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Silvicultural options in forests of the southern United States under changing climatic conditions

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Abstract

Changing climatic conditions add a measure of uncertainty to sustainable forest management in forest ecosystems of the southern United States. Increasing temperatures and decreasing patterns of precipitation especially in the Mid-South suggest that water stress, drought, and changing patterns of natural disturbance events will challenge managers in the twenty-first century. Efforts to manage southern forest stands in the face of changing climatic conditions will require a diversity of approaches including tactics to promote genetic diversity in natural and planted stands, encouragement of species diversity as new stands develop, and considering ways to promote diverse stand structures that encourage recruitment of new age cohorts within stands on a regular basis. With predicted changes in climatic conditions, forest ecosystems across the South will respond in different ways, depending upon whether or not they are currently being managed. Unmanaged stands will change in unpredictable ways that reflect the absence of management. But in managed stands, silvicultural treatments are available for foresters to apply to respond and adapt to maintain productive forests adapted to those changing conditions. Finally, one approach often advocated to deal with this uncertainty is a strategy for assisted migration, in which species are established in locations beyond their current range, where predicted climatic conditions are likely to occur at some point in the future within which those species will survive. This is basically an exercise in artificial regeneration, but will likely be more complicated than simply planting a few exotic seedlings and hoping for the best. The technical and practical challenges of planting species at the margins or beyond their natural range include a lack of research support especially for species not commonly planted in the region. Moreover, planting is costly, and because of that, intensive practices are more likely on institutional and government lands rather than family forests. In the end, all of these concepts fall within the practice of silviculture, and are tactics with which the profession is familiar.

Keywords Climate change · Assisted migration · Adaptive management · Genetic diversity · Species diversity · Structural diversity · Southern pines

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Introduction

Recent trends with respect to changing climatic conditions are troubling. Increasing atmospheric concentrations of carbon dioxide exceeded the arbitrary mark of 400 parts per million in 2013 (Monastersky 2013). The climate of the earth is warming, and since the 1950s, changes that have been reported are unprecedented historically (Pachauri et al. 2014). Projections are that global average surface temperatures will be 2.0–4.0 °C warmer at the end of the twenty-first century than they were at the start (Dale et al. 2001; Malmsheimer et al. 2008).

The practical implications of these predictions are that the climatic conditions in southern forest ecosystems at the end of the current century will be different than they are today. The effects most likely to be observed in forested systems in the short term are altered disturbance regimes involving wildfire, damage from intense wind events, insect outbreaks, ice storms, and changing patterns of precipitation leading to drought-related tree mortality (Dale et al. 2001). A simple practical demonstration of the significance of changing climatic conditions on vegetation is exemplified by the recent redistribution of the USDA plant hardiness zones in the southeastern United States, in which Zone 8 (minimum mean monthly temperature of from −12.2 to −6.7 °C) moved northward roughly 160 km from 1990 to 2012 (USDA Plant Hardiness Zone Map 1990, 2012).

These changes have triggered conversations among research scientists, land managers, and forest landowners about the effects of changing climatic conditions on southern forest ecosystems, and what might be done about it (Vose et al. 2016; Guldin 2016; Wear and Greis 2013). For example, according to interpretations of Forest Survey data from the USDA Forest Service, half of the species in the eastern US will shift northeasterly in ecologically significant ways from their current conditions (Iverson and Prasad 1998; Iverson et al. 2008). The implication is that the climate is changing faster than plants can adapt through natural migration (Williams and Dumroese 2013), and the ecological patterns that governed species migration prior to European colonization are either degraded or absent in the twenty-first century. As a result, adaptive management to address changing climatic conditions should include efforts by managers to move species from one location to another using ‘assisted migration’ (Pedlar et al. 2012).

Practically speaking, the issues facing forests in the southern US are changing patterns of temperature and precipitation. Predictions are that air temperatures across the South will increase above historic and current levels through the twenty-first century (McNulty et al. 2013). Depending upon model assumptions, the southeastern US may see increases or decreases in precipitation, but predictions suggest that the central part of the Mid-South (Oklahoma, Arkansas, northern Louisiana, and the northern and eastern parts of Texas) will show decreases in precipitation (McNulty et al. 2013).

If climatic conditions continue to change as predicted over the balance of the twenty-first century and onward, localized environmental conditions will be different from those that are found today. The effects of that on forest ecosystems will involve not only the question of higher temperatures and decreasing precipitation, but also that weather patterns might feature alterations in prevailing disturbance regimes, including extremes of fire behavior, intense wind events, unpredictable outbreaks of native and invasive insects and diseases, and variations in precipitation events that could result in flooding on one extreme and regional drought on the other. All of these endogenous events will have effects on southern forest ecosystems, including the likelihood of tree mortality from scattered to widespread occurrence.

The practice of silviculture under changing climatic conditions

In the absence of human intervention, stand conditions after the occurrence of any particular disturbance event will feature the recovery of the post-disturbance residual stand, any new age cohorts that happen to occur, or both. More to the point, the ecological pattern and process of the forest ecosystem will promote stand development of any existing and new vegetation under whatever climatic conditions prevail in the short or long term after the disturbance occurs, until the action of the next disturbance event.

The path may be different to some degree in managed forests. In the face of these changing environmental conditions, the practical advice for forest landowners and the foresters who advise them is more or less similar to ongoing management advice over the past 50 years. Silvicultural systems will be developed that reflect resistance, resilience, restoration, rehabilitation, and recovery, and that offer predictable ecological pathways and management outcomes under the prevailing environmental conditions. And, existing silvicultural systems will no doubt be adapted, modified, or redesigned completely when disturbances occur.

In stands that are under active management, plans focus on silvicultural systems that are designed to modify stands from an existing condition to a desired future condition that best meets the needs of the landowner. Disturbance events cause mortality that alters the trajectory that the silvicultural system was intended to establish. The silvicultural response to a disturbance event requires that the forester evaluate the losses, capture the economic value of those losses if possible, and redirect the direction of management in the post-disturbance stand either toward the original desired future condition, or a new one, that best meets the goals of the landowner. This is work with which foresters are familiar and experienced.

Changing patterns of disturbance events will require that silvicultural tactics remain flexible. If disturbance events become increasingly common, foresters may need to develop silvicultural prescriptions reflecting that. If the magnitude of a disturbance event occurs is such a way that markets for salvaged timber are overwhelmed, the tactics the forester uses to respond may be different. For example, in the latter part of the twentieth century, spots with infestations of southern pine beetle (*Dendroctonus frontalis* Zimm.) in Mississippi were routinely harvested and hauled to mills as a suppression tactic. However, during southern pine beetle infestations in the same state in the early twenty-first century, mills were reluctant to take beetle-killed timber; cut-and-leave suppression tactics, which are generally less effective, were more typically used (Clarke and Billings 2003; Billings 2011). The development of stands after disturbance might well be different under these different suppression alternatives. Again, this is work with which foresters are familiar, although the frequency of salvage and sanitation treatments compared to, say, scheduled thinning treatments might be different as the effect of changing patterns of disturbance events varies locally.

When a new age cohort of seedlings is established either naturally or through artificial methods, the development of that cohort will be directed by whatever environmental conditions it encounters. Foresters expects those conditions to become more variable and in some cases more severe over the twenty-first century and beyond. In the absence of management, increasingly frequent and severe disturbance events may result in increasingly prominent episodes of mortality within stands and across landscapes than has occurred in the past. In managed stands and landscapes, a management approach will be required that focuses on resilience and resilience of the existing stand, or transition to a new forest stand condition better adapted to the prevailing ecological conditions (Nagel et al.

2017). Management actions will focus on practices that can be applied in such a way as to maintain ecologically important habitats and landscapes for forest and woodland flora and fauna, as well as providing the forest resources that our burgeoning society will continue to demand.

Within an environment of unknown conditions, overarching tactics to silvicultural systems take two forms, approximating the models of genetic fitness versus flexibility (Guldin 2014). The approach modeled on genetic fitness is exemplified by management of loblolly pine (*Pinus taeda* L.) using the intensive plantation forestry model. Seedlings of known superior genetic provenance that are adapted to the site are planted, released with herbicides and fertilization, and managed to maturity with minimal thinning and other intermediate cultural treatments. Management uses short rotations to capture as much growth as possible in as short a time as possible. This is in essence a question of gain versus risk (Lambeth et al. 1984, 2005; MacKeand et al. 2003)—a gamble that the probability of the stand growing to maturity outweighs the probability that an uncontrolled stand-replacing disturbance event will occur within the 2- to 3-decade lifespan of the stand.

The second approach is modeled on genetic flexibility, and is embodied in efforts to integrate genetic diversity, species diversity, and structural diversity within stands and across landscapes. Genetic diversity is thought to be the best safeguard against unpredictable ecological events such as changing climate (Ledig and Kitzmiller 1992). There are opportunities and challenges underlying the establishment and management of stands from the perspective of diversity, and these may suggest changes in many of the management practices that are the mainstay of contemporary silviculture.

Genetic diversity

Genetic diversity in artificial regeneration, especially in southern yellow pines, depends upon better information from seedling vendors about the genetic origins of planting stock than has traditionally been available. For example, seedling prices for loblolly pine seedlings commonly vary by the opportunity for genetic gain that might be achieved. But details about the breadth of genetic diversity and the specific origin of the families that the seedlings are based are more difficult for the buyer to learn. Seed from genetically-improved seed orchards can be produced as full-sib crosses from controlled pollination where both parents are known, from half-sib crosses where open pollination from the background pollen cloud fertilize the cones in known maternal parents, or as orchard-run collections where open pollination produces seed from any of the seed-bearing trees in the orchard (Fig. 1). These come with reduced opportunities for genetic gain, respectively, but with greater breadth of genetic diversity (MacKeand et al. 2003). Some would argue that the highest opportunities for genetic gain have been developed in the last decade using clonally-produced seedlings, where entire stands are planted using genetically-identical seedlings from a small collection of parents; in some cases, all the seedlings in a stand are from the same parent. The clonal approaches obviously minimize stand-level genetic diversity; under the proper cultural conditions, clonal plantations are among the most productive of all these options, but comes with greater risk of mortality given the limited genetic base at the stand level (Bettinger et al. 2009). The more information available about the underlying genetics of planting stock, the more precisely can plans be drawn for site preparation, release treatments, thinning, and final harvest (Allen et al. 2005). But some of this information is confidentially held by seedling producers and nursery cooperatives, and it can

Fig. 1 Maturing second-year cone and new first-year conelet in a first-generation longleaf pine seed orchard, May 2014. Stuart Nursery, Kisatchie NF, Grant Parish, Louisiana. (Photo by J. M. Guldin)

sometimes be difficult for landowners to learn exactly what parent families are represented in the seedlings being planted on their lands.

Genetic diversity is also an issue in naturally-regenerated stands in southern forest ecosystems, especially in hardwood ecosystems where choices of regeneration involve trade-offs between seedlings and sprouts. Sexual reproduction in all of our forest tree species involves pollination of a cone or flower. The fertilization of the ovule involves genetic recombination and gene flow, and the result is a seedling with different genetic traits than either parent. The extent of this wave of seed with unique genetic makeup can perhaps be appreciated by mixtures of loblolly and shortleaf pine (*P. echinata* Mill.) in the upper West Gulf Coastal Plain, which produce adequate or better seed crops 4 years in five, and in bumper seed years can produce more than a million seed per acre (Cain and Shelton 2001). The genetic diversity in a bumper seed crop has an intuitive power of natural selection in changing climatic conditions when compared to planting 500 nursery-raised seedlings per acre, especially if planted seedlings are of full-sib or clonal origin.

Hardwood species that regenerate either from seed origin or sprouting present a different challenge for ensuring genetic diversity. In upland oaks (*Quercus* spp.), for example, natural regeneration dynamics often rely upon the development of advance growth, which requires several iterations of shoot dieback followed by resprouting (Carvell and Tryon 1961; Johnson et al. 2009). All the while, root growth continues, until at some point the advance growth sprouts grow large enough to serve as reliable sources of regeneration that can respond to release and form a new age cohort (Sander 1971). Proper planning for regenerating upland oak stands requires an assessment of advance growth, including the assessment of whether the advance growth saplings are large enough to be successful (Sander et al. 1984). However, if advance growth is not adequate to ensure restocking, foresters can also sample existing oaks in the stand with the expectation that stump sprouts can be used to supplement advance growth from seed (Sander et al. 1984). The challenge in the context of genetic diversity is that stump sprouts are vegetatively reproduced and thus genetically identical to the stump from which they are produced. In addition, data show that small stumps tend to sprout more successfully than large stumps (Johnson 1977); in stands that are largely even-aged, the smaller stumps are likely to be the poorer intermediate or suppressed trees from the previous stand, and relying upon sprouts from those stumps seems to be a dubious silvicultural choice. Actions that silviculturists could apply to increase genetic diversity when regenerating these upland oak stands would be to maximize adequate advance growth originating from acorns, and minimize supplemental stump sprouting from trees that lived in the previous generation. That would typically require efforts to suppress midstory development through mechanical or chemical methods, or possibly controlled burning, so as to nurture a more vigorous new age cohort of seed-origin oaks which are sufficiently large and numerous to reliably and completely stock the new stand (Loftis 1990).

Species and structural diversity

After the establishment of the new age cohort, opportunities to modify genetic diversity of the overstory component of forests are limited. Decisions about the degree to which managers want to promote species diversity can certainly come into play during the establishment of a new age cohort, especially when a stand is being regenerated using natural regeneration. Abundant anecdotal observations suggest that the first growing season is the year when the probability of mortality is highest for individual trees in the new age cohort; moreover, the ability to exactly influence species composition can be confounded by rapid changes in development of individuals of similar or different species in the first decade of development of that new forest stand. There is intuitive power in the argument to 'let Nature sort out the surviving species and individuals on a given site during changing ecological conditions', once the stand is successfully established and entering the sapling stage.

The easiest time to influence the species composition of an established stand past the sapling stage to any degree that managers deem appropriate is during early precommercial or commercial thinning treatments, when specific directions can be given to field crews about the retention of individuals based on species identity. For instance, naturally-regenerated pine stands in the new age cohort of shelterwood stands in shortleaf pine in the Ouachita Mountains of western Arkansas contain abundant oaks of seed or sprout origin, a significant component of which can be retained to promote species diversity during the first precommercial thinning (Fig. 2).

Timely thinning is certainly an important tool for silviculturists during periods of changing climatic conditions. Thinning is the silvicultural equivalent of aspirin in the twenty-first century; it seems to work, and silviculturists don't always know why. Thinning targets the retention of individual trees with the goal of redistributing available site resources such as light, nutrients, and water to a fewer number of trees; the goal is for the growth and vigor of those trees to respond favorably (Baker and Shelton 1998). The assumption foresters make is that a vigorous tree is more likely to survive a disturbance event such as drought than a neighboring tree with low vigor. But there are always exceptions to that assumption which must be evaluated with some degree of risk. For example, thinned southern pine stands have lower hazard to the southern pine beetle than unthinned stands (Guldin 2011), but the greatest damage from ice storms in southern pines occurs in young stands immediately after an initial thinning (Bragg and Shelton 2010; Bragg 2016).

Both species and structural diversity might be affected in fire-adapted southern forest stands with a regular program of cyclic prescribed burning. In southern pines, repeated prescribed burning on short 2–4 year cycles promotes a structural shift away from a dense midstory of tolerant hardwoods that develop in the absence of fire, to an open midstory condition and species-rich understory flora of forbs, grasses, and herbaceous vegetation (Fig. 3). Those conditions provide excellent habitat for a host of species that are underrepresented on the landscape, including the endangered red-cockaded woodpecker, *Picoides borealis* Vieillot (Fig. 4) (Hedrick et al. 2007). Prescribed burning is especially important in the restoration and management of southern pine ecosystems dominated by longleaf pine (*P. palustris L.*) on the lower Atlantic and Gulf Coastal Plain, and in efforts to restore shortleaf pine-dominated ecosystems across the upper Coastal Plain Atlantic Piedmont, Cumberland Plateau, and the Interior Highlands (Guldin 2008).

If silviculturists decide to manage for diverse stands, the question of the frequency and distribution of age cohorts will be a factor to consider. One or two age cohorts

Fig. 2 Precommercial thinning released both shortleaf pines and oaks in the second age cohort of this two-aged shelterwood stand. Ouachita NF, Scott County, Arkansas. (Photo by J. M. Guldin)

Fig. 3 A wetland seep in a managed well-burned longleaf pine forest; the seep is burned at the same time as the surrounding forests, and includes a diverse array of wetland species including pitcher plants (Sarracenia spp.) and pond pine (P. serotina Michx.). Sandhills Game Lands, North Carolina Wildlife Resources Commission, Scotland County, North Carolina. (Photo by J. M. Guldin)

direct foresters to the realm of even-aged silvicultural systems, whereas three or more carry foresters into uneven-aged systems (Helms 1998). In times when environmental conditions are changing, the frequency of age cohorts might become important. For example, consider the excellent fire-maintained mature longleaf pine stands on public lands on the lower Gulf Coastal Plain (Fig. 5), managed using 120-year even-aged rotations to create habitat for the red-cockaded woodpecker, gopher tortoise, wiregrass, and a host of other species of flora and fauna that are underrepresented on the landscape (Guldin 2008). A new age cohort in these stands will face whatever prevailing ecological conditions are destined to occur over the next 120 years, during which time temperatures might increase by 2 °C or more. On the other hand, similar longleaf pine stands managed using uneven-aged approaches in the Red Hills of southwest Georgia will recruit new age cohorts periodically (Guldin 2006; Masters et al. 2007), and the successful individuals in each new age cohort will be the trees that can prosper in the ecological conditions that prevail at the time (Fig. 6). The increased frequency of age cohorts contributes to enhanced structural diversity, and offers some advantages in the context of resistance and reliance to certain kinds of disturbance events (O'Hara and Ramage 2013). Deliberate management for multi-aged and multi-cohort stands is certainly a tactic for silviculturists to consider in managing stands of not only longleaf pine but other pine-, pine-hardwood, and hardwood-dominated ecosystems across the region (Bragg and Guldin 2014).

Fig. 4 Mature shortleaf pine-bluestem stand maintained using cyclic prescribed fire; banded tree contains an active nest for the endangered red-cockaded woodpecker. Ouachita NF, Scott County, Arkansas. (Photo by J. M. Guldin)

The role of assisted migration

The concept of assisted migration for forestry applications as a response to changing climatic conditions has been debated in the literature since the turn of the twenty-first century. It can be defined as the deliberate movement of species to locations that could better suit them climatically in the future (Aubin et al. 2011), or as the purposeful movement of species to facilitate or mimic natural population or range expansion (Leech et al. 2011). Variations in the concept include whether the activity is proposed for forestry-related activities versus species conservation (Pedlar et al. 2012), whether movement occurs within a species' range, an expansion adjacent to a species' native range, or translocations of exotic species (Leech et al. 2011), and whether it's largely avoided, done through a constrained approach, or done aggressively (McLachlan et al. 2007). Implicit in all of this discussion of assisted migration is a simple concept—seedlings are being planted on a site where they currently do not exist. This brings the idea within the domain of our traditional and long-standing experience in the southern US with artificial regeneration in southern pines, especially loblolly pine (Wakeley 1954; Fox et al. 2007).

Intensive management of planted pine stands provides a substantial economic return for a landowner, but planting is costly. The costs go beyond just buying seedlings and sticking them in the ground. A successful planting prescription includes important details found in any fundamental silviculture textbook (e.g. Smith et al. 1997). Key elements will include disposal of slash from any preceding harvest activity, soil amelioration treatments as

Fig. 5 Mature longleaf pine stand with wiregrass-dominated understory, Apalachicola NF, Leon County, Florida. (Photo by J. M. Guldin)

needed, control of competing vegetation (woody and herbaceous) prior to planting, release of seedlings from competing vegetation after they have been planted, control of species composition and stem density, and other treatments that might be needed to ensure the successful establishment and development of the planted seedlings.

It's disingenuous to imagine that site preparation and release treatments won't be important in an assisted migration planting application. Seedlings planted on a site at the limit of or beyond their natural range will face an environment during their first critical growing season after planting that will more closely resemble the current climatic condition rather than the condition in which those species are expected to thrive 4 or 5 decades hence. Cost estimates for the site preparation and release treatments that might be needed under typical prescriptions might average US$500–$600/ha (Dooley and Barlow 2012), and could be more costly if more extreme treatments are needed to ensure survival of seedlings being planted in conditions to which the seedlings may not yet be adapted.

For example, Dey et al. (2012) present an excellent review of the difficulty associated with planting oak seedlings in clearcut conditions, and the good survival that can be obtained by underplanting oaks beneath mature stands such as in a shelterwood system. They specify the kinds of related practices that are needed to ensure success in oaks, including reduction in stand density (especially in the midstory component), control of woody and herbaceous vegetation before and after planting, planting large seedlings, control of herbivory especially by large ungulates, eventual removal of the overstory to optimize sapling development, and continued control of competing vegetation until crown closure of the new age cohort. Their paper includes more than 150 citations, which speaks to

Fig. 6 Longleaf pine trees of different sizes and ages in a managed uneven-aged stand at the Joseph W. Jones Ecological Research Center, Baker County, Georgia. (Photo by J. M. Guldin)

the body of research necessary to build the scientific basis for silvicultural prescriptions in eastern oaks. Efforts for practical application of assisted migration across a wide constellation of species, especially those that have been less commonly studies than pines or oaks, will be hampered by a lack of supporting research on silvicultural details associated with seedling availability, seedling quality, nursery practice, and early interventions to favor seedling and sapling development such as site preparation and release.

The second question related to artificial regeneration in an assisted migration context is the land base where such treatments might be applied. The success of planted stands of loblolly and slash pine (*P. elliottii* Engelm.) in the southern US for wood production is in large measure driven by the goals of the landowner, because the land base on which they are established has in large measure been directly owned by forest industry or institutional investors (Binkley et al. 1996; Bliss et al. 2010). This makes the decision to reforest cutover native or planted stands with new planted stands an easy one, because the landowner is willing to do it as a timber or fiber investment (Fig. 7). The high cost of stand establishment dictates the use of short rotations to profitably recover the initial investment. This is one of the great success stories of southern forestry (Fig. 8)—at rotation ages of less than 30 years, the volume of wood fiber is well more than double that which native naturally-regenerated stands might optimistically produce over the same time frame (Fox et al. 2007).

This 3-decade time interval from stand establishment to final harvest perfectly epitomizes the 'gain versus risk' argument of genetic fitness discussed earlier (Lambeth et al. 1984, 2005; MacKeand et al. 2003). The gamble is that climatic conditions and associated

Fig. 7 Bedded and planted loblolly pine stand entering its second growing season, Drew County, Arkansas. (Photo by J. M. Guldin)

disturbance events won't get materially worse over a 30-year rotation; the genetic origin of the stand planted 30 years hence to survive through the following rotation can be selected at that time, based on what will certainly be better models of changing climate and continued advances in tree breeding.

The feasibility of artificial regeneration under an assisted migration application on public lands or private family forest lands might be somewhat different, given the expectation that less-intensive management over longer rotations would be involved, and thus that the economics of stand establishment might be more difficult to justify for purposes other than timber and fiber yield. Of course, public forestlands and many private family timberlands are managed for much broader objectives than simply timber production. But skimping on stand establishment costs when dealing with novel age cohorts at or beyond the limit of their current natural range may be risky as well. National Forests in the Southern Region are including plans to address changing climatic conditions in current projects (Erickson et al. 2012), but there are constraints to the ability of National Forests to champion the widespread conversion of native forests for future-adapted species not currently found on those sites. It's problematic whether private family-owned forest lands will be accessible for an organized approach to artificial regeneration in the context of an assisted migration effort, other than through appropriate modifications of cost-share programs that are already available for family forest lands.

For practical reasons such as these, artificial regeneration applied to promote efforts for assisted migration of species at the limit of or beyond their natural range on public and private forest lands is more likely to occur as a targeted silvicultural prescription in stands that

Fig. 8 First thinning in a planted loblolly pine stand entering its 12th growing season, Ashley County, Arkansas. (Photo by J. M. Guldin)

are already under active management (Fig. 9). For example, the desired future condition on public or private lands might change as a result of dramatic changes in environmental conditions, especially if a large-scale disturbance resulted in widespread tree mortality. Landowners who have an investment in managed stands will be more likely to respond to that event through restoration, rehabilitation, or recovery; in that event, assisted migration might be a tool to consider to augment, supplement, or change the species composition of a new age cohort established by appropriate methods of site preparation and planting. The concepts of genetic diversity, species diversity, and structural diversity should certainly be an element of any silvicultural systems in new, novel, or existing stands managed to accommodate changing climatic conditions through the twenty-first century.

Fig. 9 An example of successful planting to the north of a species' natural range—a productive loblolly pine stand in the Ouachita Mountains in Perry County, Arkansas. (Photo by James M. Guldin)

Conclusion

With climatic conditions forecast to change in varying ways across the southern United States through the end of the twenty-first century and beyond, southern forest ecosystems will face changing conditions. In the twentieth century, the practice of silviculture was defined as an ecological art and science designed to meet the objectives of the landowner, but subject to economic and social constraints (Smith et al. 1997). In the twenty-first century, the definition might evolve to account for not only economic and social constraints, but also ecological variability. Intensively managed planted stands of southern pines, especially loblolly and slash pine managed on short rotations with intensive site preparation and release, are one solution to changing climatic conditions, but the challenge is gain versus risk. The advantage is that a new planted stand is established about every 2–3 decades, and presumably, selections of planting stock made in the future will reflect the conditions that those planted stands are likely to face in the short term of the next rotation. In stands managed from natural or planted origin over the long term, other tactics come into play that consider diversity as a tactic for stand resistance, resilience, or transition in response to changing climatic conditions. Genetic diversity can best be captured when new age cohorts are established, species diversity bridges the period between stand establishment and early stand development, and structural diversity comes with decisions about even-aged or uneven-aged silvicultural systems. The broad application of assisted migration in the South, especially if it involves species other than pines or oaks, is likely to be difficult to implement widely because of the lack of research on species other than common commercial species, and the high cost implicit in establishing planted stands. But as a tool in the toolbox of the silviculturist working within managed forests, the tactic might be appropriate. In the end, the effects of changing climatic conditions on managed forests are fraught with uncertainty and risk. However, those are attributes with which silviculturists are familiar, and they will surely guide the profession in the management of southern forests through the twenty-first century.

References

Allen HL, Fox TR, Campbell RG (2005) What is ahead for intensive pine plantation silviculture in the South? South J Appl For 29:62–69

Aubin I, Garbe CM, Colombo S, Drever CR, McKenney DW, Messier C, Pedlar J, Saner MA, Venier L, Wellstead AM, Winder R, Witten E, Ste-Marie C (2011) Why we disagree about assisted migration: ethical implications for a key debate regarding the future of Canada's forests. For Chron 87(6):755–765

Baker JB, Shelton MG (1998) Rehabilitation of understocked loblolly-shortleaf pine stands-III. Development of intermediate and suppressed trees following release in natural stands. South J Appl For 22:41–46

Bettinger P, Clutter M, Siry J, Kane M, Pait J (2009) Broad implications of southern United States pine clonal forestry on planning and management of forests. Int For Rev 11(3):331–345

Billings RF (2011) Mechanical control of southern pine beetle infestations. In: Coulson RN, Klepzig KD 2011. Southern pine beetle II. General technical report. SRS-140. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, pp 399–413

Binkley CS, Raper CF, Washburn CL (1996) Institutional ownership of US timberland-history, rationale, and implications for forest management. J For 94:21–28

Bliss JC, Kelly EC, Abrams J, Bailey C, Dyer J (2010) Disintegration of the U.S. industrial forest estate: dynamics, trajectories, and questions. Small Scale For 9:53–60

Bragg DC (2016) Initial mortality rates and extent of damage to loblolly and longleaf pine plantations affected by an ice storm in South Carolina. For Sci 62(5):574–585

Bragg DC, Guldin JM (2014) The silvicultural implications of age patterns in two southern pine stands after 72 years of uneven-aged management. For Sci 61(1):176–182

Bragg Don C, Shelton Michael G (2010) Recovery of planted loblolly pine 5 years after severe ice storms in Arkansas. South J Appl For 34(1):13–20

Cain MD, Shelton MG (2001) Twenty years of natural loblolly and shortleaf pine seed production on the Crossett Experimental Forest in southeastern Arkansas. South J Appl For 25:40–45

Carvell KL, Tryon EH (1961) The effect of environmental factors on the abundance of oak regeneration beneath mature oak stands. For Sci 7(2):98–105

Clarke SR, Billings RF (2003) Analysis of the southern pine beetle suppression program on the national forests in Texas in the 1990s. South J Appl For 27(2):122–129

Dale VH, Joyce LA, McNulty S, Neilson RP, Ayres MP, Flannigan MD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, Simberloff D (2001) Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. AIBS Bull 51(9):723–734

Dey DC, Gardiner ES, Schweitzer CJ, Kabrick JM, Jacobs DF (2012) Underplanting to sustain future stocking of oak (*Quercus*) in temperate deciduoud forests. New Forest 43:955–978

Dooley E, Barlow R (2013) Special report: 2012 costs and cost trends for forestry practices in the South. Forest Landowner July/August, 22–28. http://digital.graphcompubs.com/publication/?i=171803&p=24. Accessed 3 Nov 2017

Erickson V, Aubry C, Berrang P, Blush T, Bower A, Crane B, DeSpain T, Gwaze D, Hamlin J, Horning M, Johnson R, Mahalovich M, Maldonado M, Sniezko R, St. Clair B (2012) Genetic resource management and climate change: genetic options for adapting national forests to climate change. USDA Forest Service, Forest Management, Washington, DC. Unnumbered publication. p 19. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1077125.pdf. Accessed 16 Mar 2018

Fox TR, Jokela EJ, Allen HL (2007) The development of pine plantation silviculture in the southern United States. J For 105(7):337–347

Guldin JM (2006) Uneven-aged silviculture of longleaf pine. Chapter 7, p. 217–249. In: Jose S, Jokela EJ, Miller DL (eds) The longleaf pine ecosystem: ecology, silviculture, and restoration. Springer, New York, p 438

Guldin JM (2008) The silviculture of restoration: a historical perspective with contemporary application, pp 23–35. In: Deal RL, tech. ed. 2008. Integrated restoration of forested ecosystems to achieve multiresource benefits: proceedings of the 2007 national silviculture workshop. General technical report PNW-GTR-733. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, p 306

Guldin JM (2011) Silvicultural considerations in managing southern pine stands in the context of southern pine beetle. In: Coulson RN, Klepzig KD (eds) Southern pine beetle II. General technical report SRS-140. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 317–352

Guldin JM (2014) Adapting silviculture to a changing climate in the southern United States. In: Vose JM, Klepzig KD (eds) Climate change adaption and mitigation management options: a guide for natural resource managers in southern forest ecosystems. CRC Press, Boca Raton, pp 173–192

Guldin JM (2016) Adapting silviculture to a changing climate in the southern United States. Chapter 7, pp 173–192. In: Vose JM, Klepzig KD (eds) 2013 Climate change adaptation and mitigation management options—a guide for natural resource managers in southern forest ecosystems. CRC Press, Boca Raton, FL, 476 p

Hedrick LD, Bukenhofer GA, Montague WG, Pell WF, Guldin JM (2007) Shortleaf pine-bluestem restoration in the Ouachita National Forest. In: Kabrick JM, Dey DC, Gwaze D (eds) Shortleaf pine restoration and ecology in the Ozarks: proceedings of a symposium; 2006 November 7–9; Springfield, MO. General technical report. NRS-P-15. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp 206–213

Helms JA (ed) (1998) The dictionary of forestry. Society of American Foresters, Bethesda, p 210

Iverson L, Prasad A (1998) Predicting abundance of 80 tree species following climate change in the eastern United States. Ecol Monogr 68(4):465–485

Iverson L, Prasad A, Matthews SN, Peters M (2008) Estimating potential habitat for 134 eastern US tree species under six climate scenarios. For Ecol Manag 254:390–406

Johnson PS (1977) Predicting oak stump sprouting and sprout development in the Missouri Ozarks. Research Paper NC-149. U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN, p 11

Johnson PS, Shifley SR, Rogers R (2009) The ecology and silviculture of oaks, 2nd edn. CABI Publishing Co., CAB International, New York, p 580

Lambeth CC, Dougherty PM, Gladstone WT, McCullough RB, Well OO (1984) Large-scale planting of North Carolina loblolly pine in Arkansas and Oklahoma: a case of gain versus risk. J For 82(12):736–741

Lambeth C, MacKeand S, Rousseau R, Schmidtling R (2005) Planting nonlocal seed sources of loblolly pine—managing benefits and risks. South J Appl For 29(1):96–104

Ledig FT, Kitzmiller JH (1992) Genetic strategies for reforestation in the face of global climate change. For Ecol Manag 50:153–169

Leech SM, Lara Almuedo P, O'Neill G (2011) Assisted migration: adapting forest management to a changing climate. BC J Ecosyst Manag 12(3):18–34

Loftis DL (1990) A shelterwood method for regenerating red oak in the southern Appalachians. For Sci 36(4):917–929

MacKeand S, Mullin T, Byram T, White T (2003) Deployment of genetically improved loblolly and slash pines in the South. J For 101(3):32–37

Malmsheimer RW, Heffernan P, Brink S, Crandall D, Deneke F, Galik C, Gee E, Helms JA, McClure N, Mortimer M, Ruddell S, Smith M, Stewart J (2008) Forest management solutions for mitigating climate change in the United States. J For 106(3):115–173

Masters RE, Robertson K, Palmer B, Cox J, McGorty K, Green L, Ambrose C (2007) Red Hills forest stewardship guide. Misc. Pub. 12. Tall Timbers Research Station, Tallahassee, p 79

McLachlan JS, Hellmann JJ, Schwartz MW (2007) A framework for debate of assisted migration in an era of climate change. Conserv Biol 21(2):297–302

McNulty S, Myers JM, Caldwell P, Sun G (2013) Chapter 3: climate change summary, pp 27–43. In: Wear DN, Greis JG (eds) 2013 The southern forest futures project: technical report. General technical report SRS-GTR-178. USDA-Forest Service, Southern Research Station, Asheville, NC, p 542

Monastersky RM (2013) Global carbon dioxide levels near worrisome milestone. Nature 497(7447):13–14

Nagel LM, Palik BJ, Battaglia MA, D'Amato AW, Guldin JM, Swanston CW, Janowiak MK, Powers MP, Joyce LA, Millar CI, Peterson DL, Ganio LM, Kirschbaum C, Roske MR (2017) Adaptive silviculture

for climate change—a national experiment in scientist–manager partnerships to apply an adaptation framework. J For 115(3):167–178
O'Hara KL, Ramage BA (2013) Silviculture in an uncertain world: utilizing multi-aged management systems to integrate disturbance. Forestry 86:401–410
Pachauri RK, Allen MR, Barros VR et al (2014) Climate change 2014: synthesis report. In: Pachauri R, Meyer L (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, p 151
Pedlar JH, McKenney DW, Aubin I, Beardmore T, Beaulieu J, Iverson L, O'Neill GA, Winder RS, Ste-Marie C (2012) Placing forestry in the assisted migration debate. Bioscience 62:835–842
Sander IL (1971) Height growth of new oak sprouts depends on size of advance reproduction. J For 69(11):809–811
Sander IL, Johnson PS, Rogers R (1984) Evaluating oak advance reproduction in the Missouri Ozarks. Research Paper NC-251. U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN, p 16
Smith DM, Larson BC, Kelty MJ, Ashton PMS (1997) The practice of silviculture, applied forest ecology, 9th edn. Wiley, New York, p 560
USDA Plant Hardiness Zone Map (1990) Agricultural Research Service, U.S. Department of Agriculture. http://planthardiness.ars.usda.gov/PHZMWeb/Images/USZoneMap.jpg. Accessed 3 Nov 2017
USDA Plant Hardiness Zone Map (2012) Agricultural Research Service, U.S. Department of Agriculture. http://planthardiness.ars.usda.gov. Accessed 3 Nov 2017
Vose JM, Clark JS, Luce CH, Patel-Weynand T (eds) (2016) Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis. Gen. Tech. Rep. WO-93b. U.S. Department of Agriculture, Forest Service, Washington Office. Washington, DC, 289 p
Wakeley PC (1954) Planting the southern pines. Agriculture monograph 18. U.S. Department of Agriculture, Washington, p 233
Wear DN, Greis JG (eds) (2013) The southern forest futures project: technical report. General technical report SRS-GTR-178. USDA-Forest Service, Southern Research Station, Asheville, NC, p 542
Williams MI, Dumroese K (2013) Preparing for climate change: forestry and assisted migration. J For 111(4):287–297