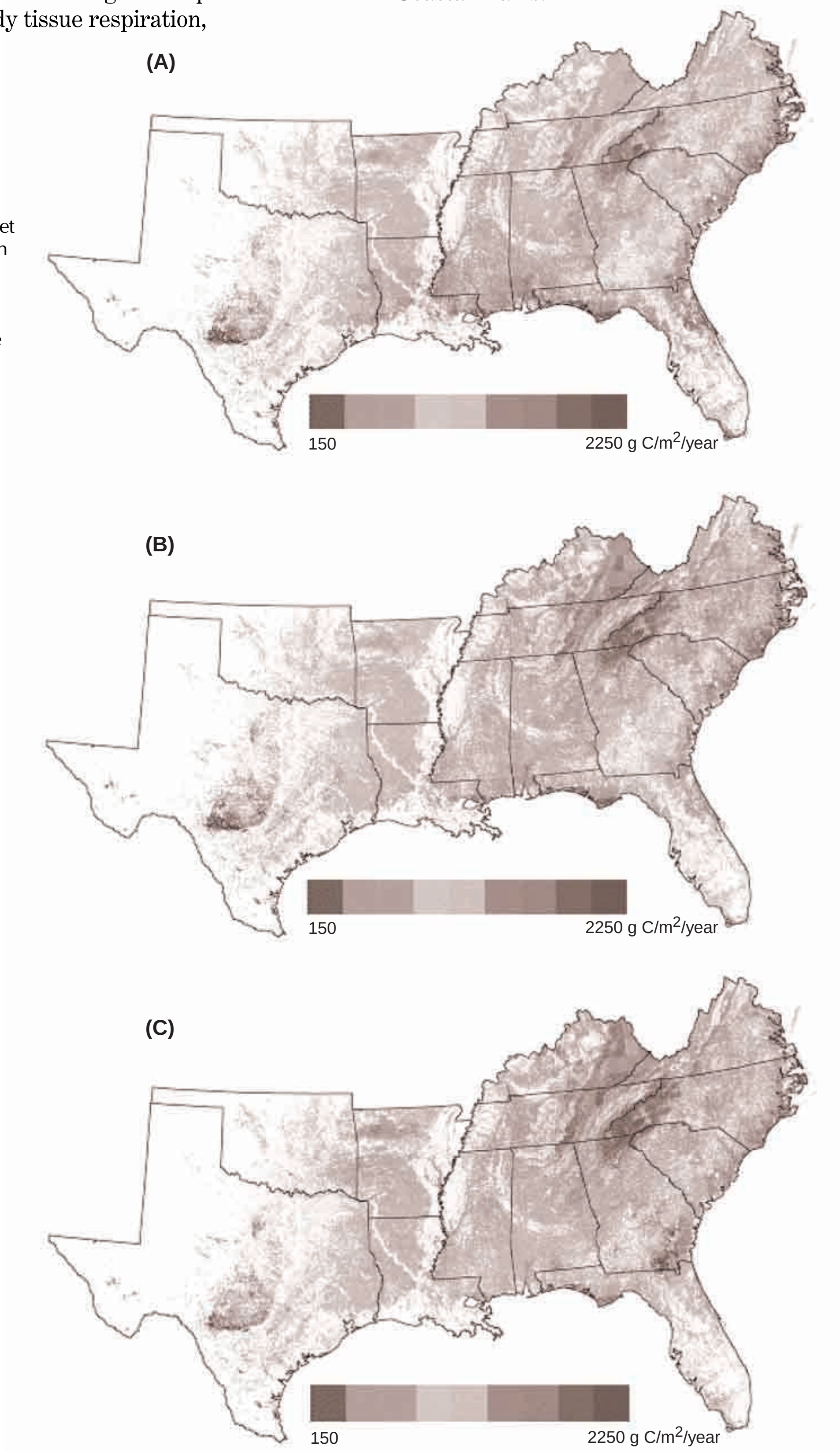

Figure 33. 6—Estimated annual net primary production [g carbon (C) m^2/year] for all forest types using the Hadley2Sul climate scenario for (A) 2000, (B) 2050, and (C) 2100.

ACKNOWLEDGMENTS

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Southern forests provide innumerable benefits. Forest scientists, managers, owners, and users have in common the desire to improve the condition of these forests and the ecosystems they support. A first step is to understand the contributions science has made and continues to make to the care and management of forests. This book represents a celebration of past accomplishments, summarizes the current state of knowledge, and creates a vision for the future of southern forestry research and management. Chapters are organized into seven sections: “Looking Back,” “Productivity,” “Forest Health,” “Water and Soils,” “Socioeconomic,” “Biodiversity,” and “Climate Change.” Each section is preceded by a brief introductory chapter. Authors were encouraged to focus on the most important aspects of their topics; citations are included to guide readers to further information.

Keywords: Biodiversity, climate change, forest health, forest history, productivity, socioeconomics, soil, water.

     

The Forest Service, United States Department of Agriculture (USDA), is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

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