7 Adapting Silviculture to a Changing Climate in the Southern United States

James M. Guldin

CONTENTS

Questions about how forests might respond to climate change are often addressed through planning, prediction, and modeling at the landscape scale. A recent synthesis of climate-change impacts on forest management and policy found that the earth is warmer than it has been in the recent past, and that 11 of the last 12 years rank among the 12 warmest since 1850 (Solomon et al. 2007). Projections are that global average surface temperatures will be 3.25–7.2°F warmer at the end of the this century, and the concern is that this will lead to an increase in the frequency and severity of natural disturbances such as wildfires, insect outbreaks, and disease epidemics (Dale et al. 2001; Malmsheimer et al. 2008).

For many scientists, the question is not whether a changing climate affects forests, but how and when the effects might occur. Certainly, major regional shifts in climate have occurred before, but not since European settlement of North America and not with the world's population at 7 billion. Within a global context, questions persist about whether climate change is a naturally occurring event, caused by human activity, or a combination of both. That debate is best conducted in academic and legislative circles, provided that sufficient and credible information is available to inform the policy decisions being considered about the ecological, economic, and social conditions that a changing climate could bring to modern society.

On the other hand, from the perspective of foresters and natural resource managers working in the woods, deciding whether climate change is a natural or human-caused phenomenon does not help answer the question of what to do about it. One obvious response is that we must alter the species composition of our forests to account for the likelihood that the natural ranges of species could change. But practical issues are at play that will likely limit our ability to promote widespread changes in species composition at the landscape scale, especially in the forests of the Southern United States.

UNLIKELY PROSPECTS FOR AN EASY SOLUTION

A sense of the scale of the challenge inherent in making dramatic changes in species composition, and some perspective on what that might cost, can be appreciated by reviewing the South's experience with the rise of intensive plantation management of southern pines (*Pinus* spp.). There are about 200 million acres of timberland in the Southern United States (Wear and Greis 2002). From about 1950 to 2010, the active management of forest lands in the South led to the conversion of about 35 million acres of that timberland from naturally regenerated stands—pines, pines and hardwoods, and oaks (*Quercus* spp.) and pines—into pine plantations. Moreover, projections are that by 2050, an additional 15 million acres beyond that currently converted will also be in plantations (Wear and Greis 2002). Most plantations occupy land owned or managed by forest industry or acquired from forest industry owners by timber investment management organizations or real estate investment trusts (Binkley et al. 1996; Bliss et al. 2010). Virtually all are being managed primarily for industrial wood production.

In essence, by 2050, it will have taken 100 years to convert a quarter of the South's 200 million forested acres from natural mixed stands to pure or mostly pure pine plantations, or about 500,000 acres a year. Because conversions occurred primarily on privately owned land managed by forest industry and timberland investment owners, they were the easiest from an operational perspective; all that was needed was a corporate decision, with minimal complications socially and politically.

This conversion has not been inexpensive. In classical forest economics, the cost of establishing a new forest stand is independent of the proceeds from harvesting the previous stand. So the investment in a new pine plantation encompasses site preparation, disposal of slash, treatment of competing vegetation, treatment of the forest floor as needed, reforestation through planting genetically improved pines, and release of the pines through chemical applications and fertilization. The cost of stand establishment was an estimated \$250 per acre for the 35 million acres established from 1950 through 2010 (Barlow et al. 2009), resulting in a nearly \$9 billion investment over the 60 years. Converting another 15 million acres from 2010 to 2050 at the current rate of \$400 per acre (Barlow et al. 2009) would cost another \$6 billion. In short, the bill for converting a quarter of the South's forests from naturally regenerated stands to intensively managed plantations during the period from 1950 to 2050 would be roughly \$15 billion (or \$150 million annually), and 500,000 acres was converted annually to stay on schedule. Forest industry and timberland investment owners were more than willing to underwrite this expense, because doing so has guaranteed a continuous supply of wood and fiber (Figure 7.1).

Given the cost, the acreage involved, and the fact that both public and nonindustrial private forest land ownership comes into play, the likelihood of a "climate change conservation program" on a significant portion of the remaining 75% of southern forests is difficult to imagine. Suppose, for example, we knew with certainty that by 2060, another 25% of the southern forested land base would be subjected to conditions not conducive for sustainability of the forest types they currently support. Harvesting those 50 million acres and replacing them with forest types that are better adapted to the expected habitat conditions could become a regional or national priority. But over the next 50 years, this would require conversion of a million acres a year (twice the historical rate of plantation conversions) at an annual cost of \$400 million, given an estimated cost of \$400 an acre. To date, no federal, state, local, or private entity has given any indication to support a climate change conservation program remotely approaching this scale and cost.

Moreover, converting lands not held by industrial or investment owners prompts questions about who has the authority to make such decisions. On private lands, which are held by a range of corporate and individual owners including farmers, retirees, families, trusts, estates, partnerships, businesses, clubs, and tribes, any conversion would probably need to be voluntary, and would have complicated social, political, and legal ramifications. It is easy to imagine that

FIGURE 7.1 Two loblolly pine plantations in Ashley County (Arkansas) typify widespread forest type conversions across the Southern United States. (Photo by James M. Guldin.)

landowners currently active in forest management would be more comfortable investing in forest conversion for climate change, especially if issues of forest health were involved. Others, who have not been active forest managers in the past, might not be persuaded to be in the future, especially if out-of-pocket investment is required. On public lands such as National Forests, regulations are in place that might allow timber sale proceeds to help support the costs of conversion. But the more difficult challenge for National Forest land managers would be convincing the public to support this activity; traditional user groups and the public in general might raise substantial questions about managing National Forests in such an intensive program of widespread forest conversion.

Finally, all this speculation assumes that natural resource managers and scientists know how to manage forests for species movement and assisted migration, and whether this would be effective—but we do not. And even if we did, our understanding of interactions among tree species, and between tree species and less dominant shrub and herb species needed to properly relocate a forest ecosystem, are virtually nonexistent. Moreover, our technical ability to raising sufficient nursery stock for herbaceous annual and woody perennial plants is limited in scale and scope. In essence, it is easy to advocate the importance of region-wide forest conversion, but the practical implementation of it at an ecologically meaningful scale for landowners who may be unwilling or unable to commit the necessary resources would be simply impossible in the current economic and political climate.

The likely outcome of this speculation is fairly straightforward: for the immediate future, the best efforts to manage forests in ways that promote adaptation to climate change will be incorporated into existing forest management activities, most likely on land where active management already occurs—by forest industry, by private landowners taking advantage of stewardship or tree farm programs with the help of consulting foresters, and by natural resource managers on federal, state, and local government lands.

A potentially more interesting question from the perspective of stand-level silviculture can be stated simply: *What can be done during the course of active management on public and private lands that would increase the resistance and resilience of forest stands within the context of climate change?* Research is needed on what silvicultural practices would be appropriate to apply to a given stand in an environment of climate change, and how a forester might apply them. As with most decisions that affect forest management, the kinds of silvicultural prescriptions that foresters might consider under a changing climate will vary depending on land ownership objectives, forest types, and the geographic location. And perhaps most importantly, implementation requires a consistent landowner commitment to active forest management.

A SILVICULTURAL PERSPECTIVE

The practical questions that foresters face in managing forest stands revolve around predictions of how a given stand would be affected by changing climate conditions and determinations of the specific silvicultural practices that would be useful in that context. The silvicultural prescription must essentially carry a stand from its current condition to some desired future condition. Increasingly, natural resource professionals and technicians with tree-marking paint guns in the woods are confronted by the uncertainty of changing climate conditions and the uncertainty of how local conditions might change, but they must implement the silvicultural prescription in spite of these uncertain outcomes.

However, this is not a great philosophical leap for foresters to make. Natural disturbances often derail long-term management plans, and foresters are adept at modifying silvicultural plans to fit new local conditions. Some thought must be given to the specific practices that promote stand resistance to disturbance, as well as those that enable forests to recover or to be reestablished should disturbance events cause significant damage. In this chapter a broad range of silvicultural concepts is suggested within the context of adaptive management under changing climate conditions that would enable existing practices to become more robust in a changing environment. Perhaps the same arguments being made about adaptive response to changing climatic conditions per se should be expanded to address other ecological forcing factors likely to be important in the future—increasing concentration of atmospheric carbon dioxide, increasing effects of invasive species, and ongoing effects of air pollution, for example.

Adaptive management to address climate change depends on two concepts that govern the response of forests to any disturbance, resistance, and resilience (see definitions in Chapter 3). Briefly, resistance is the ability to withstand impacts, allowing a stand to maintain its structure and developmental trajectory under the influence of changes. Conversely, resilience is the ability of a stand to recover from damages after a disturbance, quickly recovering its structure and developmental trajectory or assuming a different structure and developmental dynamic in the aftermath of change events.

These are practical and current questions. Regarding national forests, demand is growing for management activities that reflect a consideration of climate change, and resource managers are struggling to respond. Issues of climate change have implications for stand-level decisions on intensively managed industrial and investment lands as well. And what does a consulting forester propose if a client asks for management advice that will preserve the family forest in a changing climate?

The three dominant silviculture textbooks (Daniel et al. 1979; Nyland 2002; Smith et al. 1997) define silviculture as an ecological science subject to economic and social constraints. But the questions surrounding climate change suggest a modification, or at least a more explicit understanding, that silviculture is an applied science that will be increasingly influenced by changing ecological conditions in the future.

This definition offers foresters more freedom to adapt silvicultural practices from the academic perspective of changing ecological conditions. Those practicing in southern forests have faced significant ecological changes in the past: the loss of the American chestnut (*Castanea dentata*), changes in forest conditions created by the gypsy moth (*Lymantria dispar*) and southern pine beetle (*Dendroctonus frontalis*), and most recently, the challenges associated with the loss of eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*Tsuga caroliniana*) from the hemlock woolly adelgid (*Adelges tsugae*). The profession itself developed in response to concerns about the sustainability of eastern forests during and after the wave of logging of the virgin forests more than a century ago.

From this historical perspective, acknowledging or refuting whether climate change is occurring is less relevant than understanding how the practice of silviculture would be modified if a given forest stand faced uncertain ecological changes over time. In addition, it might be unwise to propose widely different silvicultural practices or prescriptions than those currently being used; after all, the models of projected changes may be incorrect, and observed changes may not be as ecologically important in some areas versus others. Also, consideration must be given to the geographic range of species being managed because silvicultural practices proposed for a species in the heart of its natural range may be different from those that would be proposed for the same species near the limits of its range.

SILVICULTURAL SYSTEMS

The three silviculture textbooks cited above generally separate silvicultural systems into three stages: (1) establishment of regeneration and associated treatments, (2) treatments applied to improve immature stands, and (3) reproduction cutting applied from stand maturity through final harvesting. Opportunities to prescribe stand-level treatments that address climate change will vary among these three stages.

Twentieth-century science provided the tools needed for most of the managed forest types in the South. At the beginning of the century, cutting the virgin forest left southern forests in understocked and unproductive condition. The professional response was to ensure recovery with a host of silvicultural systems and regeneration methods (Dana 1951). The range of intensity was broad. Approaches that built on natural stand management were highlighted by the "manage what remains" approach that evolved into even-aged shelterwood and uneven-aged selection methods for southern pines in the Atlantic and western Gulf Coastal Plain from the 1930s to 1960 (Chapman 1942; Guldin and Baker 1998; Reynolds 1959). Approaches that relied on artificial regeneration included tremendous efforts at afforestation of cutover lands epitomized by the Yazoo-Little Tallahatchie Flood Control Project in the 1950s (Williston 1988), development of direct seeding technology to restore vast areas of denuded forests in the lower western Coastal Plain (Derr and Mann 1971), and, of course, the development of technology for planting pines that led directly to the tree improvement programs and revolutionized intensive forestry across the South (Fox et al. 2007; Wakeley 1954). Managing second-growth southern pines created a boom in industry towns such as Franklin, VA; St. Joe, FL; Mobile, AL; Crossett, AR; Bogalusa, LA; and Diboll, TX.

The second half of the twentieth century also saw outstanding application of science to forestry, including development of genetically improved planting stock and nursery practices to outplant superior seedlings of loblolly pine (*Pinus taeda*) and three other major pines species and hardwoods such as eastern cottonwood (*Populus deltoides*) for commercial timber and fiber production. The associated science to ensure establishment, survival, and growth of planted southern pines may be the greatest success story of southern forestry. But significant advances also occurred in the development of natural regeneration methods (Figure 7.2)—the shelterwood method for sustainability of longleaf pine (*Pinus palustris*) on the Coastal Plain (Croker and Boyer 1975) and on upland stands of oak and hickory (*Carya* spp.) in the Southern Appalachian Mountains (Loftis 1990); the irregular shelterwood method in naturally regenerated loblolly and shortleaf (*Pinus echinata*) pine stands in the upper western Coastal Plain championed by the Crossett Division of Georgia-Pacific LLC through the 1990s (Zeide and Sharer 2000); the continued work with low-cost natural regeneration alternatives in southern forests for public and private landowners in North Carolina, Georgia, and Arkansas (Guldin 2004); and restoration of pine-woodland communities on Red Hills hunting preserves (Masters et al. 2007) and national forests west of the Mississippi (Guldin 2008), both of which helped reverse declines in red-cockaded woodpecker populations (Figure 7.3).

These successes of the twentieth century have helped the natural resources community focus on the fundamental question of forest sustainability. Although people often think that forest

FIGURE 7.2 The shelterwood reproduction cutting method applied in longleaf pine stands on the Savannah River Forest Site (South Carolina). (Photo by David Wilson.)

sustainability means avoiding active management altogether, the reverse is actually true for the simple reason that forests continually grow and renew themselves in dynamic ways and that southern forests especially grow rapidly. In addition, human populations are dynamic and increasing, which places an ever-increasing strain on the timber, recreation, water, and wildlife resources that southern forests provide.

Across the South, forest sustainability can be defined as the ability of forests to meet the needs of society in a continual way over time, despite the increasing influence of human populations on

FIGURE 7.3 Pine-woodland restoration of longleaf pine stands on the lower western Coastal Plain, Sam Houston National Forest in Walker County (Texas). (Photo by James M. Guldin.)

forest cover and the encroachment of urban areas into wildlands—and quite possibly, amid a changing climate. But for the silviculturist, forest sustainability is achieved one stand at a time, and the question boils down to this: how to ensure the successful establishment and development of the desired species in a new age class or stand after harvesting. This is important, because if the plans of the silviculturist are properly made, over time the new age class will eventually consist of the desired primary and dominant species from seedlings to saplings, through pulpwood size classes, and eventually into sawtimber size classes.

Regeneration Establishment

The best single opportunity to influence the future direction of management in a forest stand is during the regeneration phase. The mode of origin of a new age cohort (whether planted or from natural regeneration, from seeds or sprouts), the variability of species composition, and the genetic identity and variability within the species in the new age cohort are elements that the silviculturist can influence. They have implications for the future of the stand regardless of forest landowner or management scenario.

Moreover, once a new regeneration cohort is established and has grown past the sapling stage, the ability to add new species or genotypes quickly diminishes. That cohort is off on its own, to grow within the weather events and climate conditions that will nurture or challenge the trees within it, to the point of maturity and harvesting. The only opportunity to modify the development of that original cohort is by removing some of it, establishing a new age cohort to co-occupy the site, or by removing that original cohort and starting anew. Thus, if the concern is about conditions that may change over time, the best advice for the forester is to choose the best species to plant, or to encourage the development of the desired species, density, and distribution during natural regeneration.

Essentially, the silviculturist considering the establishment of a new age cohort on a given site should assess the likelihood of changing climatic conditions on that site over the life of that new age cohort, and should consider whether to modify the new age cohort by adding species absent from the site, or perhaps using a genetically improved family line known to be successful under those climatic conditions that are expected, such as a drought-tolerant family of loblolly pine in the western part of the species' natural range, for example.

Planting is the most certain tool for successful stand establishment and development because it offers the forester the most control over seedling density and supplemental treatments. It is also an effective way to modify the genetics of a species currently found on the site that might be of questionable origin (e.g., survivors of previous mismanagement), and it is the most certain way to import or re-introduce a species that is absent from the existing stand. Conversely, natural regeneration depends upon existing seed sources in the stand. It can vary if for no other reason than the sporadic nature of seed crops, which can range from nearly every year in loblolly pine stands on the western Coastal Plain (Cain and Shelton 2001) to one year in three for shortleaf pine stands in the Interior Highlands (Shelton and Wittwer 1996) to one or two years a decade in longleaf pine stands along the Gulf of Mexico (Boyer 1991). Textbooks tell foresters to correlate harvesting and site preparation with anticipated cone crops when planning for natural regeneration, but this is difficult to do in practice. An easier and more effective approach is to establish advance growth of desired seedlings before harvesting, and then release the already-established age cohort during harvesting—a tactic that is critical to the success of the even-aged shelterwood and uneven-aged selection methods.

These decisions about the kind of regeneration to use are closely tied to the choice of reproduction cutting method to use, which in turn affects whether the new stand is naturally regenerated or planted; whether its origin is seeds, sprouts, or clones; and whether species composition is narrow or broad. These choices influence subsequent management under even-aged or uneven-aged systems as well as the duration of even-aged rotations or length of cutting-cycle harvests.

FIGURE 7.4 A mixed shortleaf pine-oak regeneration cohort after precommercial thinning and prescribed burning, established after the seed cut in an irregular shelterwood regeneration of a shortleaf pine stand on the Ouachita National Forest in Scott County (Arkansas). (Photo by James M. Guldin.)

The establishment of a new regeneration cohort (Figure 7.4) is the single-most important decision that guides how a stand will adapt to changing climate conditions, should they occur. The desired species or mixtures of species must be robust in the current climate, because it is in the current climate that the new age cohort must be successfully established. But the new age cohort must also be robust within the context of the future climate, at least for the length of time that the forester expects the new stand to occupy the site.

Unfortunately, the early hurdles are also the highest. For natural regeneration, the probability of mortality is highest in the first growing season; similarly, for planted seedlings, mortality is highest in the first season after outplanting. So even if the new age cohort is planned for a changing climatic condition that will be robust 30 or 40 years into the rotation, the most immediate concern is in the first year from threats such as drought-related mortality (e.g., Lambeth et al. 1984).

Genetic Variability of Regeneration

Genetic diversity is recognized as the best safeguard against ecological uncertainties such as climate change (Ledig and Kitzmiller 1992). Silviculturists have long observed a difference between methods in which stands regenerate from seed (high forest) and methods in which they regenerate from sprouts and stumps (low forest). The reality is that both forms of regeneration are often at work in combination, especially in naturally regenerated stands. In pine plantations, there are questions about whether to plant seedlings from one or more genetically improved families, which would provide some degree of genetic variability; plantations can also be established using clonal stock (pines) or clonal cuttings—cottonwood (*Populus* spp.), for example—where all of the trees in the new age cohort are genetically identical from one clone, or planted using a small number of clones, within each of which individuals are genetically identical.

This distinction is important for silviculturists to consider within the context of a changing climate. Conceptually, whether a regeneration cohort is dominated by trees grown from seeds or from sprouts or clones determines whether it will be genetically variable or genetically uniform, which brings concepts of fitness versus flexibility from the domain of forest genetics into play.

Regenerating for genetic fitness: Fitness is the domain of asexual reproduction, or sprouting. The traditional approach in this context is where new sprouts develop after the parent tree is cut or top-killed. If a tree has been previously successful on a given site or in a given stand, a sprout from that parent will have identical genetic composition, and should be adapted to the site and optimized for success in the future. The underlying assumption, of course, is that environmental conditions in the future will be identical to the conditions in the past, an assumption that comes into question within the context of climate change.

In southern forestry, sprouts are important in oak-dominated forests; also occasionally in shortleaf pines (Figure 7.5) where sprouting only occurs in seedlings and saplings as an adaptation to fire (Mattoon 1915). In hardwoods, especially oaks, sprouting is a more complicated process. Some sprouts develop as seedling or sapling sprouts in the well-known process of advance growth (Johnson et al. 2002); these sprouts originated from acorn germination, and thus represent new genotypes not genetically identical to the parent trees. When established beneath a fully stocked mature stand, these oak seedlings grow, die back, resprout, grow larger, die back, resprout, grow still larger, and so on for a number of iterations. All the while, the rootstock continues to develop in size and vigor. When the overstory is removed by harvesting or through another disturbance, these larger advance-growth saplings have a good chance to dominate in the new age cohort of seedlings. But it is often the case that this desirable advance growth of seedling and sapling sprouts is inadequate to

FIGURE 7.5 Shortleaf pine resprouting after being top-killed by summer prescribed fire on the Ouachita National Forest in Scott County (Arkansas). (Photo by Richard Straight.)

reforest the site. In this situation, sprouting from stumps or roots, which in fact are clones that are genetically identical to the parent tree, are used to supplement stocking from advance growth. This process has been well quantified, and predictive models are available to determine whether advance growth in a given stand is adequate or must be supplemented with stump or root sprouts (Johnson et al. 2002; Sander 1971; Sander et al. 1984). Thus, the regeneration cohort in most naturally regenerated oak-hickory stands includes a varying mixture of seed-origin and sprout-origin stock.

Sprouts also have a role in certain intensive forestry applications. Commercial production of cottonwood on short rotations along the Mississippi River uses planting stock consisting of 0.5-m sprouts cut from the roots or stumps of preferred clones. Each sprout is planted such that most is below ground, leaving only a small portion protruding above ground with buds oriented upward so they can sprout and develop into a new sapling. Clonal propagation of pines has developed in commercial plantations as well, such that a new stand can be established with one or more genetically identical clones selected for fast growth and optimum development. The primary disadvantage is the potential for reduced genetic diversity, especially if only one clone is used in the plantation.

Regenerating for genetic flexibility: Genetic flexibility is the domain of sexual reproduction, during which genetic recombination and gene flow result in outcrossed progeny that have different genetic traits from their parents. In periods of ecological uncertainty, a diverse age cohort with many individuals that collectively have a variable genetic base would be a good starting point for establishing a new stand. As weather and climate influence the stand, seedlings and saplings will express their genetic potential and develop within the environment in which they find themselves. Some individuals will develop more capably than others, based on their ability to express dominance, capture available resources, and compete successfully with their neighbors.

Over the past 70 years, genetic improvement programs have taken advantage of the inherent genetic variability in southern pines to identify families selected from the wild that have superior growth and form, evaluate controlled crosses of those selected families in progeny tests and outplanting, and identify families that far outperform average open-pollinated pines (Allen et al. 2005; Fox et al. 2007). Most of the pine plantations established in the South derive from several dozen common improved families whose geographic origin is well known by tree improvement cooperatives, but are perhaps less well known to forest managers and landowners. In seed orchards, mature trees from these families are managed for seed production using a variety of techniques, including bulk seed orchard collections where neither parent is known, open-pollinated collections where the maternal parent is known, and full-sib collections where both parents are known (McKeand et al. 2003). Most seed collected is open-pollinated, the hope being that the paternal parent is from another improved family within the seed orchard, but pollen might also come from unimproved wild trees in the area. Whether open-pollinated or full-sib origin, though, meiosis and gene recombination occur so that collected seeds have inherent genetic variability rather than being genetically identical.

A spectrum of tradeoffs: Based on this discussion, the tree breeder's dilemma is clearly one of gain versus risk (McKeand et al. 2003): gain in product volume and homogeneity versus risk of loss should the families that are outplanted suddenly encounter a disturbance event to which they are unable to adapt.

In the spectrum of genetic variability in regenerating stands, the greatest variability consists of a diversity of species that have established a new age cohort from seed origin. Intermediate genetic variability consists of a more narrow distribution of species with new propagules of seed (or seedling sprout) origin, possibly including some clonal progeny originating as sprouts from the previously harvested stand. Plantations established using orchard bulk lot, open-pollinated families, or full sib families still have a good deal of inherent genetic variability, especially if the families that are planted vary within a given ownership across stands. The least genetic variability is found in clonal plantings, especially if only one clone is used across a stand.

Within the context of climate change, the genetic variability of a given regeneration cohort in a stand under management will be an important consideration for silviculturists, and for landowners.

The decision space will include a projection of the gain-versus-risk tradeoff for the expected duration of the new age cohort. At the more variable end of this spectrum, the silvicultural approach would be to establish a wide variety of species of seed origin and then "let nature sort them out." At the less variable end, the gamble might be that the new cohort could reach maturity "before a changing environment wipes them out."

A few pine progeny tests in the South offer some guidance with respect to movement of seed sources. Schmidtling (1992, 1994) suggests that average monthly minimum temperature is a better predictor of successful seed movement in loblolly pine than average monthly temperature. Wells and Wakeley (1966) found that northward movement of seed sources results in improved growth over local sources, but movement too far north results in damage from early bud break.

In theory, a number of opportunities exist to make better decisions along the spectrum of genetic variability, but what is missing is research to support them. For example, one way that climate change is predicted to act in the western Coastal Plain is through increases in the mean minimum monthly temperatures, but scientists do not understand the performance of open-pollinated families, full-sib families, or clones with respect to this; if we did, we might be able to recommend a given family or clone for the expected change in mean minimum monthly temperature. If a stand under management is near the southern limit of its dominant species' range and just north of another species' range, the question that arises is whether to rely on native seed through natural regeneration, use planting to enrich or supplement the genetic variability of the dominant species, or diversify by planting some of the neighboring species. Research is needed to advance understanding of silvicultural tactics such as these, especially with respect to underplanting or interplanting, which is generally less successful than planting in the open (Jones 1975; Wakeley 1968).

There are also questions about how well our existing set of improved families and clones of loblolly pine will compete in conditions different from those in which their families were initially evaluated, or in an environment where interspecific competition early on is common. Schmidtling (1994) reported that native populations of loblolly pine west of the Mississippi River behaved differently from those on the eastern side because of the confounding effect of increasingly xeric conditions, which is exactly what part of the region may face according to some climate change models. Foresters do not have much experience with planting a minor component of a different species, either within or outside its natural range, that is absent from an existing regeneration cohort.

There is a practical question as well, similar to some of the challenges faced in longleaf pine restoration, and that is finding sufficient quantities of seed of proper genetic origin for restoration in a climate change context, and sufficient nursery capacity to grow the quantity of seedlings required. And finally, there are questions about quantifying a landscape model of genetic variability within the context of changing climatic conditions that would help evaluate the potential success of a new age cohort at a given location within that landscape. The answers to these and other questions—both basic and from applied science—will be important to those making silvicultural prescriptions for managed forests in the upcoming century.

Intermediate Treatments

Intermediate treatments are applied in immature stands to ensure that individual trees of the desired species will develop and to maintain the health, diversity, productivity, and sustainability of the stand. Practices include precommercial and commercial thinning (Figure 7.6), stand improvement treatments that remove undesirable individuals or species competing with the desired species, pruning to improve wood quality, and treatments such as prescribed burning that maintain desired structural conditions (Figure 7.7).

Commercial thinning is by far the most common intermediate treatment. Usually, the trees that are cut during thinning are removed so as to improve the growth and vigor of the trees that remain, and to provide some economic return to the landowner. Sometimes these priorities get reversed, so that the financial return from harvesting is of greater interest to the landowner than the silvicultural

FIGURE 7.6 The first commercial row-thinning in an overstocked, privately-owned loblolly pine plantation in Bradley County (Arkansas). (Photo by James M. Guldin.)

FIGURE 7.7 Prescribed burning on the Crossett Experimental Forest in Ashley County (Arkansas). (Photo by Virginia McDaniel.)

benefit, but that moves the treatment away from the realm of good silviculture to the less desirable practice of high-grading or selective cutting. A proper thinning has the goal of improving stem density and growth of the best trees in the stand.

A key element in the definition of intermediate treatments is the notion of stand immaturity. These treatments are not intended to secure a new cohort of natural regeneration for a mature stand, although that is the occasional, albeit accidental, outcome. Instead, the goal is to manipulate species composition and growth so that the stand will develop more rapidly and will support habitat conditions that better meet the needs of the landowner than if the treatment had not been applied. If natural regeneration happens to result from the thinning, the savvy silviculturist is one who focuses on the future development of dominant and codominant trees rather than on the happenstance new crop of regeneration.

The value of intermediate treatments in the face of disturbances was quantified in the pest management literature from the latter part of the last century, specifically with respect to research on southern pine beetle hazard and risk by Belanger (1980). He discovered that pine stands differ in their susceptibility based on site and stand conditions, and that thinning to a certain residual basal area on certain sites at a certain stand age reduces the likelihood of outbreaks. This phenomenon is probably associated with the beneficial effect of thinning on tree vigor, because vigorous trees produce higher levels of oleoresin that are thought to defeat the beetle's effort to infest the tree.

Many foresters assume that thinning and other intermediate treatments designed to maintain vigorous stands full of healthy trees are an important defense against changing climate conditions. But success will likely depend on the nature of the disturbance events associated with changing climate. For example, an increase in the extent and severity of summer drought might increase wildfire activity. In that event, maintaining thinned stands with an open understory through midstory removals and prescribed burning might be an effective tactic. This was found to be effective in limiting stand mortality, but not in halting overall wildfire spread, during the 2002 Hayman fire in Colorado (Graham 2003). Moreover, a failure to conduct a timely thinning or to control understory vegetation in an immature stand has been viewed more as a lost opportunity than a serious silvicultural mistake, but that failure to prescribe timely treatments may become more of a risk under changing climate and associated disturbance events.

Resilience depends on the kind of damage a stand suffers during a disturbance event, and the degree to which a manageable residual stand will survive. In the upper western Coastal Plain, research on rehabilitation of understocked stands (Baker and Shelton 1998a,b,c,d) shows that naturally regenerated loblolly-shortleaf stands with as low as 30% stocking become fully stocked more quickly through management than by removing the residual material and establishing a new stand. Decision support tactics such as this might become increasingly important to help in silvicultural triage after a major disturbance event such as the landfall of a hurricane. For stands that cannot recover from disturbance, decisions will have to be made about removing the remaining material from the site, and essentially treating the stand as newly harvested and subject to the establishment of a new regeneration cohort, if the landowner can afford to do so.

In practical terms, the choice between resistance and resilience versus rehabilitation depends on whether the silvicultural system that was in place before the disturbance can proceed, or whether revisions will be needed. Changes in the prevailing silvicultural system will not be required if the stand can resist the disturbance. Conversely, if the stand is dramatically altered but still able to recover, a revision in long-term silvicultural planning will most likely be required.

Reproduction Cutting Methods

The choice and timing of reproduction cutting is typically under the direction and control of forest landowners and the foresters who advise them. The decision might be based on a long-term management plan that has been written and approved by the appropriate parties, it might be made in response to disturbance events, or it might be at the sole discretion of a landowner, perhaps one who needs cash from a timber sale or one who wants to manage newly acquired forests differently. Within these boundaries, decisions are made about even-aged versus uneven-aged methods, the specific methods that will be used, and the manner in which harvesting will be conducted. These decisions influence the new stand that will develop after the cutting.

For example, the ultimate even-aged stand is a modern plantation that grows genetically improved trees, all often planted within the same week. These stands are established after clearcutting and site preparation; after planting they are often fertilized and treated with herbicides to control woody or herbaceous competition. In southern pines, this capital-intensive silvicultural system produces fast-growing stands with an expected rotation age of 25 years at most.

Foresters managing these stands have a choice about the genetic adaptation of different planting-stock families to the site conditions, and they may have a preference for the growth rates of one family or clone over another. In a scenario where climate change might affect stand establishment and development, foresters might also need to consider the survival of a given family or clone to increasing drought or temperature in the critical first year of outplanting, and also whether the trees will survive, and thrive, in the conditions expected over the 25-year life of the stand (Lambeth et al. 1984).

The choice of gain versus risk in this context is one related to genetic diversity. Greater plantation diversity, but less of a gain in volume growth, will be found with stock from bulk orchard seed or from open pollinated families; slightly less diversity and slightly more gain will be in full-sib planting stock. Clonal stock has no inherent diversity unless mixtures of clones are selected, which again would confer some additional diversity at the expense of the maximum gain in volume growth that single clone plantations provide. When the stand is harvested 25 years later, the forester in charge will have similar decisions to make using the available technologies of the future—both to forecast the climate conditions of the next rotation and to select the best planting stock, which will probably be improved beyond that which is currently available, for the expected climate at that time.

Private nonindustrial landowners are often unable or unwilling to practice intensive forest management, given the high cash outlay that is required early in the life of a stand. For such a landowner, low-cost alternatives include even-aged naturally regenerated stands using the shelterwood or seed-tree method; managing such stands to a 40- to 50-year rotation might better suit their financial condition and management objectives (Guldin 2004; Zeide and Sharer 2000). The disadvantage to long rotations is the length of time until a new regeneration cohort is obtained, during which changing conditions might be better suited to different species or different genotypes than the parents can provide.

The most extreme example of long-term, even-aged rotations being actively used in southern pine stands is on federal lands, where foresters manage for the endangered red-cockaded woodpecker (Figure 7.8) using a regional recovery plan that calls for 80- to 120-year rotations and the irregular shelterwood method of regeneration (Guldin 2004). These foresters can only hope that new age cohorts established during the shelterwood seed cut are sufficiently robust to adapt and survive through maturity in whatever climate conditions prevail during the 80- to 120-year duration of the rotation.

The uneven-aged selection method was used to rehabilitate cutover understocked southern pine stands into fully stocked sawtimber stands from the mid-1930s through the 1960s, as demonstrated by research at the Crossett Experimental Forest in Arkansas (Guldin and Baker 1998; Reynolds 1959). The Crossett stands were managed using annual cutting cycle harvests from 1937 to 1969, and periodic cutting cycle harvests since (Baker et al. 1996). Natural regeneration is the rule with the selection method (Figure 7.9), with cutting cycles varying from 5 to 7 years for loblolly and slash (*Pinus elliottii*) pines in the western Coastal Plain (Baker et al. 1996), to 10 years for longleaf pines (Farrar 1996), and to 20 years for upland oaks (Loewenstein et al. 2000).

Thus, choosing a reproduction cutting method is the first opportunity for a forester concerned about climate change to influence the frequency of origin of new age cohorts as well as their species

FIGURE 7.8 A shortleaf pine-dominated stand after thinning and cyclical prescribed burning in a shortleaf pine-bluestem management area of the Ouachita National Forest in Polk County (Arkansas). (Photo by James M. Guldin.)

FIGURE 7.9 Uneven-aged stand structure on the Poor Farm Forestry Forty demonstration at the Crossett Experimental Forest in Ashley County (Arkansas). (Photo by James M. Guldin.)

composition. This may be the single most important way to affect how a stand will respond to changing climate conditions, should they occur. The selected species or mixtures of species must be robust in the current climate, because it is in the current climate that the new age cohort must become successfully established. But the new age cohort must also be robust within the context of what the future climate is likely to be, at least during the period that the forester expects the new stand to occupy the site.

Finally, there may be a silvicultural case to justify heterogeneity at the landscape scale to a greater degree than we have done in the past, especially for landowners holding large blocks of forest land such as National Forests or timber investment organizations. Puettmann et al. (2009) make a compelling case to manage for heterogeneity and complexity to increase resiliency at the stand and landscape scale. The value of large blocks of land under one ownership being treated with similar silvicultural systems, such as pine plantations, even if established to ensure stand-level genetic diversity, may be less resilient than a landscape or ownership where heterogeneity of age, structure, and origin of regeneration among stands are promoted.

DISCUSSION

Barring huge shifts in public attitudes about fiscal and economic priorities, the establishment of a regional climate change adaptation program for the 200 million acres of southern forest land is unlikely any time soon. Forest ownership patterns, responsibility for management decisions on public and private lands, the capital required to convert existing forests to new species, and the source of that capital are major complications. No segment within society, government, or the natural-resources profession has the wherewithal to deliver the significant changes in forest types that would be needed for even a small portion of the southern landscape in the face of a changing climate.

Instead, progress in achieving resistance and resilience to climate change will probably become an outgrowth of the ongoing activities currently being practiced on forest industry, timberland investment, and real-estate investment ownerships, on nonindustrial private forest ownerships already in active management, and on government lands such as national and state forests. The foresters who work on these landscapes will be on the front lines in modifying silvicultural prescriptions to carry stands from their existing condition to a desired future condition that includes adaptation to climate change.

Thus, managing forest stands with attention to the possibility of climate change will not be much different in principle from the work that foresters have done over the past century, only with different treatment prescriptions based on stand management objectives that include the prospect of a changing climate. Essentially the process has three steps. The first is to identify the current condition of the stand. The second is to identify and quantify the desired future condition of the stand that not only meets the ownership objectives of the landowner, but also is ecologically and silviculturally robust in the context of changing climate in the locality. The third is to develop the detailed silvicultural prescription that carries the stand from its existing condition to its desired future condition. The first two steps are no different from standard silvicultural practice over the past century, but the third step will require innovative prescriptions based on the concepts discussed in this chapter.

Ownership objectives vary, as does the detail with which the forest landowner can express those objectives. On public lands such as national forests, the stand will have been assigned to a given management area under the prevailing land and resource management plan, which spells out management standards and guides, sometimes in considerable detail. On private lands managed for industry or investment purposes, the overarching goals of ownership will also be described in detail, and the silvicultural systems available for implementation may be carefully prescribed as well based on company philosophy. In contrast, nonindustrial private forest landowners may have in mind only rudimentary objectives and outcomes that are only vaguely quantified. Regardless of scale and ownership, what is needed are improved methods of identifying how the stand being studied currently meets the objectives, or can be managed to meet them in the future.

Descriptions of a stand's current ecological and silvicultural conditions are independent of the landowner's objectives, although they will certainly have been influenced by the vigor with which the stand has been managed in the past. Key variables include stand structure, species composition, stem density, basal area, volume, and other pertinent data that would be collected during a typical stand exam or timber cruise. The history of the stand should be reconstructed, with special attention to whether the dominant and codominant trees in the stand were established by natural or artificial regeneration, whether the stand is even-aged or uneven-aged, and what overarching silvicultural system (or lack thereof) has been employed. In some instances, this information will be readily available, especially on government and private industrial or investment lands; on nonindustrial private forest lands, these data may require some silvicultural detective work.

All of this information provides the groundwork for the important final step—developing a robust silvicultural prescription that meets the landowner's needs within the context of a changing climate, as well as one that can take the existing stand to its desired future condition. The first prescription to be developed will manage the existing stand through the point of reproduction cutting and will use appropriate silvicultural practices—such as the intermediate treatments outlined above—to improve the resistance of the new stand to the climate changes that will be expected for the duration of its rotation or cutting cycle. In other words, given that there is not much ability to influence the species composition of a fully stocked immature or mature stand, the preferred treatments will be those that optimize its ability to resist the disturbance events expected through maturity. These treatments are largely consistent with standard good forestry practices: maintaining individual tree vigor through timely thinning, using prescribed burning in ecosystems adapted to fire, and perhaps considering whether the stand should be harvested prematurely.

Subsequent prescriptions to establish an entirely new age cohort in the stand will rely upon reproduction cutting methods that enable the establishment of seedlings, saplings, and sprouts, whether planted, of natural origin, or both; this new age cohort will have the desired diversity of genetics, parental families, and species, thereby developing a species composition that will allow the stand to resist, or recover from, the climate changes expected as that age cohort matures over the rotation from sapling stage through maturity. Key decisions will be whether to rely on natural or artificial regeneration, and what source to use for seeds, sprouts, or clones. The mixture of species in natural regeneration, or of families used as planting stock in plantations, is critical. The reproduction cutting method used to regenerate the next stand will dictate the number of age cohorts, which in turn affects how frequently new cohorts of regeneration can be established. Finally, the expected age to maturity of dominant trees in the new age cohort will need to be decided, whether short (<25 years), moderate (25–50 years), long (50–100 years), or very long (>100 years). All of these decisions must be integrated into a silvicultural system that is also geared to meet the needs of the landowner.

Thus, the new or modified silvicultural treatments prescribed within the context of climate change will probably share a number of common attributes. Attention to the genetic diversity of new age cohorts will be increasingly important. For planted stands, this implies a diversity of genotypes in seedlings produced from existing orchards, and a diversity of clones planted in clonal forestry plantations. There might be reason to develop a genetic "line of custody" that allows landowners or the foresters who advise them to request known seed sources, or at least to know and quantify the diversity of the plantations that are being established, and also to encourage tree improvement cooperatives to develop new ways of labeling and handling seeds and seedlings. For naturally regenerated stands, enhanced genetic diversity would mean greater reliance on seed origin stock rather than sprouts, greater species diversity in new stands, and possibly enrichment planting at levels of 50–200 stems per acre to supplement natural regeneration with species that are currently absent from the site.

Another key element may be the frequency of age cohorts, where quicker turnover of dominant and codominant species can be a hedge against changing climate conditions. If changes are rapid, establishing new age cohorts more frequently may allow for quicker natural selection of individuals and species that are adapted to the changing site conditions. The result might be shorter even-aged rotations, especially on plantations, and broader use of uneven-aged silviculture or irregular stand structures—three or more age classes with 5- to 20-year cutting cycles—on public and nonindustrial private lands. This latter approach would have the added benefit of representing low-cost management with minimal out-of-pocket investment (Baker et al. 1996) that some landowners would find to be an appealing alternative to intensive plantation management.

Using prescribed burning or mechanical/manual "fire surrogate" treatments such as mulching will likely become more important for maintaining the resistance of stands in the face of increasing wildfire hazard under changing climatic conditions. Unfortunately, increasing the use of prescribed burning may be increasingly constrained by issues such as public resistance to smoke (see Chapter 5), and a declining and aging workforce on state and federal lands. But in an environment where surface fires may become increasingly frequent, maintaining stands in a condition that resists damage from wildfire, such as by applying restoration treatments that promote and maintain open understory conditions especially in long-rotation even-aged stands on federal lands, will become more important over time.

A final key descriptor will probably relate to forest health. The kinds of silvicultural practices that have effectively maintained forest health in the past, such as frequent thinning and management at low basal areas to maintain individual tree vigor, are probably a good place to begin preparing the forest stands of today for the changes expected over the next several decades.

SUMMARY

Climate change offers challenges and opportunities to the silviculturist, in the short- and long term. The short-term challenges are likely to be related to disturbance events that interfere with existing management plans, and that will require a response that ameliorates or rehabilitates affected stands through practices that promote continued resistance, resilience, or recovery from the disturbance depending upon the degree to which the current management program was disrupted. Challenges in the long term will focus on an enhanced understanding of the genetic diversity and species composition of the new regeneration cohorts that are established to replace the existing stand and that will be robust in future climatic conditions that are projected to occur, and the degree to which species not currently on the site but forecast to be suited to it can be successfully established. The likelihood of seeing a stand develop as planned from sapling stage to maturity will probably vary inversely with rotation age or the interval between new age cohorts. All in all, rather than developing overarching management plans for forested properties that are not likely to change over time, the role of silviculturists in the future will more closely resemble incident response, bringing adaptive management to bear in the face of changing ecological conditions over time.

REFERENCES

Allen, H.L., Fox, T.R., and Campbell, R.G. 2005. What is ahead for intensive pine plantation silviculture in the South? *Southern Journal of Applied Forestry.* 29, 62–69.

Baker, J.B. and Shelton, M.G. 1998a. Rehabilitation of understocked loblolly-shortleaf pine stands-I. Recently cutover natural stands. *Southern Journal of Applied Forestry*. 22, 35–40.

Baker, J.B. and Shelton, M.G. 1998b. Rehabilitation of understocked loblolly-shortleaf pine stands-III. Development of intermediate and suppressed trees following release in natural stands. *Southern Journal of Applied Forestry*. 22, 41–46.

Baker, J.B. and Shelton, M.G. 1998c. Rehabilitation of understocked loblolly-shortleaf pine stands-III. Natural stands cutover 15 years previously but unmanaged. *Southern Journal of Applied Forestry*. 22, 47–52.

Baker, J.B. and Shelton, M.G. 1998d. Rehabilitation of understocked loblolly-shortleaf pine stands-IV. Natural and planted seedling/sapling stands. *Southern Journal of Applied Forestry*. 22, 53–59.

Baker, J.B., Cain, M.D., Guldin, J.M., Murphy, P.A., and Shelton, M.G. 1996. Uneven-aged silviculture for the loblolly and shortleaf pine forest cover types. General Technical Report SO-118. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 65 p.

Barlow, R.J., Smidt, M.F., Morse, J.Z., and Dubois, M.R. 2009. Cost and cost trends for forestry practices in the South. *Forest Landowner*. 68(5), 5–12.

Belanger, R.P. 1980. Silvicultural guidelines for reducing losses to the southern pine beetle. In: Thatcher, R.C., Searcy, J.L., Coster, J.E., and Hertel, G.D. (eds.). *The Southern Pine Beetle.* Technical Bulletin 1631. Washington, DC: U.S. Department of Agriculture, Forest Service.

Binkley, C.S., Raper, C.F., and Washburn, C.L. 1996. Institutional ownership of US timberland—History, rationale, and implications for forest management. *Journal of Forestry*. 94, 21–28.

Bliss, J.C., Kelly, E.C., Abrams, J., Bailey, C., and Dyer, J. 2010. Disintegration of the U.S. industrial forest estate: Dynamics, trajectories, and questions. *Small-Scale Forestry*. 9, 53–60.

Boyer, W.D. 1991. Anticipating good longleaf pine cone crops—The key to successful natural regeneration. *Alabama's Treasured Forests*. Fall 1996: 24–26.

Cain, M.D. and Shelton, M.G. 2001. Twenty years of natural loblolly and shortleaf pine seed production on the Crossett Experimental Forest in southeastern Arkansas. *Southern Journal of Applied Forestry*. 25, 40–45.

Chapman, H.H. 1942. *Management of Loblolly Pine in the Pine-Hardwood Region in Arkansas and in Louisiana west of the Mississippi River*. Bulletin #49. New Haven, CT: Yale University, School of Forestry. 150 p.

Croker, T.C. Jr. and Boyer, W.D. 1975. Regenerating longleaf pine naturally. Research Paper SO-105. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 21 p.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J. et al. 2001. Climate change and forest disturbances. *Bioscience*. 51, 723–734.

Dana, S.T. 1951. The growth of forestry in the past half century. *Journal of Forestry*. 49, 86–92.

Daniel, T.W., Helms, J.A., and Baker, F.S. 1979. *Principles of Silviculture*, 2nd ed. New York: McGraw-Hill 521 pp.

Derr, H.J., Mann, W.F. Jr. 1971. *Direct Seeding Pines in the South*. Agriculture Handbook 391. Washington, DC: U.S. Department of Agriculture.

Farrar, R.M. 1996. *Fundamentals of Uneven-Aged Management in Southern Pine*. Misc. Pub. 9, Tallahassee, FL: Tall Timbers Research Station. 52 p.

Fox, T.R., Jokela, E.J., and Allen, H.L. 2007. The development of pine plantation silviculture in the southern United States. *Journal of Forestry*. 105, 337–347.

Graham, R.T., tech. (ed.). 2003. *Hayman Fire case study: Summary*. Gen. Tech. Rep. RMRS-GTR-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 32 p.

Guldin, J.M. 2004. Reproduction cutting methods for naturally-regenerated southern pine stands in the South. In: H.M. Rauscher and K. Johnsen (eds.), *Southern Forest Science: Past, Present, and Future*. General Technical Report SRS-75. USDA Forest Service, Asheville, NC, pp. 83–95.

Guldin, J.M. 2008. The silviculture of restoration: A historical perspective with contemporary application, p. 23–35. In: Deal, R.L., tech. (ed.), *Integrated Restoration of Forested Ecosystems to Achieve Multiresource Benefits: Proceedings of the 2007 National Silviculture Workshop*. Gen. Tech. Rep. PNW-GTR-733. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 306 p.

Guldin, J.M. and Baker, J.B. 1998. Uneven-aged silviculture, southern style. *Journal of Forestry.* 96(7), 22–26.

Guldin, J.M., Strom, J., Montague, W., and Hedrick, L.D. 2004. Shortleaf pine-bluestem habitat restoration in the Interior Highlands—Implications for stand growth and regeneration, pp. 182–190. In: Shepperd, W.D. and Eskew, L.D. (compilers). *Silviculture in special places: proceedings of the 2003 National Silviculture Workshop* Proceedings, RMRS-P-34. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 255 p.

Johnson, P.S., Shifley, S.R., and Rogers, R. 2002. *The Ecology and Silviculture of Oaks*. New York, NY: CABI Publishing. 503 p.

Jones, E.P. Jr. 1975. Interplanting is futile in slash pine plantations. *Tree Planters' Notes* 25(1), 19–22.

Lambeth, C.C., Dougherty, P.M., Gladstone, W.T., McCullough, R.B., and Wells, O.O. 1984. Large-scale planting of North Carolina loblolly pine in Arkansas and Oklahoma: A case of gain versus risk. *Journal of Forestry* 82(12), 736–741.

Ledig, F.T. and Kitzmiller, J.H. 1992. Genetic strategies for reforestation in the face of global climate change. *Forest Ecology and Management* 50, 153–169.

Loewenstein, E.F., Johnson, P.S., and Garrett, H.E. 2000. Age and diameter structure of a managed uneven-aged oak forest. *Canadian Journal of Forest Research*. 30, 1060–1070.

Loftis, D.L. 1990. A shelterwood method for regenerating red oak in the southern Appalachians. *Forest Science*. 36(4), 917–929.

Malmsheimer, R.W., Heffernan, P., Brink, S., Crandall, D., Deneke, F., Galik, C., Gee, E. et al. 2008. Forest management solutions for mitigating climate change in the United States. *Journal of Forestry*. 106(3), 115–173.

Masters, R.E., Robertson, K., Palmer, B., Cox, J., McGorty, K., Green, L., and Ambrose, C. 2007. Red Hills forest stewardship guide. Misc. Pub. 12. Tallahassee, FL: Tall Timbers Research Station. 79 p.

Mattoon, W.B. 1915. *Life History of Shortleaf Pine.* Bulletin 244. Washington, DC: U.S. Department of Agriculture. 46 p.

McKeand, S., Mullin, T., Byram, T., and White, T. 2003. Deployment of genetically improved loblolly and slash pines in the South. *Journal of Forestry* 101(3), 32–37.

Nyland, R.D. 2002. *Silviculture: Concepts and Applications*, 2nd edition. The McGraw-Hill Companies, New York. 704 pp.

Puettmann, K.J., Coates, K.D., and Messier, C.C. 2009. *A Critique of Silviculture: Managing for Complexity*. Island Press, Washington, D.C. 188 p.

Reynolds, R.R. 1959. *Eighteen years of selection timber management on the Crossett Experimental Forest*. Tech. Bull. 1206. Washington, D.C.: U.S. Department of Agriculture, Forest Service. 68 p.

Sander, I.L. 1971. Height growth of new oak sprouts depends on size of advance reproduction. *Journal of Forestry* 69(11), 809–811.

Sander, I.L., Johnson, P.S., and Rogers, R. 1984. Evaluating oak advance reproduction in the Missouri Ozarks. Research Paper NC-251. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station. 16 p.

Schmidtling, R.C. 1992. A minimum-temperature model for racial variation in loblolly pine provenance tests. In: *Proceedings, 12th North American Forest Biology Workshop*, Sault Ste. Marie, Ont., Canada. 124 p.

Schmidtling, R.C. 1994. Use of provenance tests to predict response to climatic change: Loblolly pine and Norway spruce. *Tree Physiology*. 14, 805–817.

Shelton, M.G. and Wittwer, R.F. 1996. Shortleaf pine seed production in natural stands in the Ouachita and Ozark Mountains. *Southern Journal of Applied Forestry*. 20(2), 74–80.

Smith, D.M., Larson, B.C., Kelty, M.J., Ashton, P.M.S. 1997. *The Practice of Silviculture, Applied Forest Ecology*, 9th edition. John Wiley & Sons, New York. 560 pp.

Solomon, S., Qin, D., Manning, M., Chen, Z., Maquis, M., Averyt, K.B., Tignor, T.M., and Miller, H.L. (eds.), 2007. Summary for policymakers. Climate change 2007: The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Wakeley, P.C. 1954. *Planting the Southern Pines*. Agriculture Monograph 18. Washington, DC: U.S. Department of Agriculture. 233 p.

Wakeley, P.C. 1968. Replacement planting of southern pines unsuccessful. USDA Forest Service, Research Note SO-85. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 4 p.

Wear, D.N. and Greis, J.G. 2002. *The Southern Forest Resource Assessment: Summary Report*. Gen. Tech. Rep. SRS-54. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 103 p.

Wells, O.O. and Wakeley, P.C. 1966. Geographic variation in survival, growth, and fusiform rust infection of planted loblolly pine. *Forest Science Monograph*. 11, 40 p.

Williston, H.L. 1988. The Yazoo-Little Tallahatchie Flood Prevention Project: A history of the Forest Service's role. Forestry report R8-FR. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region. 63 p.

Zeide, B. and Sharer, D. 2000. Good forestry at a glance: A guide for managing even-aged loblolly pine stands. Arkansas Forest Resources Center Series 003. Division of Agriculture, Arkansas Agricultural Experiment Station, University of Arkansas, Fayetteville, AR, 19 pp.