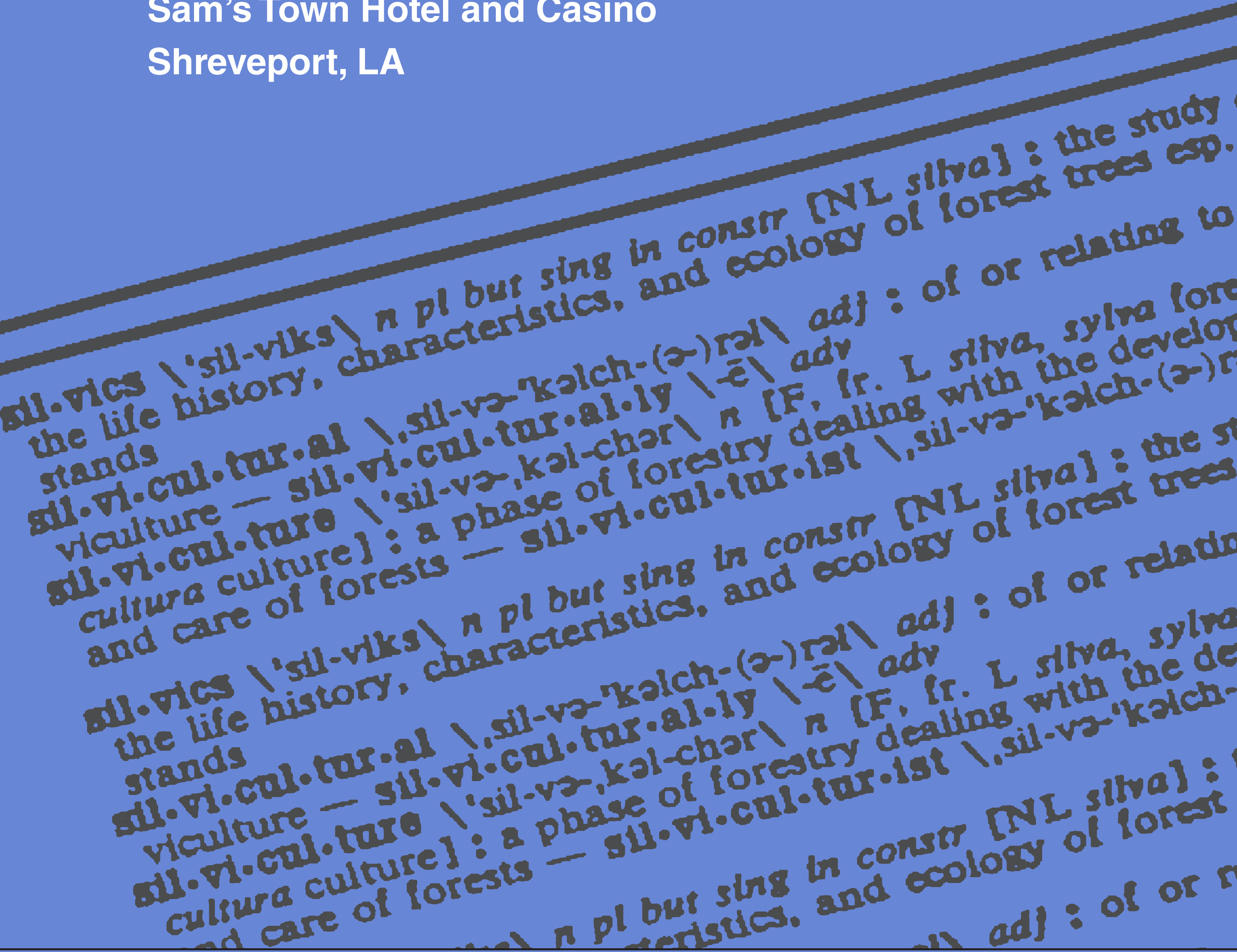
United States Department of Agriculture

Proceedings of the 20th Biennial Southern Silvicultural Research Conference

March 12-14, 2019
Sam’s Town Hotel and Casino
Shreveport, LA



Forest Service
Southern Research Station
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EDITORS' NOTE

Papers published in these proceedings were submitted by authors in electronic media. Some editing was done to improve the readability, accuracy, and consistency of contributed papers. Authors are responsible for content and accuracy of their individual papers and the quality of illustrative materials.

August 2020

Southern Research Station
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March 12-14, 2019
Sam's Town Hotel and Casino
Shreveport, LA

Edited by

Don C. Bragg

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Hosted by

School of Agricultural Sciences and Forestry, Louisiana Tech University

USDA Forest Service, Southern Research Station

Preface

The 20th Biennial Southern Silvicultural Research Conference (BSSRC) was held March 12-14, 2019, at Sam's Town Hotel and Casino, Shreveport, LA. This conference was the 20th in this series of meetings designed to provide a forum for the exchange of knowledge among silviculturists, researchers, managers, and students. Over the decades, those interested in forest management have found the conferences and their proceedings to be valuable sources of information on current and developing trends in southern forest silviculture.

The three-day event kicked off with two keynote presentations dealing with the past, present, and future of the BSSRC. The first keynote featured Jim Barnett, Emeritus Scientist, Southern Research Station, USDA Forest Service, who presented a review of silvicultural research in the South and the 40-year history of the conference. The second keynote was a panel discussion on the current and future BSSRC, and included representatives from academia, the timber industry, and the USDA Forest Service. This panel, moderated by Gordon Holley, Professor, Louisiana Tech University, consisted of Andy Ezell, Emeritus Professor and Head, Mississippi State University; Conner Fristoe, Silviculture Manager, MSLA Region, Weyerhaeuser; and Don Bragg, Project Leader, Southern Research Station, USDA Forest Service.

During the first two days of the conference, the presenters offered 68 oral and 35 poster presentations in four concurrent sessions. These presentations emphasized research in fire, measurements, modeling, stand management, hardwood regeneration, longleaf and shortleaf pines, and vegetation control. Of those presentations, 39 were presented by students (23 oral and 16 posters). Two field tours were offered on the final day: a Forest Industry Operational Tour hosted by Conner Fristoe (Weyerhaeuser), Mickey Rachal (RoyOMartin), and David Wilkinson (Hancock Forest Management) and a Silvicultural Research Tour of Louisiana State University AgCenter's Hill Farm Research Station hosted by Michael Blazier (Professor and statewide extension specialist, Louisiana State University, AgCenter, Hill Farm Research Station). In all, more than 220 people attended the conference.

Acknowledgments

With 40 years of history, the BSSRC remains an important venue for sharing and disseminating silvicultural research and training the next generation of silviculturists. This conference would not have been possible without the dedication and collaboration between universities, the USDA Forest Service, State and private agencies, and our forest industry partners. We gratefully acknowledge the Louisiana Tech University Foundation for its handling the fiscal responsibilities and for assistance in the registration process. Special thanks to all the committee members for their countless hours of dedication and work over the many months it took to facilitate this conference.

Program Chairs and Local Arrangements:

Gordon Holley, Louisiana Tech University
Don Bragg, USDA Forest Service, Southern Research Station

Steering Committee Members:

Joshua Adams, Louisiana Tech University
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Don Bragg, USDA Forest Service, Southern Research Station
Kyle Cunningham, University of Arkansas
Tom Dean, Louisiana State University
Andy Ezell, Mississippi State University
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Buck Vandersteen, Louisiana Forestry Association
David Wilkinson, Hancock Forest Management

Continuing Education Credits:

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Field Tour I: Industry Operational

Mickey Rachal, Chair, RoyOMartin
Conner Fristoe, Weyerhaeuser
David Wilkinson, Hancock Forest Management

Field Tour II: Silvicultural Research

Mike Blazier, Louisiana State University AgCenter, Hill Farm Experiment Station

Moderator Organization:

Brian Oswald, Stephen F. Austin State University

Poster Session:

Joshua Adams, Chair, Louisiana Tech University
Gordon Holley, Louisiana Tech University
Tara Keyser, USDA Forest Service, Southern Research Station

Print Materials:

Don Bragg, Chair, USDA Forest Service, Southern Research Station
Gordon Holley, Louisiana Tech University

Proceedings:

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Conner Fristoe, Chair, Weyerhaeuser
Buck Vandersteen, Louisiana Forestry Association
David Wilkinson, Hancock Forest Management

Records:

Michelle Moore, Texas A&M Forest Service

Registration:

Gordon Holley, Louisiana Tech University

Student Oral and Poster Contest:

Brian Lockhart, Chair, USDA Forest Service, Southern Research Station
Andy Ezell, Mississippi State University
Tom Dean, Louisiana State University

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Callie Schweitzer, Chair, USDA Forest Service, Southern Research Station
Matt Olsen, University of Arkansas, Monticello

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20th BSSRC Student Oral and Poster Presentation Contest Winners (Major Professor in parentheses)

Oral Presentations:

Nathan Bolner – Louisiana Tech University (undergraduate student, research directed by Dr. D. Paul Jackson)
Connor Crouch – University of Missouri (Dr. Benjamin Knapp)
Alicia McAlhaney – Louisiana State University (Dr. Tom Dean)

Poster Presentations:

Bridgette Blood – Clemson University (Dr. Geoff Wang)
Brittany DiRienzo – Clemson University (Dr. Geoff Wang)
Kathryn Schmidt – Oklahoma State University (Dr. Rod Will)

Moderators

■ March 12, 2019

Keynotes – Gordon Holley, Louisiana Tech University

Session A:

Forest Measurements and Modeling – David Wilkinson, Hancock Forest Management

Session B:

Fire – Rebecca Kidd, Stephen F. Austin State University

Session C:

Longleaf Pine – Brian Oswald, Stephen F. Austin State University

Session D:

Hardwood Regeneration – Michael Blazier, Louisiana State University AgCenter, Hill Farm Experiment Station

Poster Session (no moderator)

■ March 13, 2019

Session A:

Fire – Rebecca Kidd, Stephen F. Austin State University
Hardwood Regeneration – Brian Lockhart, USDA Forest Service, Southern Research Station

Session B:

Intermediate Management and Stand Development –Tom Dean, Louisiana State University

Session C:

Vegetation Management – Andy Ezell, Mississippi State University
Shortleaf Pine – Don Bragg, USDA Forest Service, Southern Research Station

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Andy Ezell

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Don Bragg

1. Keynote I

Moderator:

Gordon Holley

SILVICULTURAL RESEARCH IN THE SOUTH: ITS HISTORY AND THE ROLE OF THE BIENNIAL SOUTHERN SILVICULTURAL RESEARCH CONFERENCE

James P. Barnett

Abstract—Through the application of silvicultural research, the forests of the South that were devastated by aggressive harvesting in the early 20th century have been restored to become the most productive and sustainable forests in the world. The development of this research capability and its application throughout the South is documented, and the role of the Biennial Southern Silvicultural Research Conference is discussed.

INTRODUCTION

The impact of silvicultural research of southern forest species on the restoration of the South's and the Nation's economy is remarkable. In less than 100 years, the forests of the South have been transformed from cutover "stumpscapes" to the some of the most productive and sustainable forests of the world. Why and how did this happen?

Early in the 20th century, forestry in the United States was in its infancy and depended upon foresters trained in Europe to implement management and provide forestry training. In this era, development of the lumbering industry following the Civil War brought jobs and businesses that began to restore the South's economy. The "golden age of lumbering" began and, in the first quarter of the 20th century, the harvest of much of the virgin pine forests in the South occurred in what has been described as "probably the most rapid and reckless destruction of forest known to history" (Cooper and Terrill 1991).

When the Southern Pine Association cosponsored a "Cut-Over Land Conference of the South" in New Orleans in 1917 to discuss the problem of cutover lands, the possibility of reforestation was scarcely considered because it seemed economically infeasible (Barnett and Carter 2017).

The magnitude of the cutover land was brought into focus when a survey was conducted by the Southern Pine Association in 1919—the South's cutover land equaled the combined areas of Alabama, Mississippi, and Louisiana! This survey reported that 92 million acres of land had most of the timber removed (Heyward 1958). Thus, the seriousness of this situation began to be understood. During the first decade of the 20th century, President Theodore Roosevelt and the U.S. Forest Service's Chief Forester, Gifford Pinchot, predicted that the once-boundless resources of the country might be reduced to the state of some impoverished Mediterranean country (Williams 1988).

Not all of this land was barren stumpland since all sawmills did not practice the same degree of utilization, nor did all make use of steam skidders (fig. 1), a form of logging which caused great damage to any timber left standing. However, little of this acreage was capable of becoming productive again without help. Cutover lands were a man-made problem and warranted a man-made solution.

EARLY REFORESTATION EFFORTS

Slowly, lumbermen and the general public became interested in some kind of reforestation. The leader of this effort, Henry Hardtner, President of the Urania Lumber Company in the backwater town of Urania, LA, was one of the first to recognize that cutover lands were a serious problem. Although he had no formal forestry training, he read widely about forestry and crusaded for the forestry cause. Hardtner's ideas on reforestation were ahead of the professional knowledge of the time. At his request, in 1909, the Forest Service, U.S. Department of Agriculture, sent W.W. Ashe and, later, W.R. Mattoon and Austin Cary, to Urania (Burns 1978). While Hardtner's belief that a second crop of trees could be grown profitably after the virgin timber was cut was widely ridiculed, these Forest Service specialists, who published some of the earliest documents on the silvics

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Figure 1—This massive rail-mounted Clyde skidder could harvest 40 acres of timber at one setting. Four cables could pull timber from up to 1,000 feet.

of major southern species (Ashe 1915, Mattoon 1922), gave credibility to Hardtner's reforestation efforts.

Hardtner set out to develop methods to regenerate longleaf pine (*Pinus palustris*), even though he estimated that it would take 60 to 100 years to grow a merchantable-size tree (Carter and others 2015). By applying some basic forestry principles to his land—leaving seed trees, fencing to exclude hogs, and establishing a primitive fire protection system—Hardtner demonstrated the potential of growing another crop of pines. In 1917, Hardtner, who also believed in research and education, invited the annual Yale University School of Forestry spring field camp to be located at Urania. Professor H.H. Chapman, who supervised and trained the students, began to conduct research efforts to clarify the role of fire in longleaf pine management and established some early growth-and-yield guidelines (Barnett and Carter 2017).

Others quickly recognized the potential of reforestation. For example, in 1919 A.C. Goodyear (President) and W.H. Sullivan (General Manager) of the Great Southern Lumber Company visited Hardtner to learn how to modify their company's logging practices and begin a reforestation program. Great Southern Lumber Company started leaving seed trees, reduced the impact of skidding operations, fenced their longleaf regeneration to exclude hogs, and established a tree nursery program. By the following year, the Great Southern Lumber Company assigned the task of establishing its reforestation program to a 24-year-old named F.O. "Red" Bateman. Bateman was not trained in forestry, but he had worked in the forests since high school and possessed an intuition and perception that allowed him to become, in the words of Philip C. Wakeley, "one of the greatest silviculturists the South has known… For many years all the rest of us merely followed or wrote up what he developed and showed us" (Wakeley 1976). By 1922, Bateman succeeded in naturally regenerating longleaf pine, established a nursery, and developed methods for seed collection, seedling production, and planting (fig. 2). He also invented a planting tool, "the dibble," and a method of "slit" planting that became an enduring standard across the South (Carter and others 2015).

PROGRAMS FOR DEVELOPING FORESTRY EXPERTISE

At the turn of the century, it was apparent that there was a critical need for forestry training and education. In the late 1800s, Gifford Pinchot, who later became Chief of the Forest Service, established a forestry program at George Vanderbilt's Biltmore Estate near Asheville, NC. After Pinchot left the Biltmore Estate, a professionally trained forester from Germany named Carl A. Schenck was hired as his replacement. Schenck established the Biltmore Forest School in 1898; its curriculum focused on providing 1 year of practical forestry management

Figure 2—The Great Southern Lumber Company reforestation program gained international recognition—in 1925, this group toured the effort. From left kneeling: R.D. Forbes. Director of the Southern Forest Experiment Station; Roy Hogue, State Forester of Mississippi; W.R. “Billy” Hine, State Forester of Louisiana. Standing from the left: J.K. Johnson, Great Southern; Norman Gore, Louisiana State Ranger; Dr. Tor Jonson, leading professional Forester in Sweden; Harry Lee Baker of the Forest Service Washington Office; Mr. Johansson, Dr. Jonson’s interpreter; F.O. “Red” Bateman, Great Southern; E.L. Demmon, who succeeded Forbes as Director of the Southern Forest Experiment Station.

training. It is considered the first forestry school in the United States, although Cornell University, University of Minnesota, Michigan State University, and Yale University created 4-year forestry schools shortly after the Biltmore experiment began.

Schenck’s Biltmore Forest School closed after 15 years, but as unconventional as it was, it trained about 400 students, some of whom made notable contributions to forestry in the United States. Schenck and his students established a few plantations, but their focus was more on stand management. In the South, the University of Georgia (1906) and Louisiana State University (1926) led in establishing forestry programs. H.H. Chapman of Yale University brought many students down to the South as early as 1909 to give them additional field opportunities in forestry. It is fitting, perhaps, that it was forestry graduates from northern universities who began moving into the South to lead reforestation efforts resulting from the forest devastation caused largely by northern lumbermen.

Forestry expertise developed through other sources as well. About this same time period, the newly created U.S. Forest Service received requests for assistance and information on reforestation from lumber companies and individuals scattered across the South. To satisfy this demand, the Forest Service recruited individuals with practical experience related to the issues of concern. Although they had little forestry training, these individuals had exceptional ability to observe nature, draw tentative conclusions, and make practical recommendations. The most notable of these “transients” who traveled widely throughout the South were Austin Cary, W.W. Ashe, and W.R. Mattoon (Barnett 2011).

EARLY RESEARCH OF THE U.S. FOREST SERVICE EXPERIMENT STATIONS

In 1921, the U.S. Forest Service established the Southern Forest Experiment Station (headquartered in New Orleans, LA) and the Appalachian Forest Experiment Station (Asheville, NC). The Southern Forest Experiment Station was responsible for research in the southern pine types. This included all of the Coastal Plain areas in Georgia and South Carolina; all of Florida, Alabama, Mississippi, and Louisiana; Texas and Oklahoma as far as the pine type went; and Arkansas south of the Arkansas River. The Appalachian Forest Experiment Station emphasized the mountainous pine-hardwood types.

Carter and others (2015) attributed three U.S. Forest Service publications that highly influenced the development of forestry in the South. First, from the earliest days of interest in managing southern pine, industrialists, landowners, and foresters had been asking, “How fast do southern pines grow, how long does it take to grow a sawlog, and how much volume of second growth can I expect to grow on an acre?” Miscellaneous Publication 50 (USDA Forest Service 1929) or MP-50, as *Volume, Yield, and Stand Tables for Second-growth Southern Pines* was known, provided answers to these questions. The pocket-sized MP-50 became a constant companion to foresters and continued to be in such demand that it was reprinted in 1976, nearly 50 years after it was first published (Carter and others 2015) and it is still available as an electronic publication on the Forest Service's Treesearch website (https://www.fs.usda.gov/treesearch/pubs/24559).

The second milestone contribution from the Southern Forest Experiment Station was Philip C. Wakeley's development of the technology for establishing and managing southern pine plantations. When Wakeley was recruited to work for the Southern Forest Experiment Station in 1924, there were fewer than 20 professional foresters working in the entire South (Wakeley and Barnett 2011). Nearly a third of these were on the Southern Forest Experiment Station's staff, and almost as many were employed by the Appalachian Forest Experiment Station. When Wakeley arrived at the Station, he was assigned to work with the Great Southern Lumber Company's reforestation program underway at Bogalusa, LA. The Great Southern program ended in the 1930s when the company went into receivership. Wakeley moved his research effort to the Kisatchie National Forest's Stuart Nursery in central Louisiana in 1935. This effort culminated with the publication of Wakeley's (1954) monograph, *Planting the Southern Pines* (earlier versions appeared in 1929 and 1935). As the basis for most reforestation efforts across the South after World War II, this publication is probably the most frequently cited forestry publication in the South and is still well cited although it has been out of print for many decades.

The Southern Forest Experiment Station's third pioneering contribution was the first forest survey of the South following the passage of the McSweeney-McNary Forest Research Act of 1928, which authorized a nationwide forest inventory. The challenge of this effort was enormous—an inventory of over 200 million acres of forest stretching from the Carolinas to east Texas. The Southern Station began fieldwork in 1932 and remarkably completed this task by 1936. To conduct this first survey, compass lines were run 10 miles apart across each State from the Tennessee line southward to the tip of Florida. At every 660 feet along each line, a 0.25-acre plot was measured—all trees were counted and their size, species, and other information determined. A steady stream of information came from the analyses of these data, and releases on results were eagerly sought. The amount of data was so massive that it was about 1944 before all the results were published. Benefits of the survey have been summarized as astounding, as people had no idea of the amount and distribution of the timber, how fast it grew, or its stage of development—this knowledge would soon help bring the pulp and paper industry to the South (Barnett 2018, Maunder and Eldredge 1960). Although this effort is not pure silvicultural research, it provided the information needed for the expansion of industrial forestry in the South and the data required for the rapid development of forest management technology.

SILVICULTURAL RESEARCH IN THE POST-WORLD WAR II YEARS

During World War II, forestry research reached a low ebb—many employees served overseas in military services, and those remaining at home were given war-related responsibilities. Field studies could not be maintained, and data were lost. However, the postwar environment began to energize and expand the research program. Fortunately, forestry schools were now crowded with veterans going to school on the GI Bill. In the late 1940s, the war's end brought a great need for intensified research. Even as late as 1960, up to 29 million acres of forest land in the South were in need of reforestation and management technology (Wahlenberg 1960). With an increasing need for forestry-related research in the South, the Forest Service restructured for its greatly enhanced mission (at the time, there were no forest industry-sponsored research programs and university research was in its infancy).

Realignment of Experiment Stations

A major element of the Forest Service's restructuring was the realignment of the boundaries of the Southern and Appalachian Forest Experiment Stations. Officials of the Southern Forest Experiment Station had learned that the vastness of the Station—the entire southern Coastal Plain—made administration of the organization challenging. So, in 1946, the extent of the New Orleans-based Southern Forest Experiment Station was altered. Tennessee and all of Arkansas were added to the Southern Forest Experiment Station, and South Carolina, Georgia, and Florida were reassigned to the remainder of the Appalachian Forest Experiment Station, now called the Southeastern Forest Experiment Station (which was still headquartered in Asheville).

Creation of Research Centers

The Forest Service also changed how the forest experiment stations were organized. In the early version of the Southern Forest Experiment Station, individual scientists reported directly to the Station Director and usually only one or two scientists were assigned to an area of research. The new organization was patterned more like a military organization, with the Station Director having a staff of both administrative and program Assistant Directors. Leaders of field research centers reported to the Assistant Directors, and the research centers generally consisted of a number of scientists of differing disciplines. For example, modern, state-of-the art research facilities at the Alexandria Research Center in central Louisiana were created in 1946. Located in the Alexandria Forestry Center (which also housed units of the U.S. Forest Service's National Forest

System and State and Private Forestry), the Alexandria Research Center's mission was to develop technology for establishing and managing southern pine plantations in Louisiana and Texas. When the author was assigned to the Alexandria Research Center in the spring of 1961, it had a large scientific staff: W.F. "Bill" Mann was the Research Center Leader and worked wherever his interests lay; Gene Shoulders studied nursery and soil concerns; Vince Duvall worked in range research; Harold Derr researched direct seeding; Bob McLemore (and the author) studied seed problems; Bob Blair investigated wildlife relationships; John Moser worked with insects; Glen Hatchell researched growth and yield; Fred Peevy investigated woody plant control; Harold Grelen worked on botany and range issues; and Hans Enghardt (a scientist assigned by the Louisiana Forestry Commission) investigated plantation management.

Similar research centers were located in different geographic areas across the Southern Forest Experiment Station. Many of these developed very strong political alliances; centers were able to create "advisory committees" that included the foremost forestry leaders within the State. Most of these forestry leaders served in the military during World War II and knew how to organize supportive programs. The centers became very effective research organizations, and many of the research center leaders became so politically astute that Station Directors had difficulty managing them.

Statistical Training

In the 1950s and early 1960s, those hired as researchers brought a mixed bag of scientific credentials—some had a bachelor's degree (including the author, hired in 1957 with only a Bachelor of Science in Forestry), others had a master's degree, and only a few had doctorates. The stations were liberal in their support of scientists' needs for continuing education—time was provided and expenses were covered for those obtaining advanced degrees. During these years, however, few forestry students got college training in sampling, statistics, and other relevant courses needed to effectively conduct scientific research. As a result, the Southern Forest Experiment Station began to provide training in sampling and statistics. Workshops were held for new employees, and "cookbooks" were written to lead the scientists though common techniques that were needed to conduct statistical analyses. Probably more important was the availability of statisticians on the Station's staff for counseling and review of all study plans, final reports, and publications for proper use of statistics.

Establishment of Research Work Units

A major realignment of Forest Service research occurred in 1963 when research centers were broken up into smaller units, called "research work units" (RWUs), and the establishment of local advisory committees was banned. These were the Station Directors' efforts to reduce the political influence of the powerful Center Directors with their constituents, especially with respect to procuring budgets for center research programs from Congress, for which the Directors might not approve!

At the Alexandria Research Center, this resulted in center scientists being reassigned to one of five different RWUs: timber (later renamed forest), range, fire, insects, and wildlife. The Center Leader position was abolished, and Project Leaders assumed leadership role for RWUs. Typically, RWUs had a staff of three to five scientists and a good support staff of technicians and clerical positions.

Funding for Research

During the early 1960s, funding for scientific research blossomed, largely related to the successful aerospace program and support from forest industries. Up to this time, Forest Service Research and Development (R&D) was the primary provider of technical information for the rapidly developing forestry efforts across the South. Slowly, forest industry began to provide some funding for their more specific internal needs. In addition, Federal funding for forestry research by land-grant universities was provided by the McIntire-Stennis Act of 1962, which enabled universities to develop their research programs to support a broad array of regional forestry needs.

Maturation of the South's Research Programs

By the late 1970s, forestry research in the South had matured. The Southern and Southeastern Forest Experiment Stations were still the primary providers of forestry research, but industrial and university research efforts had also expanded the scope of their programs. During this period, collaborative efforts became prominent. Numerous cooperative programs were established to pool scientific capabilities among government, industry, and university specialists. These occurred in areas such as genetics and tree improvement, soil productivity, nursery production, biometrics, growth and yield, and herbicide application. Also, during this time the adequate dissemination of information became a concern and focus—frequently called for was the need for greater coordination and transfer of technology to user groups.

THE ROLE OF THE BIENNIAL SOUTHERN SILVICULTURAL RESEARCH CONFERENCE

Although the transfer of scientific information is an obvious justification for establishing the Biennial Southern Silvicultural Research Conference, there were some more pragmatic reasons as well. Within Forest Service R&D, the Southern and Southeastern Forest Experiment Stations were conducting research in the same region and on the same species, so there were always some turf issues around who was primarily responsible for any particular topic. Initially, these issues were resolved by the program Assistant Directors of the two stations, but over time the number of Assistant Directors declined. There, too, was a level of frustration among silviculturists because their research was generally long term and there was a lack of outlets to publish preliminary data.

A venue where Forest Service silviculturists could meet, share information, and coordinate their programs' efforts was needed. Needed, too, was the involvement and inclusion of silviculturists from universities and forest industry. In 1978, long-term Project Leader Bill Mann at the Alexandria Research Center in Pineville proposed the conference, and the idea was supported by the Directors of the two stations. The administrative Assistant Directors of both stations were charged with making arrangements for hotels and providing other administrative support. The author was named to chair a committee selected to plan the biennial conference that would begin in the fall of 1980, and other committee members selected from the two stations' geographic regions included Tommy R. Dell, Southern Station; David L. Bramlett and William R. Harms, Southeastern Station; George L. Switzer, Mississippi State University; and Klaus Steinbeck, University of Georgia.

Conference Mission and Organizational Structure

The committee met and established some guidelines for the conference. The mission of the conference was to provide a forum for exchange among silviculturists, research coordination, continuing education for researchers, review of research in progress, and presentation of new approaches or techniques of general interest, as well as a published conference proceedings to help disseminate preliminary results of long-term studies.

Since a number of concurrent sessions were anticipated, the committee wanted to establish a structure that would ensure participants could move easily from one session to another. Hence, presentations were limited to 20 minutes, allowing 5 minutes for discussion and 5 minutes for movement to another session. Moderators were charged to keep sessions on schedule. This system worked well and has been used in all succeeding meetings.

The first Biennial Southern Silvicultural Research Conference proved to be a success and became the format for continuing conferences for the next 40 years. Subsequent meetings have had at least 100 presentations and an attendance of about 250 individuals. Optional field tours following the meeting were soon incorporated into the conference.

Publication of the Proceedings

Prompt publication of a proceedings was seen as important by the committee. Since this session was in the pre-computer word processing era, the authors were required to submit the documents in camera-ready form and were responsible for the content of their papers. To assure uniformity of the written material, large oversized sheets with blue outlines showing the needed format were sent to each author—this would allow the written material to be photocopied and reduced to normal page size for publication by the Southern Forest Experiment Station.

The job of the Conference Chair was to collect the documents from the authors, ensure they met the format criteria, organize the material for publication, and submit it to the Southern Forest Experiment Station's publication group. The documents were published without further review. Seventy-five papers were included in the first proceedings of the conference, and the proceedings was distributed within 6 months of the meeting. The computer age has added a number of complications for the Conference Chair. Papers now need to be submitted in an electronic format, and the agency has stricter guidelines for peer review and editorial standards. Because of these added layers, the Conference Chair and those involved in the publishing process must work diligently to ensure that users can still receive the published proceedings in a timely manner. Though the proceedings are now published online only (no hard copies), they are now available on demand for anyone in the world to read. Times have changed!

CURRENT STATUS OF SILVICULTURAL RESEARCH

Driving a few miles down almost any highway in the forested areas of the South, one can observe beautiful and productive forests that are the backbone of the region's economy. The restoration of forests on over 20 million acres of cutover land over the last 5 or 6 decades is a major accomplishment—one due to the development and application of silvicultural research.

This effort has been effective because silvicultural knowledge is now available to manage our major forest species. But that success has included an unintended outcome—the perception that there is a reduced need for the continued intensive silvicultural research found throughout the latter half of the 20th century. This is borne out by declining support within Forest Service R&D. The Southern and Southeastern Forest Experiment Stations merged in 1995, and appropriated funding levels for research continue to decrease. In addition, the number of active Forest Service-wide Research Forester positions has declined, from about 350 positions in 1985 to 94 in 2016. Forest industries are selling their forest land and minimizing forest management programs. Funding available to universities for silvicultural research is declining as well, and university forestry departments are merging with other departments on campus as enrollments decline. These trends affect the Biennial Southern Silvicultural Research Conference, with the numbers of presentations and attendees slowly dropping.

There will be, however, a continuing need for silviculturists and silvicultural research. Nature is never stagnant—our climate is changing and manufacturing technology continues to advance. If forestry in the South is to remain competitive in world markets, we must have updated silvicultural knowledge to adjust to changing conditions and markets. Coordination of these efforts through events such as the Biennial Southern Silvicultural Research Conference will continue to be needed.

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2. Forest Measurements and Modeling

Moderator:

David Wilkinson

CALIBRATING A GROWTH-AND-YIELD MODEL FOR LOBLOLLY PINE IN THE MISIONES/PARANÁ REGION OF SOUTH AMERICA—AN OVERVIEW

Ralph L. Amateis and Harold E. Burkhart

Abstract—Data from permanent remeasurement plots established in loblolly pine (*Pinus taeda* L.) plantations growing in the Misiones/Paraná region of South America were used to develop and test a system of equations for predicting and projecting volume yields for thinned and unthinned stands in that region. Component equations parameterized with the data included dominant height/site index, basal area prediction and projection, survival, and total volume yield prediction. Improved estimates of yield were achieved when geographic coordinates were included in the basal area and total volume yield equation. Yield projections suggest that the system as a whole can be a useful tool for modeling growth and yield in this region of South America.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.), planted extensively across its native range in the Southeastern United States, has proven to grow well as an exotic in other regions including the Misiones/Paraná areas of southern Brazil, northern Uruguay, and Argentina (fig. 1). Under intensive management, internal rates of return can range from 9 percent to 17 percent (Cubbage and others 2007). With a membership that includes cooperators managing land in this very productive area of South America, the Forest Modeling Research Cooperative (FMRC) has been working toward developing tree growth and stand development models to support intensive loblolly pine plantation management in that region. Initial work centered on testing extant dynamic component models of dominant height/site index, survival, and basal area projection equations using permanent inventory plot data from Argentina. Specifically, models from Acerbi and others (2002), Costas and others (2007), and Eisfield and others (2005) were selected because they were developed using data from southern Brazil and northern Uruguay in the Misiones/Paraná region. In addition, a set of models from the Atlantic Coastal Plain areas of the Southeastern United States were also included (Amateis and Burkhart 2017, 2018).

Residual analyses indicated no clear trends for the equations tested across all soil drainage classes and soil textures. The North American models from the Atlantic Coastal Plain generally underpredicted, with basal area and survival having a larger underprediction bias than dominant height. This underprediction bias in basal area translated through to underprediction of the total volume yield. In summary, no specific set of component equations could be identified as significantly superior using these limited data.

Subsequently, additional data became available that encompassed areas of southern Brazil and northern Uruguay. These data augmented those from Argentina, thus significantly expanding the geographic distribution of plots in this region. They also included geographic coordinates (latitude and longitude in decimal degrees), which have been shown to be significant regressors when used to develop growth-and-yield models in North America (Russell and others 2010, 2012). The purpose of this study was to combine all available data and develop a set of model components and an integrated model system for use in the Misiones/Paraná region of South America.

METHODS

Data

Data from 921 permanent inventory plots in operational loblolly pine plantations located in the Misiones/Paraná region of Argentina, Brazil, and Uruguay (fig. 1) were available for modeling. Some plots received no mid-rotation management treatments. Others were thinned or thinned and pruned once and some received multiple thinning and/or pruning treatments. Plot variables included age (years), dominant height (m), basal area (m^2 ha^{-1}), trees surviving (trees per hectare), and total volume yield (m^3 ha^{-1}). The precision of all variables, including age, was to one decimal. Of those, 585 plots included geographic coordinates (latitude and longitude in decimal degrees). Most of the plots were remeasured

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Figure 1—Map showing the general location (in red) of the Misiones/Paraná region in South America.

at least once and some multiple times; autocorrelation was not taken into account in model fitting. Remeasurement intervals varied. Table 1 summarizes the combined data for all unthinned and thinned plots.

Models

Dominant height/site index—Because stand dynamic relationships are influenced strongly by site quality, a dominant height/site index equation is a central component equation of most growth-and-yield model systems. For this project, an improved dominant height/site index equation capable of expressing the height-age relationship across a broad range of ages and growing conditions was needed. While the definition of dominant height in South America is generally expressed as the average height of the 100 trees with the greatest diameter at breast height (d.b.h., 1.37 m) per hectare, there is no standard base age used across the region. Thus, to be broadly applicable, any site index model must have the property of base-age invariance (Burkhart and Tomé 2012).

Table 1—Summary statistics across all measurements for 921 permanent plots in operational loblolly pine plantations in the Misiones/Paraná region of South America

Variable	Mean	SD	Minimum	Maximum
Age (years)	11.6	4.7	3.0	25.8
Dominant height (m)	17.4	5.1	4.2	33.9
Basal area (m^2 ha^{-1})	30.6	11.0	6.2	81.8
Trees (per hectare)	829.5	422.0	140.0	2486.0
Total volume over bark (m^3 ha^{-1})	258.3	151.9	6.5	1159.1
Latitude (decimal degrees)[a]	-28.1778	0.2936	-29.0084	-27.4178
Longitude (decimal degrees)[a]	-56.1309	0.2109	-56.5492	-55.6875

SD = standard deviation.

[a] 585 plots had latitude and longitude data.

To model the height-age trend in these data, several base-age invariant candidate models were examined. The model developed by Bailey and Clutter (1974) and tested by Cao (1993) was found to be superior for these data:

$$HD_2 = exp\{b_1 + (ln\ (HD_1) - b_1)\ (A_1/A_2)^{b_2}\} \qquad (1)$$

where A_1, A_2 = age (years); HD_1, HD_2 = average height (m) of the 100 thickest trees per hectare at ages A_1 and A_2, respectively; and b_1, b_2 = parameters. By substituting a site index value, S, for HD_1 at A_1 and solving for S, equation (2) can be used to estimate site index from dominant height and age:

$$S = exp\{b_1 + (ln(HD) - b_1)\ (A/A_I)^{b_2}\} \qquad (2)$$

where A_I is index age and b_1 and b_2 are the same as in equation (1).

Basal area prediction—When basal area for an existing stand is not available or when initiating a plantation at young ages, an estimate of initial basal area is needed. Equation (3) was found to be suitable for this purpose:

$$ln(BA) = b_0 + b_1\ ln(N) + b_2\ ln(HD) + b_3\ ln(A) + b_4\ LONG \qquad (3)$$

where BA is basal area (m^2 ha^{-1}); N=trees per hectare; $LONG$=longitude expressed in decimal degrees; and b_0-b_4 are parameters.

Basal area projection—Basal area projection equations suitable for unthinned and thinned stands for the area are required. The model of Clutter and Jones (1980), modified with variables that account for the effects of thinning and geographic locale (equation (4)), was found to be appropriate for these data:

$$ln(BA_2) = (HD_1/HD_2)^{b_1}\ (ln(BA_1))^{(b_{21} + b_{22}\ THIN + b_{23}\ LONG)} + b_3\ (N_1^{b_4})\ (1 - HD_1/HD_2)^{b_1} \qquad (4)$$

where BA_1 and BA_2 are basal area (m^2 ha^{-1}) at time 1 and time 2, respectively; N_1=trees per hectare at time 1; $THIN$=1 if the stand has been previously thinned, 0 otherwise; and b_1-b_4 are parameters.

Survival projection—Projections of trees per hectare surviving are obtained using the baseline equation from Clutter and Jones (1980) modified with a variable that accounts for the effects of thinning. Efforts to improve the model by including geographic coordinates were not successful. Therefore, equation 5 was accepted:

$$N_2 = [N_1^{\ (b_{11}+b_{12}{}^*THIN)} + b_2\ (\ (A_2/10)^{b_3}) - (A_1/10)^{b_3})\ ]^{\ (1/(b_{11}+b_{12}{}^*THIN))} \qquad (5)$$

where N_1 and N_2 are trees per hectare at time A_1 and A_2, respectively, and other variables as previously defined.

Total yield—A total volume yield outside bark model that can be viewed as a stand-level analog to the individual tree combined variable equation (Burkhart and Tomé 2012) was selected to predict total volume (m^3 ha^{-1}) for all plots 5 years of age or older.

$$TVob = (b_{01} + b_{02}THIN + b_{03}LAT)\ BA^{b_1}\ HD^{\ b_2} \qquad (6)$$

where $TVob$ is total volume yield (m^3 ha^{-1}) outside bark; and LAT = latitude expressed in decimal degrees. The variable THIN takes on a value of 1 for a stand previously thinned or 0 for an unthinned stand and b_{01}-b_{02} are parameters.

RESULTS

Equations 1-6 were fitted to the data and fit statistics are shown in table 2. Because equation (1) is not indexed to any specific base age, it can be used with equation (2) to determine dominant height/site index for any specified base age. For the basal area prediction and projection equations, including geographic coordinates reduced the mean squared error (MSE) only minimally. However, including geographic coordinates in the total volume yield equation reduced MSE considerably. Including a switch for thinned or unthinned stands was significant for the basal area projection model, the survival projection model, and the total volume yield model.

The fitted equations were compiled into a dynamically linked library and installed into the FMRC's growth-and-yield software shell for projection. Three hundred and three unthinned plots and 442 thinned plots with initial age of at least 5.0 years were projected to each remeasurement age where the projected dominant height, basal area, and total volume yield outside bark were compared to the observed values. Percent residuals [(observed – predicted)/observed*100] for these variables are shown in table 3 and figures 2 and 3.

DISCUSSION

The set of models presented here can be used for predicting and projecting stand characteristics for managed loblolly pine plantations growing in the Misiones/Paraná area of South America. Loblolly pine growth in this region slows during the winter months but never enters a true dormant season. Therefore, it is important to specify stand age to tenths of a year. Due to a lack of individual tree data for these plots it was not possible to directly extend these stand-level component equations and obtain diameter class or merchantable yields for these plots.

Because equation (1) is not indexed to any specific base age, it can be used with equation (2) to determine

Table 2—Fit statistics for equations 1-6 applied to data from 921 permanent plots in operational loblolly pine plantations in the Misiones/Paraná region of South America using all observations and only observations with geographic coordinates

	All plot observations		Observations with geographic coordinates		
Equations	*n*	MSE	*n*	MSE with geographic coordinates	MSE without geographic coordinates
1 and 2	1926	0.9733			
3	2804	0.0166	2007	0.0126	0.0133
4	1260	0.00357	802	0.0033	0.0034
5	1223	1043.7			
6	2679	95.01	1949	43.53	55.1

n = number of observations, some plots were measured multiple times; MSE = mean squared error.

Table 3—Summary statistics for mean percent residuals [(observed-predicted)/observed*100] for dominant height, basal area, and total volume yield outside bark of 442 thinned and 303 unthinned plots following projection from plot establishment to subsequent remeasurement ages

	Unthinned				Thinned			
Variable	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
HD	-0.3	6.4	-18.1	20.9	-0.3	3.4	-29.9	10.5
BA	-4.3	14.0	-64.2	22.0	-1.3	13.4	-55.2	26.8
TVob	-7.3	19.5	-58.1	29.0	-1.5	15.4	-61.7	31.2

SD = standard deviation, HD = average height (m) of 100 thickest trees by diameter at breast height (cm) per hectare, BA = basal area (m^2 ha^{-1}), TVob = total volume outside bark (m^3 ha^{-1}).

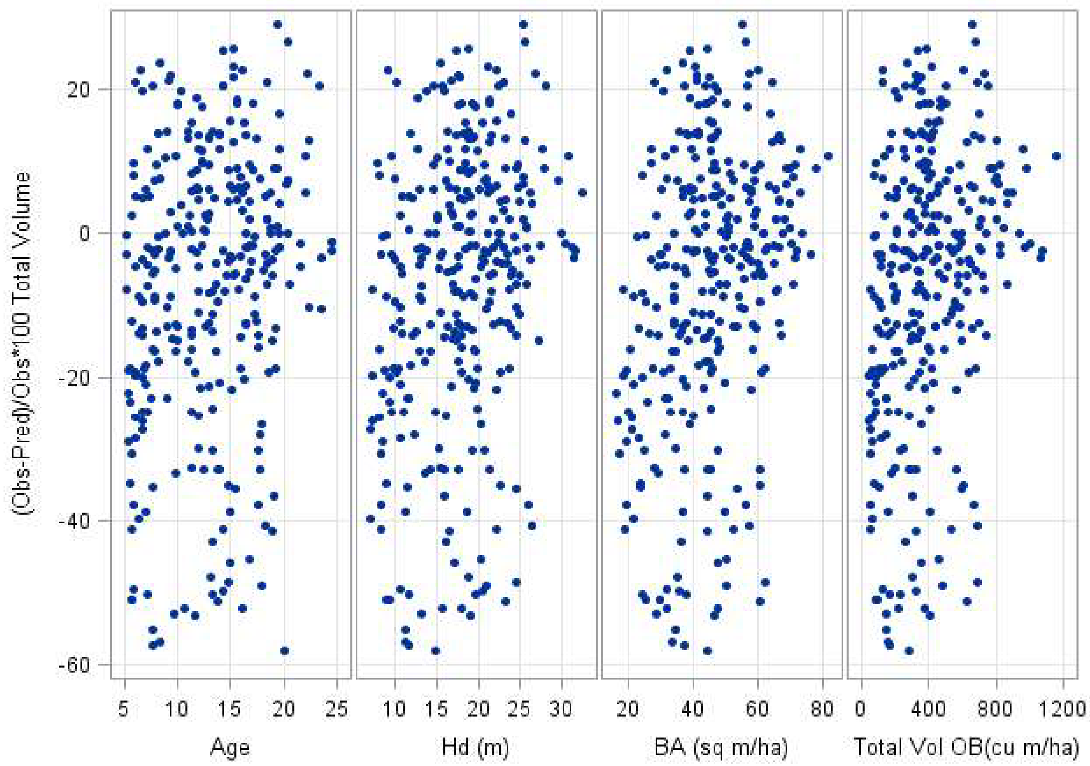

Figure 2—Percent residuals of total volume yield outside bark (observed – predicted)/observed*100 for 303 unthinned plot observations in the Misiones/Paraná region of South America.

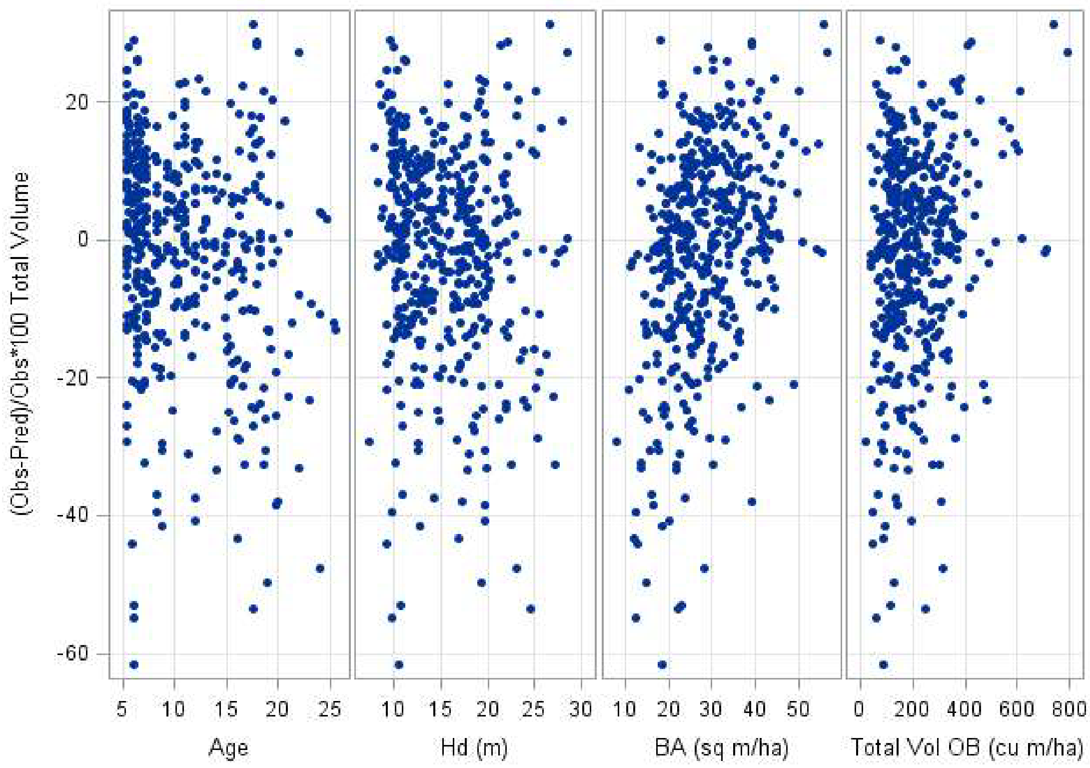

Figure 3—Percent residuals of total volume yield outside bark (observed – predicted)/observed*100 for 442 thinned plot observations in the Misiones/Paraná region of South America.

site index at any desired base age from a given height-age pair. This is desirable because there are several commonly used base ages for this particular region.

When predicting and projecting basal area and total volume yield, including geographic coordinates in equations (3), (4), and (6) significantly reduced the MSE over the same equations fitted without including geographic coordinates. The use of geographic coordinates improves predictions for specific locales within a large region such as the Misiones/Paraná just as it does within the natural loblolly pine growing area of North America.

Thinning type and intensity in terms of basal area per hectare or trees per hectare removed was not available for these plots. Therefore, the effects of thinning were incorporated into equations (3), (4), and (6) by including a parameter to "switch" from unthinned to thinned stands. No attempt was made to distinguish between the effects of first and subsequent thinnings on these plots. Therefore, when implementing thinnings during stand projection or when starting projections with a previously thinned stand, the thinning parameter should be set to 1.

Pruning selected crop trees at time of thinning is a common silvicultural practice in this region. Since no information was available on the number of trees pruned or the intensity of pruning, it was not feasible to include the effects of pruning in this study. However, results from a pruning study established in North America suggest that removing up to one-half the live crown in young loblolly pine plantations has minimal effect on subsequent height and diameter growth (Amateis and Burkhart 2011). Therefore, the pruned and thinned plots were combined with the thinned only plots for this study.

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DIFFERENCES IN FIXED-RADIUS PLOT SAMPLE SIZE ESTIMATES WHEN USING THE INHERENT VARIABILITY AMONG DIAMETER CLASSES IN STAND TABLES RATHER THAN AVERAGE VALUES

Curtis L. VanderSchaaf

Abstract—As part of many forest inventories, sample sizes needed to meet some desired level of precision are estimated. In many timber inventories, based on estimates of the inherent variability (e.g., coefficient of variation, CV), sample sizes are estimated for average total merchantable volume or for the most valuable product class such as average sawlog volume. However, often foresters are equally interested in producing accurate and precise stand tables. Stand tables contain number of trees by diameter and/or height classes while stock tables contain amount of volume by diameter and/or height classes. The most important component of most timber prospectuses in the Southeastern United States is actually stand and/or stock tables, not average values. This study attempted to quantify differences in sample size estimates of fixed-radius plots when using variability among diameter classes in stand tables as opposed to the variability in average values in the sample size equation. Several methods were proposed to quantify the CV among diameter classes within stand tables. Fixed-radius plots of varying sizes from many inventories conducted across the Southeastern United States and a few from other parts of the country were examined. In most cases, sample sizes needed for stand tables were at least twice as large when compared to estimating average trees per acre. However, when using Method Four at an 80 percent probability, sample size estimates (n = 27) were similar to sample sizes for average volume per acre at 95 percent probability (n = 29).

INTRODUCTION

Forest inventories are used to estimate the resources that exist on a site and aim to balance both accuracy and precision while minimizing time and cost. As part of many inventories, sample sizes needed to meet some desired level of precision are estimated. In many timber inventories, sample sizes are estimated for variables such as average total merchantable volume or for the most valuable product class such as average sawlog volume, etc. (e.g., Avery and Burkhart 2002: 37-39, 255; Shiver and Borders 1996: 22, 106-108).

However, foresters are often equally interested in producing accurate and precise stand and stock tables. Stand tables contain average number of trees by diameter and/or height classes while stock tables contain the amount of volume by diameter and/or height classes. The most important component of most timber prospectuses and even management plans in the Southeastern United States are stand and stock tables rather than average or total values. These stand tables and stock tables allow loggers, procurement foresters, timber buyers, managers, etc., to see what product classes exist and how many trees are in each product class. Other examples in forestry where stand tables are important are forest nursery inventories, where managers are more interested in number of seedlings by diameter class rather than total number of seedlings.

This study examined several ways to determine sample sizes using stand tables. It then examines the differences in sample size estimates for stand tables compared to the more traditional means of using some average value per acre for fixed-radius plots. Although most data are from pine plantations in the Southeastern United States, some studies are of hardwoods in the Southeastern United States and some studies are of species in other regions of the United States.

METHODS

Quantifying Variability within Stand Tables

Sample size is often estimated using equation (1):

$$n = \left[\frac{z\ CV}{\%E}\right]^2 \qquad (1)$$

where

n = sample size needed to meet some desired level of precision, or a given bound on the error of estimation with a specified degree of confidence (Shiver and Borders 1996: 106),

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z = z-value needed for a particular percent confidence (probability),
CV = coefficient of variation, and
%E = allowable error expressed as a percent.

Occasionally, with fixed-area plots, the finite population correction sample size equation is used. For this study equation (1) was used.

Allowable error of 10 percent is common (e.g., State of Florida Timber Cruise/Timber Appraisal Standards, https://floridadep.gov/lands/bureau-appraisal/documents/timber-cruise-timber-appraisal), although some have used values such as 15 percent (Coble and Grogan 2007). Agencies may allow probability levels as low as 68 percent when conducting inventories for management plans (State of Florida). However, timber appraisals will likely require probability levels no lower than 80 percent.

All proposed methods to quantify uncertainty (e.g., CV in equation (1)) are based on using separate plot stand table estimates. There are generally three acceptable ways to estimate CV within a stand/site prior to conducting the operational cruise. First, conduct a pilot/preliminary study where 2 to 15 plots are measured throughout the stand. These plots are then used to estimate the CV. Second, use CVs from inventories of similar stands. Three, use CVs from previous inventories of the stand/site. This study will use the first approach, estimating sample sizes using a pilot/preliminary study.

It is assumed the CV estimated on the pilot/preliminary studies is our best estimate of the true value, and hence it is assumed this estimate equals the true value. Thus, the z-value is used within equation (1) and not a t-value. Some foresters use the t-value based on the pilot/preliminary sample size.

Method One—The first proposed method to quantify variability (CV) is to calculate sample size within each observed diameter class across all plots within a site and then take an average of the sample size estimates across all diameter classes. Hence, first the CV is calculated across all plots for a particular diameter class, sample size is then estimated by diameter class, and then the final sample size needed to estimate a stand table for a particular site is the average sample size across all diameter classes.

Method Two—Method Two is the same as Method One, except the sample sizes within diameter classes are weighted such that diameter classes with a greater number of trees have a greater impact on the sample size estimate. This will likely reduce the needed sample size to meet a desired level of precision while also ensuring that, similar to the concept of variable-radius sampling, you are not spending a substantial amount of time establishing many plots because of a rare diameter class being found in one plot.

For example, five pilot plots may have been established in a chip-and-saw stand and in all five plots diameters range from 8 to 11 inches, with the exception of one plot that had a 5-inch tree. Because that one small tree is going to substantially increase the sample size estimate for the stand, weighting by the number of trees within diameter classes will reduce the impact of that individual.

Method Three—The third proposed method to quantify uncertainty is to calculate the CV by diameter class among all plots within a site, obtain an average CV across all diameter classes, and then use this average CV in equation (1) for a particular site.

Method Four—In a similar fashion to Method Two, the fourth method is the same as Method Three, except the CVs within diameter classes are weighted such that diameter classes with a greater number of trees have a greater impact on the sample size estimate.

Method Five—First, the standard deviation among all plots for a particular diameter class is calculated, followed by the CV of the diameter class standard deviations within a site. This CV is then placed into equation (1).

Method Six—First, the CV among all plots for a particular diameter class is calculated, and then the CV of the CVs is calculated and inserted into equation (1).

Method Seven—this is the traditional means of determining sample size, using some average value per acre.

Data Sources

A variety of data sources were examined based on availability of the data. Table 1 provides a list of studies that were used during this analysis. DBHs were placed into 1-inch diameter classes. As examples, the 5-inch class was defined as all d.b.h.s ranging from 4.6 inches to 5.5 inches, and the 9-inch class was defined as all d.b.h.s ranging from 8.6 inches to 9.5 inches. Table 2 contains average stand-level summary statistics by measurement age for each study described in table 1.

Table 1—Study descriptions

Study	Location	Species	Treatments	Ages	Site	Operational/ Research	Plot shape and size	*n*	Reference
1	Monticello, AR	LP	Thinning (30, 50, 70, and 90 sq ft/acre) and pruning (25, 40, and 50%) study. Plus unthinned/unpruned	12,15,16,19, 24,27	OF	O, R	S, 0.1	3, 4	General et al. (2013)
2	Crossett, AR	LP	Thinning study	10,13,16,19,22, 25,28,31,34,36, 40,46,53,57	OF	O, R	S, 0.25	3	Baldwin et al. (1998)
3	East Texas	LP	Operational plantings	Varies	CO	O	S, 0.25	2	Coble (2009)
		SP					S, 0.25		
4	Winston Co., MS	LP	Planting density trial (1,742, 778, and 484 seedlings/acre)	8,10,12,14,15, 17,19,20,23, 25, 28,30	OF	R	R, 0.5	4	VanderSchaaf (2010)
5	Tattnall Co., GA & Hampton Co., SC	LP	Seedling size and management intensity study	3,4,8,10	CO	R	R, 0.11	3	VanderSchaaf and South (2003)
6	Macon Co., AL	LP	Seedling size and planting density study	3	CO	R	-	4	South et al. (2005)
7	Haile, LA	LP	Thinning trial (70 sq ft to 105 sq ft/acre). Plus unthinned	25	CO	O	-	5	Carroll Walls/C. McDavid Hughes
8	Saucier, MS	LP	Management intensity study	8,9,25,39	CO	R	S, 0.52	4	Schmidtling (1987)
		SP							
		LL							
9	SE AR (6 sites)	LP	Operational plantings. Unthinned/Thinned	11,12,18,19, 24,25	CO	O	C, 0.10 or 0.25	2 or 3	Bragg et al. (2004)
10	Colt, AR	LP	Operational planting	8	OF	O	S, 0.16	2	-
12	Homerville, GA	SP	Site preparation study	7	CO	O	-	5	Shrock (1994)
13	Quitman, LA	LP	Operational planting	Mature	CO	O	C, 0.1	14	-
14	Monticello, AR	SG	Fertilization study	5,6,7,8,9,13, 14,15,21,24, 25,26,27	OF	R	S, 0.045	6	Guo et al. (1998)
15	Potlatch, ID	DF	Multi-nutrient fertilization study	14,15	CO	O	S	2	VanderSchaaf (2008)
		PP	Multi-nutrient fertilization study	14,15	CO	O	S	2	
16	Farmington, IA	EWP	Operational planting	Mature	-	O	C, 0.016	2	-
17	Arbo, MN	WS	Operational planting	Mature	-	O	C, 0.016	2	-
18	Grand Rapids, MN	RP	Operational planting	Mature	-	O	C, 0.03	4	-

Species: LP is loblolly pine (*Pinus taeda* L.), SP is slash pine (*Pinus elliottii* Engelm.), LL is longleaf pine (*Pinus palustris* P. Mill.), SG is sweetgum (*Liquidambar styraciflua* L.), DF is Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), PP is ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), EWP is eastern white pine (*Pinus strobus* L.), WS is white spruce (*Picea glauca* (Moench) Voss), RP is red pine (*Pinus resinosa* Aiton).

Site: OF is old-field, CO is cutover.

Operational/Research: O is operational, R is research.

Plot shape and size: R is rectangular, S is square, C is circular; area is in acres.

n is number of replications.

Note: Study 11 was dropped.

Table 2—Stand-level summary statistics of the studies

Study	Age	Species	TPA	Dq	BAA	Vol/acre
1	12	LP	334	6.6	80	1400
	15		271	8.0	95	2125
	16		155	8.8	66	1559
	19		112	10.5	68	1916
	24		109	12.2	89	2921
	27		84	13.2	79	2633
2	10	LP	1083	3.5	71	1597
	13		718	5.2	87	1959
	16		337	7.4	72	1627
	19		251	9.3	83	2332
	22		166	10.8	83	2337
	25		126	12.3	88	2471
	28		104	13.6	91	2573
	31		78	15.0	84	2378
	34		63	16.2	80	2261
	36		63	16.8	87	2437
	40		63	18.1	101	2834
	46		63	19.1	112	3160
	53		56	20.2	111	3140
	57		56	20.7	117	3303
3	Many	LP	445	5.9	89	2492
4	8	LP	893	4.4	85	1499
	10		861	5.4	119	2088
	12		813	6.1	147	2577
	14		772	6.7	167	2931
	15		747	7.0	175	3937
	17		687	7.4	187	4432
	19		641	7.8	195	5489
	20		614	7.9	195	5481
	23		513	8.5	193	5434
	25		478	8.9	197	5555
	28		411	9.7	205	5763
	30		364	10.1	196	5505
5	3	LP	508	0.9	2	14
	4		555	1.2	4	28
	8		539	5.5	89	861
	10		550	6.0	108	1897
6	3	LP	436	1.6	6	46
7	25	LP	161	13.4	159	4465
8	8	LP	258	5.0	35	619
		SP	227	3.5	15	272
		LL	262	4.7	31	545
	9	LP	242	5.4	38	664
		SP	212	3.9	17	309
		LL	243	5.0	33	583
	25	LP	132	7.7	42	1192
		SP	154	7.6	48	1349
		LL	151	8.0	53	1480
	39	LP	99	9.5	49	1370
		SP	140	9.6	70	1982
		LL	120	9.9	64	1811
9	11,12	LP	621	5.4	100	1764
	18,19		230	8.3	86	2423
	24,25		95	10.3	55	1547
10	8	LP	395	6.3	86	834
12	7	SP	483	3.8	39	688
13	Mature	LP	54	17.6	92	2984
14	5	SG	406	2.0	9	63
	6		407	2.3	12	95
	7		390	2.8	16	142
	8		381	3.5	25	257
	9		366	3.4	23	278
	13		366	4.6	42	132
	14		362	5.0	49	345
	15		365	5.4	57	525
	21		366	6.3	79	850
	24		360	6.9	93	1264
	25		359	7.0	95	1401
	26		366	7.1	100	1618
	27		362	7.2	102	1719
15	14,15	DF	539	2.61	20	-
	14,15	PP	379	4.67	45	-
16	Mature	EWP	246	14.3	276	-
17	Mature	WS	339	11.1	227	-
18	Mature	RP	234	11.4	167	-

Species: LP is loblolly pine, SP is slash pine, LL is longleaf pine, SG is sweetgum, DF is Douglas-fir, PP is ponderosa pine, EWP is eastern white pine, WS is white spruce, RP is red pine.

TPA is trees per acre, BAA is basal area per acre (feet^2), Dq is quadratic mean diameter (inches), and Vol/acre is cubic foot volume per acre.

RESULTS AND DISCUSSION

Table 3 and figure 1 clearly show that the d.b.h. class-weighted sample size estimates were reasonable (Methods Two and Four). However, sample size estimates using the non-d.b.h. class-weighted methods were restrictively high (Methods One, Three, Five, and Six). On average, to obtain a stand table at a probability level of 90 percent when using a 10 percent error, Method Four requires around five times as many plots as compared to just estimating the total number of trees per acre (Method Seven using trees per acre). Figure 1 shows the general trend in sample size estimate across the methods as compared to simply estimating average number of trees per acre (Method Seven using trees per acre) when using a probability level of 90 percent.

However, when using an 80 percent probability level sample sizes were reduced essentially consistently around 40 percent. For the 80 percent probability level, only three times as many plots were required for Method Four relative to just estimating the average number of trees per acre (Method Seven using trees per acre) when using a 90 percent probability level (e.g., 27 plots for Method Four at 80 percent versus 8 plots at 90 percent for Method Seven using trees per acre).

When using 95 percent probability, the required sample sizes obviously greatly increase. As compared to the 90 percent probability level, they consistently increase around 41 percent. Foresters may use 95 percent probability when estimating sample sizes for average trees per acre. This will require on average a sample size of 12 (e.g., 12 plots for Method Seven using trees per acre at 95 percent).

If a forester is willing to accept 80 percent probability levels when estimating sample sizes for stand tables, then sample sizes are only about twice that of current commonly used methods when using Method Four (e.g., 27 plots for Method Four at 80 percent versus 12 plots for Method Seven using trees per acre at 95 percent. If a forester is willing to accept 80 percent probability levels when estimating sample sizes for stand tables, then sample sizes (when using Method Four, n = 27) are on average almost identical to using the currently used method of calculating sample sizes using average tree volume at a 95 percent probability level (Method Seven using volume, n = 29).

Table 3—Mean, minimum, maximum, and standard deviation (SD) of sample size estimates at 80 percent, 90 percent, and 95 percent probability levels, by method

	80 percent confidence				90 percent confidence				95 percent confidence			
Method	Mean	Minimum	Maximum	SD	Mean	Minimum	Maximum	SD	Mean	Minimum	Maximum	SD
	trees per acre											
One	101	0.0	1366	75.7	166	0.0	2250	124.6	235	0.0	3194	176.9
Two	38	0.0	629	48.2	63	0.0	1035	79.4	89	0.1	1470	112.7
Three	66	0.0	1175	64.1	108	0.0	1935	105.5	153	0.0	2747	149.7
Four	27	0.0	483	45.0	45	0.0	796	74.1	64	0.1	1130	105.1
Five	135	0.0	603	80.1	222	0.0	993	131.9	315	0.0	1410	187.3
Six	142	0.0	764	88.2	233	0.0	1257	145.2	331	0.0	1785	206.2
Seven	5	0.0	146	9.8	8	0.0	241	16.2	12	0.0	341	23.0

Sample size is 1907.

A 10 percent error was used (%E in equation (1))

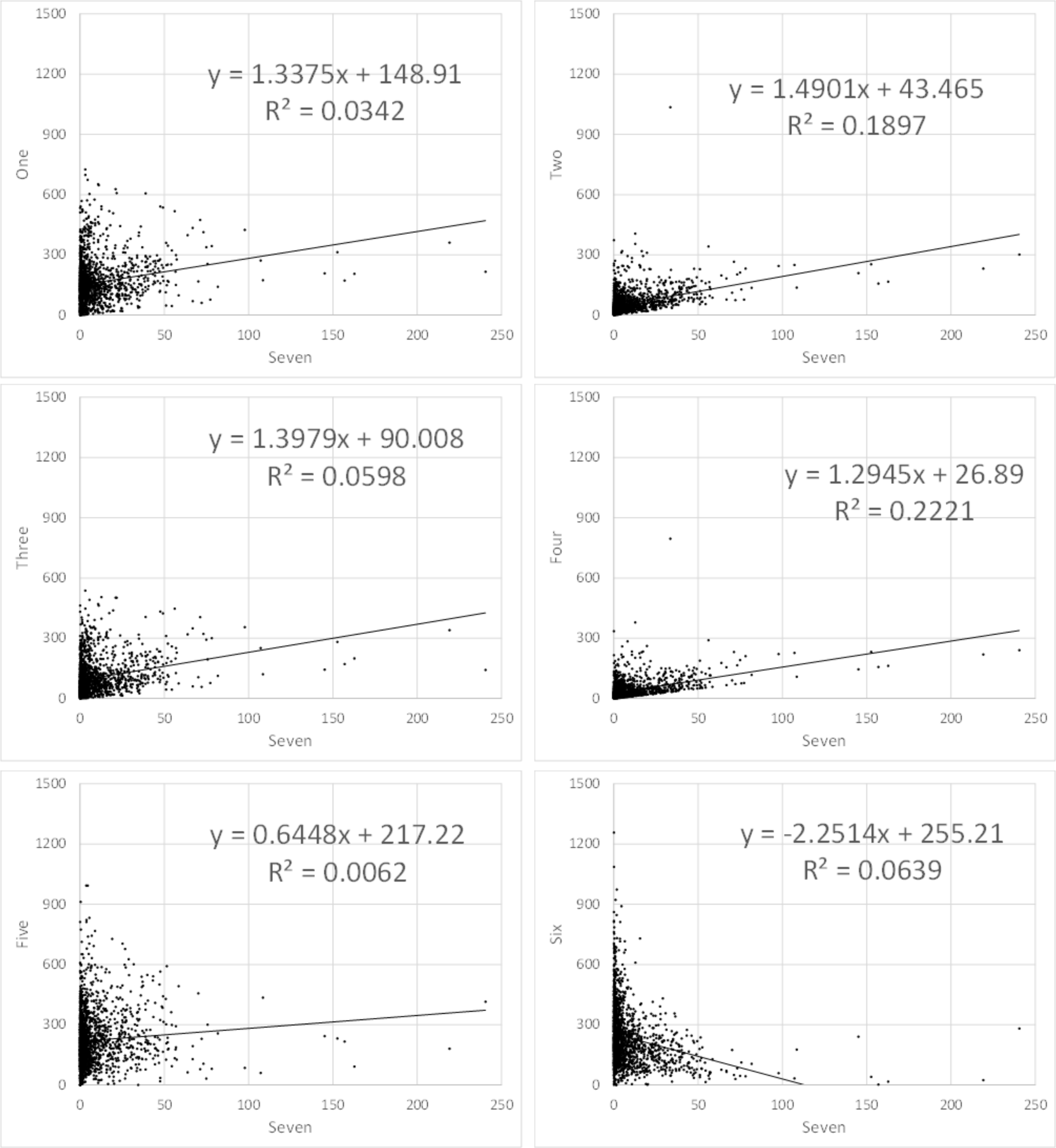

Figure 1—General trend in sample size estimates across the methods as compared to simply estimating average number of trees per acre (Method Seven using trees per acre) when using a probability level of 90 percent (*n* = 1907).

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WOOD-BARK DENSITY OF HYBRID SWEETGUM STEMS AT AN AFFORESTED SITE IN NORTH LOUISIANA

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Abstract—This is the third in a series of studies to quantify yields of hybrid sweetgum (*Liquidambar formosana* x *styraciflua*) biomass at an afforested site in north Louisiana. Pooling across herbicide and varietal treatments to produce a single model system to estimate weight was determined to be statistically appropriate on the 2-year-old (1-0) seedling stock. An equation constructed from that study, where moisture content on the oven-dry basis averaged 107.5 percent (51.8 percent wet-basis), estimated the weight of standing trees. Field measurements of stem diameter occurred at 1-foot increments along the height of the stem beginning at the groundline, with height determined from pole measurements. The volume of each section was calculated using Smalian's formula and summed to provide total stem volume. Bulk density was calculated as pounds per cubic foot (pcf) green, basic density was calculated as oven-dry weight per cubic foot green volume, and specific gravity was the ratio of basic density to the density of water. Bulk density, basic density, and specific gravity were all calculated outside bark. Mean values for bulk density, basic density and specific gravity were 61.6 pcf, 29.7 pcf, and 0.48, respectively. The results suggested the hybrid sweetgum density properties exceeded published values for native sweetgum (*L. styraciflua*), while moisture content was lower. Seasonal influences could have affected moisture content and bulk density. However, basic density and specific gravity findings suggest potential exists to benefit a number of both traditional (e.g., logging, pulp, and paper) and newer (pellet, biofuel) industries, as wood properties correlate strongly with product output in these industries.

INTRODUCTION

Sweetgum (*Liquidambar styraciflua*) is the most populous hardwood species growing on southern pine sites in the South (Koch 1985). While sweetgum lumber is visually appealing, maintaining lumber quality through the drying process is very difficult. The value of sweetgum to the hardwood industry is mostly in lower-valued industrial products, such as railroad ties, pallets, and mats.

The chemical characteristics and timber value of sweetgum, however, could make wood fuel conversion more cost effective. The species has long been a resource suited to pulping and is increasingly being pelletized where that market exists in the South. Partially hydrolyzing sweetgum to harvest wood sugars for biofuels was concluded as more favorable than other high-volume hardwood species, such as red oaks (*Quercus* spp.) and yellow-poplar (*Liriodendron tulipifera*) (McConnell and Shi 2011). The high percentage of 5-carbon sugars and hemicellulose fraction make sweetgum a more efficient choice for wood sugar harvesting. Recent positions of the United States regarding global relations and trade continue to emphasize the need for energy independence. Thus, efforts should be continued to convert lignocellulosic materials, including wood, to solid or liquid fuel. Regardless, global timber consumption is directly related to population (FAO 2018). Meeting the needs of 9 billion people by 2050—whether wood, fiber, or fuel—will require novel forest management strategies.

A relatively new forestry practice becoming more commonplace is short rotation woody crop (SRWC) forestry, where the goal is to cultivate a crop of trees as rapidly as possible using techniques needed to improve growth rates (Kaczmarek and others 2012). Genetic improvements in the last couple of decades within the *Liquidambar* genus and others through hybridization within genus, genetic manipulation, and clonal replication created faster-growing individuals capable of rapidly responding to fertilizer or release treatments to capitalize on monetary inputs to the stand (Scott and others 2004b). Sweetgum, along with its associated hybrids, is being investigated as a SRWC resource, but many questions regarding SRWC need

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answering. Some, such as fertilization requirements, must be considered prior to establishing a SRWC plantation (Kline and Coleman 2010), while others, such as estimations of biomass and volume, are also needed to periodically assess stand productivity.

Both biomass and volume involve the raw material from the perspective of the processor, that is, the purchaser. Wood density and specific gravity correlate well with many product properties (Shmulsky and Jones 2011). Thus, an understanding of wood-bark stem density at a young age can help managers across the value chain assess the viability of the species in a SRWC setting.

A study was established in north Louisiana to examine the interactive effects of herbaceous competition control (two treatments) and genotype (five varieties) on growth and yield of hybrid sweetgum (*Liquidambar formosana* x *styraciflua*). The objective of this component of the study was to determine wood-bark stem density in response to these treatments.

METHODS

The study was located at Louisiana Tech University, South Campus (32° 30’ 49.84” N. 92° 39’ 11.59” W) in Ruston, LA. The study site was largely on an Angie fine sandy loam soil (Aquic paleudult), with a small portion on a Sacul very fine sandy loam (Aquic hapludult) (USDA NRCS 2019). The site had been used for grazing and hay production since 1990. During this time, horse manure was spread over the field occasionally as fertilizer. Prior to 1990, the site was the interior of a racetrack dating back to the late 1970s, during which time Christmas trees were periodically grown on the site.

No fertilizer treatment was applied prior to planting because of the history of manure fertilization of the site (Scott and others 2004a). In preparation for planting, the site was subsoiled (ripped) to a 24-inch depth in late summer. One week before planting, 3 quarts per acre of glyphosate was applied (Accord XRTII® [Dow; Indianapolis, IN]) via ATV sprayer to remove any herbaceous vegetation present. Prior to planting, containerized seedlings were left outside under a covered awning and watered daily to prevent soil from drying out. Seedlings were planted by hand in late October 2015; no significant slope was present.

Five hybrid sweetgum varieties were tested (AGHS1, AGHS2, AGHS3, AGHS4, AGHS8). The study was laid out in a split-plot design, with herbicide being the main plot and genotype as the sub-plot. Five replications were installed. Each row of the study was considered one plot, receiving a random herbicide treatment. The rows were divided into sub-plots of eight seedlings of each genotype; the internal six seedlings of each sub-plot were considered the test sub-plot, while the seedling at either end of the sub-plot was considered a border tree and removed from analysis. A total of 640 seedlings were planted. The seedlings were planted 5 feet apart along the row, and rows were 10 feet apart.

The herbicide tested was sulfometuron methyl (Oust XP®). Oust XP® was applied in a 36-inch wide band using a boom sprayer attached to a tractor at 2 ounces per acre directly over the seedlings. The rate of 2 ounces per acre was selected in accordance with recommendations for sweetgum based on prior studies (Kushla and Self 2013). Four herbicide timing treatments were conducted: a no-herbicide control, mid-winter, late winter, and early spring. In the component of the study reported here, trees within two of the herbicide treatments were studied, the control and the late winter timing. For the late-winter treatment Oust XP® was applied on February 17, 2016. This treatment coincided with the chemical company recommendations for Oust XP® to prevent seedling damage, while still controlling competing vegetation into the growing season.

Measurements on 80 standing trees were conducted in November 2017. To determine if herbicide application and/or variety caused a change in growth characteristics of seedlings after 2 years, randomly chosen seedlings from each block were measured. Height was measured in 1-foot increments using a height pole from the ground level up to the highest living bud present on the seedling. Diameter was measured in millimeters using calipers at each increment on the lower and upper ends of the stem section beginning at the groundline. Groundline diameter (GLD) was measured at ground level unless roots were exposed above the ground, where instead GLD was taken at the root collar. Stem volume—both wood and bark—was calculated using Smalian’s formula for each section and summed to obtain total stem volume. GLD, total height, green volume, green weight, and oven-dry weight are provided in table 1.

Statistical analysis (e.g., dummy variables) of stem weight concluded separate biomass equations were not necessary by herbicide, variety, or herbicide and variety interaction. The data were therefore pooled across varietal and herbicide treatments to produce a single model system:

$$\widehat{WT} = 146.6221 + 0.001874 D_G^2 H \qquad (1)$$

where

D_G^2 is the square of GLD and H is total tree height (both measured in metric units; VanderSchaaf and others 2018).

Table 1—Descriptive statistics for groundline diameter, total height, green volume, green weight, and oven-dry weight of hybrid sweetgum grown on an afforested site in north Louisiana (*n* = 80 trees)

Statistic	Groundline diameter	Total height	Green volume	Green weight	Oven-dry weight
	inches	*feet*	*cubic feet*	*pounds*	*pounds*
Mean	1.35	6.83	0.025	1.45	0.70
Standard deviation	0.32	1.07	0.013	0.70	0.34
Maximum	2.17	9.25	0.075	3.87	1.87
Minimum	0.74	4.70	0.006	0.59	0.28
Median	1.32	6.87	0.023	1.27	0.62

Green volume and green weight at 107.5 percent moisture content.

Destructive samples of 80 standing trees taken in March 2018 were used to obtain green stem weights. Samples were then dried in a laboratory oven at 140 °F until a constant weight was obtained for calculating moisture content on an oven-dry basis. All measurements were converted to English units (inches and feet) for this work.

Bulk density was measured as green weight per unit green volume of wood-bark (pounds per cubic foot, pcf). This bulk density calculation differs from the more common expression of bulk density as green weight of wood-bark per cubic foot of wood, but it is similar to Patterson and Wiant (1993) as well as Lenhart and others (1995) interpretations. Basic density was calculated as oven-dry weight per cubic foot green volume of wood-bark. Specific gravity was the ratio of basic density to the density of water. Because varietal and herbicide treatment effects were not significantly different for the earlier biomass study (Equation 1, VanderSchaaf and others In press), the results here were likewise pooled across herbicide and variety.

We used one-sample *t*-tests (assuming equal variance, Equation 2) to compare our specific gravity results with the means reported for natural sweetgum from Clark and others (1985), Manwiller (1979), and the Forest Products Laboratory (2010):

$$t_{stat} = \frac{\bar{x} - \mu}{s / \sqrt{n}} \qquad (2)$$

Where t_{stat} was the test statistic calculated from a *t* distribution, $\bar{x}$ was our sample's mean specific gravity, μ was the published mean being compared, and $s / \sqrt{n}$ was our sample's standard error.

The test statistic was compared to a critical value, $t_{critical}$, at $\alpha = 0.05$ and $n - 1 = 79$ degrees of freedom. The effect of moisture content was eliminated from specific gravity, thus only that measure's results were tested for significant differences.

RESULTS AND DISCUSSION

Descriptive statistics for bulk density, basic density, and specific gravity are provided in table 2. Bulk density averaged 61.6 pcf at an average moisture content of 107.5 percent, dry basis (51.8 percent wet basis). Bulk density ranged from 45.5 pcf to 97.2 pcf, with a 95 percent confidence interval of 59.4 pcf to 63.9 pcf. Basic density averaged 29.7 pcf, with a 95 percent confidence interval of 28.6 pcf to 30.7 pcf. Specific gravity ranged from 0.35 to 0.75, with an average of 0.48. The interval at 95 percent confidence was 0.46 to 0.49.

Little data on direct biomass measurements for similarly sized trees and site conditions are available, but other regional works have highlighted stem property estimates of naturally grown, native sweetgum wood-bark. Clark and others (1985) found saplings 1.0 to 4.9 inches in diameter at breast height (d.b.h.) in the Gulf and Atlantic Coastal Plains averaged a specific gravity of 0.46. Moisture content averaged 106 percent, while mean bulk density was 56.0 pcf for wood and bark. Manwiller (1979) determined wood-bark stem bulk density of 6-inch native sweetgums growing on pine sites averaged 59.2 pcf, with a specific gravity of 0.44. Wood-bark bulk density averaged 61.6 pcf across a d.b.h. range of 6 to 30 inches for naturally grown sweetgum in east Texas and west Louisiana (Lenhart and others 1995); the smallest d.b.h. class in that study, 6 to 8 inches, averaged 59.4 pcf bulk density. The Wood Handbook (Forest Products Laboratory 2010) reported an average wood specific gravity of 0.46 across the species home range. Typical on-the-stump moisture contents were presented as 137 percent for sapwood and 79 percent for heartwood.

Specific gravity results from the *t*-test between the hybrid sweetgum and those from Clark and others (1985) suggested the results obtained here were significantly higher ($t_{stat} = 2.302 > t_{critical} = 1.645$). The hybrid sweetgum also produced results significantly

Table 2. Descriptive statistics for bulk density, basic density, and specific gravity of hybrid sweetgum grown on an afforested site in north Louisiana (*n* = 80 trees)

Statistic	Bulk density	Basic density	Specific gravity
	pounds per cubic foot at 107.5 percent moisture content	*oven-dry pounds per green cubic foot*	
Mean	61.6	29.7	0.48
Standard deviation	10.2	4.86	0.08
Standard error	1.14	0.54	0.01
Margin of error	2.24	1.06	0.02
95% Confidence interval lower bound	59.4	28.6	0.46
95% Confidence Interval upper bound	63.9	30.7	0.49
Median	58.7	28.3	0.50
Maximum	97.2	46.8	0.75
Minimum	45.5	21.9	0.35
Range	51.6	24.9	0.40

greater than Manwiller (1979) ($t_{stat} = 4.102 > t_{critical} = 1.645$). Mean differences were less between the hybrid sweetgum and the published value in the Wood Handbook (Forest Products Laboratory 2010), but were still significantly different ($t_{stat} = 1.740 > t_{critical} = 1.645$).

The results obtained here, while limited in scope, are encouraging. Higher specific gravity is indicative of higher fiber content and less air void space per unit volume. If this is indeed the case for the hybrid over naturally grown sweetgum, it can potentially lead to greater processing yields. A specific gravity increase of 0.02, for example, extrapolates to approximately 1.25 oven-dry pounds of wood-bark per green cubic foot that would be available for conversion to fiber products or fuel. Moreover, a lower moisture content indicates more wood can be hauled at an equivalent payload. Assuming loaded trucks average 27 tons, a 2 percent decrease in moisture content provides loggers 1,080 additional pounds of available payload. These conditions equate to hauling four more 35-foot-long pulpwood sticks measuring 6 and 3 inches outside the bark at each end, where each stick possesses the average bulk density from table 1. At current (spring 2019) north Louisiana delivered pulpwood prices of $34.80/ton (TimberMart-South 2019), this equates to $18.80 more revenue per truck (1,080 divided by 2,000 pounds per ton multiplied by $34.80). Were 15 truckloads delivered per day, this would exceed $280 per day of additional revenue.

Moisture content directly affects bulk density measurements, as bulk density is weight per cubic foot at a specified moisture content. Koch (1985) recorded multiple studies across the South that reached varying conclusions regarding moisture content seasonality of southern pine site hardwoods. Some reported no seasonal differences, while others reported complex, multi-variable interactions. Doruska and Patterson (2006) found seasonal differences in loblolly pine (*Pinus taeda* L.) pulpwood logs in southeast Arkansas. Newbold and others (2001) concluded water comprised a greater fraction of green weight in young plantations up to 20 years of age, but moisture content of planted loblolly pine overall was not seasonally influenced in north Louisiana. Where tree/log moisture content seasonality has been found, winter moisture contents were generally lower than at least one other season.

Moisture content for this project was determined in a companion study in March 2018. If a seasonality effect were present, it is possible that the moisture content, and thus bulk density, found here may be lower than the annual average. If this is the case, logging productivity could be affected seasonally since water would represent a higher percentage of the delivered load weight when seasonal moisture contents are higher.

From a mill's perspective, whether paper or liquid/solid fuel, basic density and specific gravity are the wood properties better correlated with fiber input and product output, and each property is moisture invariant. This is because both basic density and specific gravity are calculated using wood (or wood-bark) oven-dry weight and green volume. Both are assumed to be constant, as the wood weight does not change at zero percent moisture content. Likewise, wood does not change volume in the green condition above fiber saturation point (approximately 30 percent moisture content across species). The moisture content of the living tree is thus negated. Using native sweetgum as a guide (e.g., Clark and others 1985), both basic density and specific gravity should increase with tree age to financial maturity.

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CAN A MIXED-EFFECTS BASAL AREA EQUATION FIT USING ONE SPECIES PRODUCE ACCURATE ESTIMATES FOLLOWING CALIBRATION USING DATA OF ANOTHER SPECIES?

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Abstract—Stand-level basal area mixed-effects models are commonly being developed for species around the World. We wanted to determine if a stand-level basal area mixed-effects model fit using one species (for example, loblolly pine (*Pinus taeda* L.) plantations where biological and economical rotation ages can range from 20 to 40 years) could produce accurate estimates following calibration using data from another species. This approach would be useful in those situations where there is limited data available for a species (for example, naturally regenerated black spruce (*Picea mariana* (Mill.) Briton, Sterns & Poggenb.) where biological and economical rotation ages can range from 75 to 150 years) to model basal area across the entire range of biological or economical rotation ages. Perhaps a mixed-effects model fit using data of a species where repeated measurements have been made across the entire biological or economical rotation age could be calibrated to produce accurate predictions for those species where data is limited at, say, mid-rotation or final rotation ages. When entering data into traditional growth-and-yield models, in a sense the model is "calibrated." However, mixed-effects could be advantageous because calibration can include more than one temporal observation that may allow for a better prediction of the basal area trajectory. Additionally, this approach could be useful where there are insufficient measurement ages across a rotation for newer silvicultural treatments.

INTRODUCTION

Growth-and-yield models are integral components of forest management. Models help managers identify the productive capability of a particular species and how different cultural treatments will likely affect financial returns. Mixed-effects models are becoming popular modeling tools to provide more site-specific predictions of stand development. Mixed-effects models provide an efficient means to obtain cluster-specific, or for this particular example, stand-specific, parameters through the prediction of cluster-specific random effects. For example, basal area can be predicted using the following equations:

$$\ln BA_j = \beta_0+\beta_1\ln(Age_{j-1}/Age_j)+\beta_2\ln BA_{j-1} +\varepsilon \qquad (1)$$

$$\ln BA_j = \beta_0+\beta_1\ln(Age_{j-1})+\beta_2\ln(Age_j)+\beta_3\ln BA_{j-1} +\varepsilon \qquad (2)$$

where

ln is natural logarithm; BA is basal area (square feet per acre); β_0, β_1, β_2, and β_3 are parameters to be estimated; and ε is random error where it is assumed $\varepsilon \sim N(0, \sigma^2 I)$.

Equations (1) and (2) provide what is often termed a population average estimate of BA given ages and the previous BA. The parameters β_0, β_1, β_2, and β_3 are assumed to be fixed, or that the parameter estimates apply to every experimental unit (for example, stand) in a population. Whether a stand is located in Florida or Arkansas, the parameter estimates are assumed to be correct. However, stand-specific characteristics such as soil type, nutrient status, competition from herbaceous vegetation, elevation, aspect, genetic stock, etc., may result in the parameters differing across stands. Thus, specific stands may have what are generally termed "random parameters" in mixed-effects model terminology. Equations (1) and (2) can be altered by adding stand-specific random effects to the population average parameters to produce stand-specific parameters:

$$\ln BA_j = (\beta_0+u_{0i})+(\beta_1+u_{1i})\ln(Age_{j-1}/Age_j)+ (\beta_2+u_{2i})\ln BA_{j-1} +\varepsilon \qquad (3)$$

$$\ln BA_j = (\beta_0+u_{0i})+(\beta_1+u_{1i})\ln(Age_{j-1})+ (\beta_2+u_{2i}) \ln(Age_j)+(\beta_3+u_{3i})\ln BA_{j-1} +\varepsilon \qquad (4)$$

where u_{0i}, u_{1i}, u_{2i}, and u_{3i} are stand-specific random effects, assumed to be $N(0, \sigma^2_0)$, $N(0, \sigma^2_1)$, $N(0,\sigma^2_2)$,

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and N(0, σ^2_3), respectively; (β_0+u_{0i}) is the stand-specific intercept; (β_1+u_{1i}), (β_2+u_{2i}), and (β_3+u_{3i}) are stand-specific slopes; *i* indexes a specific stand; and all other variables as previously defined.

Additionally, a covariance can be assumed to exist between any of the random effects. Although the parameter estimation efficiency of mixed-effects models is an advantage, often the greatest advantage is the ability to calibrate the model using data independent of those used in model fitting.

Although several basal area mixed-effects models have been developed, no study has examined whether parameters fit using data from one species can be used to obtain cluster-specific random effects of another species. The advantage of using parameters from a species where more complete data in terms of stand ages, planting densities, site qualities, stand development, etc., exist, is that more reasonable extrapolations of stand development for another species may potentially be obtained. For instance, can a calibration using young data of a black spruce (*Picea mariana* (Mill.) Briton, Sterns & Poggenb.) trajectory "borrow" information from a loblolly pine (*Pinus taeda* L.) trajectory fit using data from across the entire biological rotation age to produce adequate estimates of a black spruce trajectory at older ages? Another advantage (given land tenure issues) is that most industrial timberland owners and managers need short-term solutions to long-term operations, as they are only interested in planning horizons of 5 to 10 years (not 20 to 50 years, as in the past). Hence, they do not want to invest large amounts of capital into long-term growth-and-yield studies.

Cluster-specific (or stand or plot) random parameters depend on the amount of estimated variability in the random effects and the population average parameter estimates. Thus, differences in site requirements, structural constraints, growth habits, etc., among species may not allow for mixed-effects models fit using one species to produce reasonable predictions of stand development for another species. This may occur when the population average parameter estimates of the model-fitting species are not correct for the model calibration species, and/or the variability in the cluster-specific random effects of the model-fitting species is not representative of the variability in the model calibration species.

Loblolly pine is one of the most commercially important species in the Southeastern United States and therefore several long-term studies given economical and biological rotation ages have been initiated. However, for many species, fewer and sometimes even no studies have been established that have measurements across the entire range of biological or economical rotation ages. Hence, this concept asks if absolute age can be modified such that it is a relative measure rather than an absolute measure, and if so, perhaps the biological growth patterns can be applied across a range of species. As shown in figure 1, can a basal area growth trajectory of loblolly pine be "stretched" out, out and up, out and down, up, down, etc., such that it will provide reasonable predictions for another species?

VanderSchaaf (2008) showed that using a loblolly pine plantation mixed-effects height-diameter (H-D) model when calibrated using sweetgum (*Liquidambar styraciflua* L.) data produced reasonable results to predict height of sweetgum plantations. A similar concept was proposed by Huang (2016) in which he uses the term "universal" model to describe calibrating models across species. According to Huang (2016), if you can calibrate a single mixed-effects model across species, then all species can be considered to be in the same population. He found that "composite" H-D equations, or equations fit using several species, following calibration, often produced similar predictions to species-specific mixed-effects H-D models. This "universal" approach is similar in nature to Zeide's (1978) two-point principle. He suggested for several stand-level variables that growth curves common across many species could be tailored for an individual stand by obtaining measurements of that variable in that stand at only two ages.

Thus, when entering data into traditional growth-and-yield models (for example, a stand table), the simulator can be considered to be "calibrated" to site-specific conditions. However, mixed-effects models could be advantageous because calibration can include more than one temporal observation that may allow for a better calibration and ultimately prediction of the future basal area trajectory. Additionally, this approach could be useful where there are insufficient measurement ages across a rotation for newer silvicultural treatments.

The objective of this study was to determine if basal area trajectories fit using different species could be calibrated for another species using younger data to produce reasonable predictions at older ages. Additionally, this study attempted to quantify if the use of different ages in calibration impacted predictive ability at older ages.

METHODS

Data Used in Model Fitting and Prediction

Loblolly pine–East Texas Pine Plantation Research Project (ETPPRP—A total of 178 plots were originally established in 1984 throughout East Texas at planting densities ranging from 350 to 1350 seedlings per acre (Lenhart and others 1985). Plantations represented by these plots ranged in age from 2 to 35 years, 30 to 850

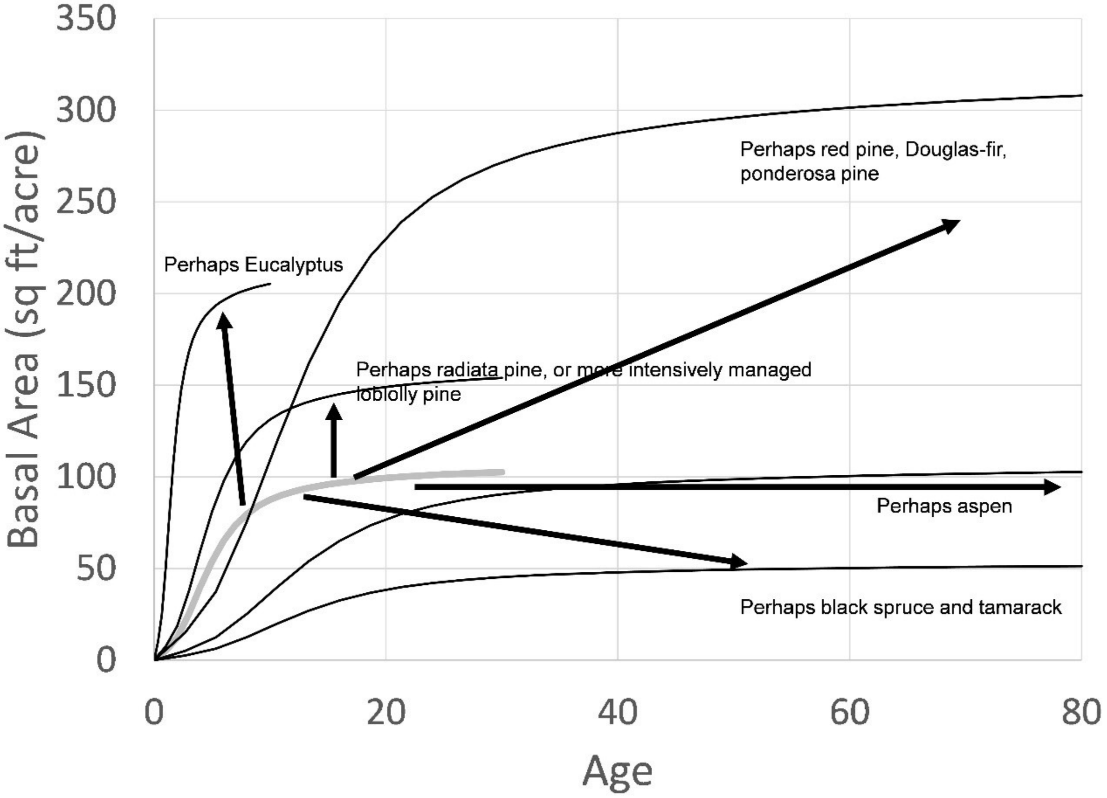

Figure 1—Thick gray curve is a loblolly pine basal area trajectory. Can we, through mixed-effects model calibration using younger ages of another species, "stretch" the loblolly pine trajectory to produce viable estimates of trajectories for other species that have limited data at older ages? Or in some cases, can we "stretch" the trajectory for newer silvicultural practices of loblolly pine plantations? Possible trajectories for aspen (*Populus* spp.), black spruce, Douglas-fir, eucalyptus (*Eucalyptus* spp.), more intensively managed loblolly pine, ponderosa pine, radiata pine (*Pinus radiata* D. Don), red pine, and tamarack (*Larix laricina* (Du Roi) K. Koch) are shown.

trees per acre, and 40 to 90 feet site index (base age 25 years). Measurement ages used during this study ranged from 2 years to 33 years.

Loblolly pine–Mississippi State University (MSU)—Tree- and plot-level measurements were obtained from a 1959 spacing trial located in an old-field on a floodplain in Winston County, MS, using 1-0 local seed source seedlings (VanderSchaaf 2010). Site index was estimated to be near 75 feet (base age 25 years). Three initial densities were established: a 5 feet by 5 feet spacing, a 7 feet by 8 feet spacing, and a 9 feet by 10 feet spacing. For the 7-foot by 8-foot spacing, one of the reps was not used for this study because some trees were removed due to the presence of beetles near the age of 20 years. Thus, a total of 11 experimental units were used (4 replications x 3 planting densities minus the one missing replication mentioned above) for this study. Measurements were conducted at ages 8, 10, 12, 14, 15, 17, 19, 20, 23, 25, 28, and 30 years.

Ponderosa pine–Intermountain Forest Tree Nutrition Cooperative (IFTNC)—In 1985, the IFTNC established 10 nitrogen (N) fertilization trials in stands dominated by ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) (IFTNC 1998). The trials were located throughout northeastern Oregon and central Washington. In 1987, IFTNC members established six additional ponderosa pine trials in Montana to study the effects of N and potassium fertilization on tree growth and survival. Measurement ages ranged from 32 to 110 years.

Red pine–Ontario—A spacing trial was planted in 1953 on abandoned fields near Chalk River, Ontario (Penner and others 2001). The study site was of high productivity for red pine (*Pinus resinosa* Aiton) with a site index of 80 feet at base age 50 years. Bareroot seedlings were machine-planted in 1953 at 4-foot by 4-foot, 5-foot by 5-foot, 6-foot by 6-foot, 7-foot by 7-foot, 8-foot by 8-foot, 10-foot by 10-foot, and 14-foot by 14-foot spacings. In addition, in 1965 part of the 10-foot by 10-foot spacing area was thinned to a spacing of 20-feet by 20-feet and it was assumed that future growth represented an initial planting configuration of 20-feet by 20-feet. For the plots used in this analysis, no thinnings were conducted. Measurements were conducted at ages 10, 15, 20, 25, 30, 35, 40, and 45 years.

Table 1 provides summary statistics by study.

Model Development and Parameter Estimation

Parameters were estimated using Proc NLMIXED of SAS (SAS Institute Inc., Cary, NC) and the Newton-Raphson algorithm (NEWRAP in NLMIXED). Random errors were assumed to be normally distributed. Full versus reduced model tests were conducted to determine if β_0, β_1, β_2, and β_3 should be considered random and if covariances existed among them.

A linear model form was selected to achieve statistical convergence of a common model form, which will help ensure when comparing predictive ability among different model-fitting datasets that the same model form will be compared. When using nonlinear models sometimes consistent convergence of the same model form/structure is more difficult when using different species in the model-fitting dataset. Hence, using a linear model form should help obtain a more consistent model form/structure across model-fitting datasets that will ensure the ability to determine if the ability, or lack of ability, to calibrate across species is due to what species are used in the model-fitting dataset or due to the number of random-effects in the model (for example, model form/structure). Additionally, it will help us better identify what stand-level variables may be useful in the calibration process. This information may be useful when nonlinear model forms are tested.

Initial Testing

The initial approach to modeling and calibrating was to fit models using the ETPPRP loblolly pine data. Results of calibrating the model for the ponderosa pine and red pine datasets were not as good as desired. Hence, the approach was modified such that all four (loblolly

Table 1—Summary statistics of data used in model fitting and model validation

		Age				TPA				BA			
Dataset	*n*	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
LP ETPPRP	568	14	2	33	6	465	30	858	144	91	1	215	52
PP IFTNC	392	74	32	110	21	183	55	370	65	133	62	316	46
RP	8	10	-	-	-	1001	193	2300	724	22	4	39	13
		15	-	-	-	877	107	2280	739	74	17	122	39
		20	-	-	-	871	103	2277	739	135	48	192	52
		25	-	-	-	814	100	1858	632	170	78	218	52
		30	-	-	-	794	100	1722	599	192	96	235	52
		35	-	-	-	773	99	1663	570	213	118	253	48
		40	-	-	-	715	99	1334	481	231	131	283	52
		45	-	-	-	684	98	1218	443	244	144	287	48
LP MSU	11	8	-	-	-	911	356	1632	511	85	46	122	26
		10	-	-	-	875	354	1572	471	119	79	158	27
		12	-	-	-	825	346	1482	423	146	112	181	24
		14	-	-	-	783	340	1404	380	167	132	197	23
		15	-	-	-	756	338	1316	351	175	143	203	20
		17	-	-	-	694	332	1164	292	187	157	211	17
		19	-	-	-	647	332	1052	248	195	170	212	13
		20	-	-	-	618	328	984	224	194	174	210	11
		23	-	-	-	520	310	758	147	195	181	204	8
		25	-	-	-	484	302	676	124	199	183	211	9
		28	-	-	-	417	280	542	91	207	185	219	9
		30	-	-	-	369	238	480	73	197	174	220	15

LP ETPPRP = loblolly pine in east Texas, PP IFTNC = ponderosa pine at Intermountain Forest Tree Nutrition Cooperative, RP = red pine, and LP MSU = loblolly pine at Mississippi State University.

LP ETPPRP and PP IFTNC data were obtained from several plots that were remeasured, and thus *n* equals the number of remeasurements across all plots, while RP was obtained from a published figure showing trajectories through time for 8 planting densities, and hence *n* = 8, and LP MSU had a total of 11 plots that were remeasured at the ages reported. Min = minimum; Max = maximum; SD = standard deviation; TPA = trees per acre; and BA = basal area, square feet per acre.

pine–ETPPRP, loblolly pine–MSU, ponderosa pine–IFTNC, and red pine) datasets were combined into one model-fitting dataset and equations (1) and (2) were refit – further referred to as the ALL dataset. Including species into the model-fitting dataset that have longer rotation lengths and maximum carrying capacities will provide more flexibility when trying to calibrate the model for species that have longer rotations and greater maximum carrying capacities relative to loblolly pine.

Initially, it was desired that for both equations (1) and (2) that all parameters would be considered random. However, in most cases convergence was not obtained. When model fitting, the ETPPRP dataset was considered the standard to ensure fair comparison between the mixed-effects model developed using the loblolly pine ETPPRP dataset and the ALL model as well as the mixed-effects models developed using other species. For example, the mixed-effects models fit using the ALL dataset were forced to have the same form/structure as the best model form/structure fit when using only the ETPPRP dataset in model fitting.

Based on likelihood ratio tests and Akaike's Information Criterion (AIC), for equation (1) a model where both β_0 and β_2 were considered to vary across plots and the presence of a covariance term, was found to be best (table 2). For equation (2) a model where only β_0 was considered random was best (table 3).

In many cases random effects account for nearly all autocorrelation among observations when using longitudinal datasets; however, a modeler can also directly model the random error structure. When estimating parameters in a mixed-effects model framework using data from one species and calibrating for another, the measurement intervals may not be the same among the datasets. This can cause problems when trying to estimate covariances of the random errors because a covariance structure that is appropriate for the model-fitting dataset may not be appropriate for the model calibration dataset. For this particular study, since measurement intervals differed among the datasets, the random error covariance-variance matrix was assumed to be $\sigma^2 I$.

Table 2—Parameter estimates and standard errors (in parentheses) of equation (1) by model-fitting dataset for both fixed-effects only and mixed-effects models

Dataset	Model	b_0	b_1	b_2	Var	b_0Var	b_2Var	Covar (b_0,b_2)	neg 2LL	AIC	*n*
LP ETPPRP	Fixed	2.1919	-0.7865	0.5276	0.04722	-	-	-	-100.0	-92.0	465
		(0.0856)	(0.1233)	(0.0144)	(0.00310)	-	-	-			
	Mixed	2.6179	-0.1782	0.4583	0.02071	0.1505	0.006589	-0.02998	-265.1	-251.1	95
		(0.1038)	(0.1218)	(0.0187)	(0.00164)	(0.0352)	(0.001717)	(0.00766)			
PP IFTNC	Fixed	0.1857	-1.0149	0.9672	0.002098	-	-	-	-1009.0	-1001.0	303
		(0.0396)	(0.0894)	(0.0082)	(0.000171)	-	-	-			
	Mixed	-	-	-	-	-	-	-	-	-	-
		-	-	-	-	-	-	-			
RP	Fixed	1.0346	-2.3417	0.7540	0.006669	-	-	-	-119.5	-111.5	55
		(0.1608)	(0.2377)	(0.0242)	(0.001273)	-	-	-			
	Mixed	-	-	-	-	-	-	-	-	-	-
		-	-	-	-	-	-	-			
ALL	Fixed	1.9127	-0.9456	0.6007	0.04152	-	-	-	-326.8	-318.8	951
		(0.0568)	(0.0747)	(0.0104)	(0.00191)	-	-	-			
	Mixed	2.1755	-0.4686	0.5508	0.01518	0.2563	0.01236	-0.05446	-771.0	-757.0	200
		(0.0984)	(0.0858)	(0.0194)	(0.00084)	(0.0615)	(0.00293)	(0.01344)			

b_0Var and b_2Var are estimates of the random effects variance components when applicable, Covar (b_0,b_2) is the covariance estimates between b_0 and b_2 when applicable, neg 2LL is -2 negative log-likelihood, and AIC is Akaike Information Criterion.

LP ETPPRP = loblolly pine in east Texas, PP IFTNC = ponderosa pine at Intermountain Forest Tree Nutrition Cooperative, RP = red pine, and ALL = combined data.

For both model fitting criterion, more negative numbers are superior. For the fixed-effects models *n* is the number of observations (plots and remeasurements of plots) used in model fitting while for the mixed-effects models, *n* is the number of clusters (or plots) used in model fitting.

Prediction errors, following transformation back to the original units, were compared between equations (equations (1) and (2)) and model-fitting datasets (ETPPRP, ALL, red pine, and IFTNC) using the validation process proposed by Arabatzis and Burkhart (1992). The difference between the observed and predicted basal area per acre ($e_{ij} = BA_{ij} - PBA_{ij}$, respectively, for each individual plot (*i*) and age (*j*)) was calculated for all equation and model-fitting dataset combinations. The mean residual ($\bar{e}$) and the sample variance (v) of residuals were computed and considered to be estimates of bias and precision, respectively. An estimate of mean square error (MSE) was obtained combining the bias and precision measures using the following formula:

$$MSE=\bar{e}^2 + v \qquad (5)$$

Values of MSE were compared between the equation and model-fitting dataset combinations to determine which one was most appropriate for a particular prediction dataset. To account for logarithmic transformation bias, the procedure recommended by Baskerville (1972) was used. All validation statistics presented in this paper are based on untransformed errors.

RESULTS AND DISCUSSION

In general, equation (2) had slightly better model fit statistics (tables 2 and 3). In almost all cases, parameters were significant at the $p < 0.05$ level. For the mixed-effects model of a particular equation, attempts were made to have all parameters random, but convergence did not occur or the random effects variance components were not significant. This suggests that in most cases for both equations (1) and (2) having all parameters random is not necessary. When convergence for only one or two random parameters was met for a particular equation, the parameter(s) selected to be random was determined based upon the log-likelihood fit statistics for the loblolly pine (ETPPRP) mixed-effect model for that equation. The ETPPRP loblolly pine model was considered the standard because the initial analysis was to see if a loblolly pine model could be calibrated for other species. The same mixed-effects equation fit using a different dataset used the same set of random parameters such that predictive ability is not confounded with the number of random parameters. For a particular equation then (either equation (1) or (2)), when using different datasets, the ability to calibrate mixed-effects models is only due to differences in the model-fitting dataset and not the number of random parameters.

Table 3—Parameter estimates and standard errors (in parentheses) of equation (2) by model-fitting dataset for both fixed-effects only and mixed-effects models

Dataset	Model	b_0	b_1	b_2	b_3	Var	b_0Var	neg 2LL	AIC	*n*
LP ETPPRP	Fixed	2.4690	-0.6540	0.5469	0.5347	0.04665	-	-105.7	-95.7	465
		(0.1440)	(0.1346)	(0.0165)	(0.1618)	(0.00306)	-			
	Mixed	2.5331	-0.2047	0.4052	0.3147	0.02750	0.02655	-188.1	-176.1	95
		(0.1209)	(0.1170)	(0.0193)	(0.1316)	(0.00209)	(0.00536)			
PP IFTNC	Fixed	0.1505	-1.0609	0.9650	1.0711	0.002089	-	-1010.0	-999.9	303
		(0.0506)	(0.0984)	(0.0085)	(0.1026)	(0.000170)	-			
	Mixed	0.1757	-1.0739	0.9584	1.0855	0.001641	0.000447	-1026.0	-1014.0	84
		(0.0603)	(0.0894)	(0.0107)	(0.0925)	(0.000157)	(0.000147)			
RP	Fixed	-2.8154	-5.9350	0.7824	6.8172	0.002838	-	-166.5	-156.5	55
		(0.4608)	(0.4467)	(0.0162)	(0.5442)	(0.000545)	-			
	Mixed	-	-	-	-	-	-	-	-	-
		-	-	-	-	-	-			
ALL	Fixed	1.7025	-1.1775	0.6067	1.2220	0.04106	-	-337.5	-327.5	951
		(0.0853)	(0.1024)	(0.0105)	(0.1121)	(0.00188)	-			
	Mixed	2.4124	-0.4430	0.4556	0.5061	0.02016	0.03038	-604.4	-592.4	200
		(0.0796)	(0.0902)	(0.0117)	(0.0971)	(0.00108)	(0.00397)			

b_0Var = estimates of the random effects variance components when applicable, neg2LL = -2 negative log-likelihood, and AIC = Akaike Information Criterion.

For both model fitting criteria, more negative numbers are superior.

For the fixed-effects models n is the number of observations (plots and remeasurements of plots) used in model fitting while for the mixed-effects models, n is the number of clusters (or plots) used in model fitting.

LP ETPPRP = loblolly pine in east Texas, PP IFTNC = ponderosa pine at Intermountain Forest Tree Nutrition Cooperative, RP = red pine, and ALL = combined data.

Model Prediction/Validation Results

Red pine—For red pine, following calibration, equation (2) produced better predictions relative to equation (1) when only loblolly pine (ETPPRP) was included in the model-fitting dataset, but when including all datasets (ALL), equation (1) generally produced better predictions (tables 4 and 5). Overall, equation (2) performed slightly better. Obviously, by comparing PA (population average) – Not calibrated to Mixed-Calibrated, calibrating the mixed-effects models greatly improved prediction.

After examining initial prediction results, it was desired to see whether a fixed-effects model using initial measurements of the desired model fitting calibration species (red pine) would produce better predictions than calibrating a mixed-effects model fit using other species when using the same initial measurements (table 5) – this is Fixed – RP. Two sets of ages were used in model fitting, either ages 15 to 30 or ages 15 to 35 (table 6). Results showed that using initial measurement ages of red pine to fit a fixed-effects model of the same species produced better results than calibrating a mixed-effects model fit using other species. Future research should concentrate on looking at predictions when using a greater difference in model fitting/calibration ages and predicted ages (e.g. calibrating using ages 15 to 35, but predicting at ages 75 or 80 rather than predicting at ages of 40 or 45). The ability to "borrow" biological relationships (for example, inflection point, carrying capacity or the asymptote, etc.) from other species when calibrating mixed-effects models may prove more useful for longer projections.

Following calibration, unlike the loblolly pine (ETPPRP) and ALL models, the ponderosa pine (IFTNC) model overpredicted future red pine basal area (table 7). The model developed using ponderosa pine (IFTNC) showed poorer results relative to the loblolly pine (ETPPRP) and the ALL datasets (table 7). It was thought that since ponderosa pine and red pine generally have longer rotations than loblolly pine that predictions may be better. However, an issue with the IFTNC dataset is that the range in measurement ages for a particular site is only 12 years at most. Perhaps a model fit using ponderosa pine data that has a greater range in measurement ages at the same plot/site would produce better results following calibration for red pine.

Table 4—Model validation results following calibration of equation (1) using the red pine dataset

Dataset	Fixed–red pine			PA–not calibrated			Mixed–calibrated			
PAge	*e*	*v*	MSE	*e*	*v*	MSE	Calibration ages	*e*	*v*	MSE
ETPPRP										
40	-12.5	174.2	330.0	-67.8	1062.4	5656.2	15, 20	-47.5	495.2	2748.5
							15, 20, 25	-38.9	334.0	1850.0
							15, 20, 25, 30	-32.3	208.3	1249.6
							15, 20, 25, 30, 35	-25.9	154.0	823.0
45	-18.7	136.3	487.5	-73.5	982.8	6386.9	15, 20	-53.0	461.0	3264.8
							15, 20, 25	-43.9	283.5	2209.2
							15, 20, 25, 30	-36.8	158.7	1510.1
							15, 20, 25, 30, 35	-29.9	111.6	1005.0
ALL										
40	-12.5	174.2	330.0	-52.1	734.3	3451.3	15, 20	-31.6	436.7	1432.4
							15, 20, 25	-26.8	291.4	1009.5
							15, 20, 25, 30	-22.8	164.2	685.0
							15, 20, 25, 30, 35	-17.7	122.5	437.0
45	-18.7	136.3	487.5	-56.8	662.3	3888.3	15, 20	-36.4	388.7	1712.4
							15, 20, 25	-31.2	228.0	1202.9
							15, 20, 25, 30	-27.0	108.3	834.9
							15, 20, 25, 30, 35	-21.5	79.0	539.9

The fixed–red pine model used all red pine measurement ages when model fitting (ages 15 to 45) and hence is considered the optimum predictive situation.

PA–not calibrated is the "population average" prediction for a model-fitting dataset where no calibration of the mixed-effects model occurred.

For each predicted age (PAge) and calibration age combination, $n = 8$.

e = residual, or the difference between the observed and predicted basal area and *v* =variance of residuals

Table 5—Model validation results following calibration of equation (2) using the red pine dataset

Dataset	Fixed–red pine			PA–not calibrated				Mixed–calibrated			Fixed–RP		
PAge	*e*	*v*	MSE	*e*	*v*	MSE	Calibration ages	*e*	*v*	MSE	*e*	*v*	MSE
ETPPRP													
40	-4.6	122.1	143.1	-60.5	1148	4814.1	15, 20	-34.6	255.9	1451.4	-	-	-
							15, 20, 25	-30.4	199.1	1120.8	-	-	-
							15, 20, 25, 30	-26.8	156.2	873.9	-23.0	210.5	737.6
							15, 20, 25, 30, 35	-23.0	133.2	661.4	-4.8	134.9	158.2
45	1.2	55.4	56.9	-64.5	1056.3	5221.9	15, 20	-37.7	280.4	1698.6	-	-	-
							15, 20, 25	-33.2	209.2	1314.7	-	-	-
							15, 20, 25, 30	-29.5	164.6	1035.8	-24.8	152.2	766.3
							15, 20, 25, 30, 35	-25.5	141.3	793.5	1.0	65.1	66.1
ALL													
40	-4.6	122.1	143.1	-59.7	1010.1	4572.2	15, 20	-31.2	205.7	1179.7	-	-	-
							15, 20, 25	-28.6	157.7	978.0	-	-	-
							15, 20, 25, 30	-25.9	123.4	791.8	-23.0	210.5	737.6
							15, 20, 25, 30, 35	-22.3	106.5	603.3	-4.8	134.9	158.2
45	1.2	55.4	56.9	-64.6	928.7	5100.4	15, 20	-35.3	232.4	1476.4	-	-	-
							15, 20, 25	-32.6	163.3	1224.7	-	-	-
							15, 20, 25, 30	-29.7	126.1	1006.7	-24.8	152.2	766.3
							15, 20, 25, 30, 35	-26.0	108.9	783.1	1.0	65.1	66.1

The fixed–red pine model used all red pine measurement ages when model fitting (15 to 45 years) and hence is considered the optimum predictive situation.

PA–not calibrated is the “population average” prediction for a model-fitting dataset where no calibration of the mixed-effects model occurred.

For each predicted age (PAge) and calibration age combination *n* = 8.

For the mixed-effect model, calibration ages are those ages used in calibration, for the fixed–RP model the ages are those ages used in fitting the fixed-effects model (either ages 15 to 30 or ages 15 to 35 years).

e = residual, or the difference between the observed and predicted basal area and *v* = variance of residuals

Table 6—Parameter estimates and standard errors (in parentheses) of equation (2) by model-fitting dataset for only fixed-effects models

Dataset	Model	b_1	b_2	b_3	b_4	Var	neg 2LL	AIC	*n*
PP IFTNC	Fixed 1st measure	-0.1618	-3.3813	0.9442	3.4731	0.000666	-376.1	-366.1	84
		(0.3424)	(1.8785)	(0.0092)	(1.9469)	(0.000108)			
RP	Fixed 1530	-1.1198	-4.5903	0.7618	5.0688	0.003291	-89.2	-79.2	31
		(1.2058)	(0.9647)	(0.0190)	(1.2623)	(0.000842)			
	Fixed 1535	-2.6822	-5.7765	0.7670	6.6505	0.003059	-115.1	-105.1	39
		(0.7837)	(0.6771)	(0.0176)	(0.8607)	(0.000698)			

PP IFTNC = ponderosa pine at Intermountain Forest Tree Nutrition Cooperative and RP = red pine.

neg2LL = -2 negative log-likelihood and AIC = Akaike Information Criterion, and *n* is the number of observations used in model fitting.

For both model fitting criteria, more negative numbers are superior.

For ponderosa pine, Fixed 1st measure only uses data from the first measurement for model fitting. For red pine, fixed 1530 uses data from ages 15 to 30 years, and fixed 1535 uses data from ages 15 to 35 years in model fitting.

Table 7—Model validation results for the red pine dataset following calibration of equation (2) fit using the ponderosa pine (IFTNC) dataset, loblolly pine (ETPPRP) dataset, and the ALL dataset

		Mixed–IFTNC			Mixed–ETPPRP			Mixed–ALL			Fixed–RP		
PAge	Calibration ages	*e*	*v*	MSE	*e*	*v*	MSE	*e*	*v*	MSE	*e*	*v*	MSE
40	15, 20	63.9	295.4	4372.7	-34.6	255.9	1451.4	-31.2	205.7	1179.7	-	-	-
	15, 20, 25	55.9	175.7	3299.9	-30.4	199.1	1120.8	-28.6	157.7	978.0	-	-	-
	15, 20, 25, 30	47.8	128.8	2414.0	-26.8	156.2	873.9	-25.9	123.4	791.8	-23.0	210.5	737.6
	15, 20, 25, 30, 35	41.8	95.8	1846.1	-23.0	133.2	661.4	-22.3	106.5	603.3	-4.8	134.9	158.2
45	15, 20	71.2	442.6	5511.3	-37.7	280.4	1698.6	-35.3	232.4	1476.4	-	-	-
	15, 20, 25	62.8	291.4	4235.8	-33.2	209.2	1314.7	-32.6	163.3	1224.7	-	-	-
	15, 20, 25, 30	54.2	226.5	3163.0	-29.5	164.6	1035.8	-29.7	126.1	1006.7	-24.8	152.2	766.3
	15, 20, 25, 30, 35	47.8	175.6	2462.7	-25.5	141.3	793.5	-26.0	108.9	783.1	1.0	65.1	66.1

Mixed-effects models were calibrated using a variety of ages. For each predicted age (PAge) and calibration age combination $n = 8$.

For the mixed-effect models, Calibration ages are those ages used in calibration; for the fixed-RP model, the ages are those ages used in fitting the fixed-effects model (either ages 15 to 30 or ages 15 to 35 years). Mixed-ETPPRP, Mixed-ALL and Fixed–RP are repeat of table 5.

ETPPRP = loblolly pine in east Texas, IFTNC = ponderosa pine at Intermountain Forest Tree Nutrition Cooperative, RP = red pine, and ALL = combined data.

e = residual, or the difference between the observed and predicted basal area and *v* = variance of residuals

Average bias error in predicted BA ($\bar{e} / \overline{BA}$) following calibration for equation (1) ranged from 7.7 to 23.0 percent while for equation (2) percentages ranged from 9.7 to 16.3 percent. Average error in predicted BA ($\sqrt{MSE} / \overline{BA}$) following calibration for equation (1) ranged from 9.1 to 24.8 percent while for equation (2) percentages ranged from 10.6 to 17.9 percent. Average BA for the prediction ages was 230.8 square feet per acre. As table 7 shows, in general, future stand development was underpredicted when calibrating the loblolly pine (ETPPRP) and ALL models while for the ponderosa pine (IFTNC) model basal area was overpredicted.

An error of 10 percent equates to around an error of 23 square feet per acre. As compared to the Fixed – RP, where errors ranged from 3.5 to 12.0 percent ($\sqrt{MSE} / \overline{BA}$), a 10 percent error is acceptable.

A further analysis of equations (1) and (2) for red pine was conducted to see how well the calibrated mixed-effects models predicted future stand development relative to the optimal prediction system (Fixed-Red Pine – tables 4 and 5). The optimal prediction system is to fit a fixed-effects model for red pine using the entire red pine dataset. Tables 2 and 3 contain parameter estimates. As expected, when models fit using the same data that is predicted, the predictions are very good–for equation (1) calibration using additional ages resulted in the two mixed-effects model results becoming more comparable to the results from Fixed-Red Pine but for equation (2) the Fixed-Red Pine validation statistics were clearly superior (tables 4 and 5) regardless of the number of ages used in calibration.

With that said, it should be recognized that even the ALL models fit using ALL datasets is somewhat optimal because for red pine, for example, the red pine dataset was included when fitting the ALL model. Hence, you are using the data itself to predict red pine data. Thus, for a particular equation, (1) or (2), you would expect the ALL model to be superior to the loblolly pine (ETPPRP) model and the IFTNC model. This is also true for the ponderosa pine analysis.

Ponderosa pine—For ponderosa pine, equation (2) produced better predictions relative to equation (1) when only loblolly pine (ETPPRP) was included in the model-fitting dataset but when including all datasets (ALL) when model fitting equation (1) produced better predictions (table 8). Across all predictions, equation (2) performed slightly better than equation (1). For the mixed-effects models, following calibration, equation (2) always had less bias but for the ALL model-fitting dataset it had more variability relative to equation (1).

After examining initial prediction results, it was desired to see whether a fixed-effects model using the initial two measurements of the desired model fitting calibration species (ponderosa pine) would produce better

Table 8—Model validation results following calibration of equations (1) and (2) using the ponderosa pine dataset (IFTNC)

	First observation used in model calibration						First two observations used in model calibration					
Dataset	Equation (1)			Equation (2)			Equation (1)			Equation (2)		
Model	*e*	*v*	MSE	*e*	*v*	MSE	*e*	*v*	MSE	*e*	*v*	MSE
LP ETPPRP												
Not calibrated	-17.9	942.6	1264.4	1.1	878.7	879.8	-17.9	942.6	1264.4	1.1	878.7	879.8
Calibrated	-15.1	413.0	640.2	-5.2	344.4	371.9	-13.2	243.6	417.2	-6.3	200.4	240.0
ALL												
Not calibrated	-14.2	682.8	884.7	-8.4	830.0	900.1	-14.2	682.8	884.7	-8.4	830.0	900.1
Calibrated	-10.4	200.2	309.0	-9.6	257.2	348.8	-9.0	114.0	194.9	-8.8	145.0	222.9
PP IFTNC												
Fixed 1st measure	-	-	-	13.1	238.3	410.9	-	-	-	-	-	-

LP ETPPRP = loblolly pine in east Texas, PP IFTNC = ponderosa pine at Intermountain Forest Tree Nutrition Cooperative, and ALL = combined data.

Mixed-effects models were calibrated using either the first observation for a plot or the first two observations for a plot. Fixed 1st measure only uses data from the first ponderosa pine measurement age for model fitting.

n, or the number of predicted values, is equal to 140. The number of clusters is 84 (or treatment and replication combination).

e = residual, or the difference between the observed and predicted basal area and *v* = variance of residuals

predictions than calibrating a mixed-effects model fit using other species using the first two observations (table 8). This was only conducted for equation (2). When model fitting (table 6), all parameters were significant when just using the initial measurement age in model fitting but when using both the first and second measurement ages in model fitting some parameters were highly nonsignificant. Hence, only the model fit using the initial measurement age was compared. When comparing a fixed-effects model fit using data from an initial measurement (Fixed 1st Measure) to the calibrated mixed-effects models using the initial measurement age, calibration improved model prediction (table 8).

As expected, the use of two measurement ages in calibration generally improved model prediction. However, bias for equation (2) increased for the loblolly pine ETPPRP model from 5.2457 to 6.2873, but, the variance greatly decreased. Outside of the increase in bias for equation (2) for the loblolly pine ETPPRP dataset, bias was reduced by 7.8 to 13.8 percent. MSEs were consistently reduced by nearly 35 percent. Average bias error in predicted BA ($\bar{e} / \overline{BA}$) following calibration for equation (1) ranged from 6.0 to 10.1 percent, while for equation (2) percentages ranged from 3.5 to 6.4 percent. A prediction bias of only 3.5 percent is fairly good. Average error in predicted BA ($\sqrt{MSE} / \overline{BA}$) following calibration for equation (1) ranged from 9.3 to 16.9 percent while for equation (2) percentages ranged from 10.0 to 12.9 percent. Average BA for the prediction ages was 149.6 square feet per acre. As table 8 shows, following calibration, in general future stand development was underpredicted. An error of 10.0 percent equates to around an error of 15 square feet per acre. As compared to the Fixed 1st Measure, which had a 20.3 percent error, this error is reasonable. However, interestingly the Fixed 1st Measure overpredicted future stand development.

CONCLUSIONS

In conclusion, results from this study demonstrate a mixed-effects model fit using one species but calibrated for another produced reasonable predictions. Future research should concentrate on using different linear and nonlinear model forms. The major issue is to somehow standardize time such that the impacts of growth rates on the timing of various biological growth traits of a basal area (or volume) trajectory such as the asymptote, inflection point, etc., can be eliminated. Greater differences in the calibration and predicted ages may show a greater advantage of using calibrated mixed-effects models relative to fixed-effects models fit using the desired predicted species.

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ESTIMATED IMPACTS TO LOUISIANA HARDWOOD TIMBER PRODUCT RECEIPTS FOLLOWING EMERALD ASH BORER INVASION: A 25-YEAR SCENARIO

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Abstract—Hardwoods significantly contribute to Louisiana's forest economy. Unfortunately, the emerald ash borer (*Agrilus planipennis*), or EAB, will have untold impacts on those contributions. Here, we estimated one scenario's effects on Louisiana's hardwood timber product value. Ash (*Fraxinus* spp.) mortality due to EAB was assumed to follow a Beta distribution to eliminate essentially all ash within 25 years. Mortality rates were relatively slow in the near future, peaked after the middle stage of infestation, and tapered precipitously near the end of the projection period. Annual growth of ash was assumed to be a constant proportion (1.8288 percent) equal to the current rate estimated from the U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis data. Future volumes of ash mortality were discounted to the present and valued using TimberMart-South prices to estimate the annualized effect on timber receipts. Assuming the dead timber would have otherwise been typical trees of average quality, stumpage was valued at $1.57 million, with deliveries totaling $3.48 million. A salvage arrangement using the double declining balance method coupled with a second Beta distribution depreciated the timber's value monthly over 1 year, as Louisiana's high heat and humidity rapidly degrade timber quality. The Beta cumulative distribution function was centered upon Louisiana's current 2.8 percent proportion of harvest volume to timber inventory. We found salvage receipts for stumpage ranged from $24,200 to $35,800, while deliveries ranged from $53,700 to $79,400 at 95 percent confidence. The final result was an average annual decline in stumpage revenues of -$1.53 million to -$1.55 million, while delivered values fell by -$3.40 to -$3.43 million at 95 percent confidence.

INTRODUCTION

National forest inventory data document more than 8 billion ash (*Fraxinus* spp.) trees in United States forests and woodlands (USDA Forest Service 2018). The invasive insect emerald ash borer (EAB, *Agrilus planipennis*) has killed tens of millions of ash trees since its introduction in Michigan in 2002 (Poland and McCullough 2006). The EAB is a bark-boring beetle, with one generation per year being typical. The larvae are the primary culprits that lead to tree death, where they tunnel in S-shaped galleries to feed in an ash tree's inner bark and outer sapwood region through summer and into fall. The persistent tunneling in the vascular system over multiple generations eventually limits the tree's ability to transport water and nutrients and leads to death. A key identifier of EAB infestation is the insect's distinct D-shaped exit holes (Herms 2007).

Quarantines to limit the movement of ash wood were initiated by States in the beginning phases of infestation, but over time they have typically been abandoned in favor of statewide bans. Twenty-one States are currently contained fully within the Federal EAB quarantine and authorized transit zone (USDA APHIS 2018), but this species continues to spread. Unfortunately, the EAB was discovered in Louisiana, the 25th State to verify its presence. The first official EAB identification in Louisiana came in February 2015, in the north Louisiana parish of Webster, and as of July 2017 it had spread to eight other parishes.

Ash inventory on Louisiana timberlands exceeds 678 million cubic feet (20 million green tons) (fig. 1), with green ash (*Fraxinus pennsylvanica*) being the predominant commercial species. Hardwoods, both sawtimber and pulpwood, comprise a $91.5 million annual business in Louisiana, with $41.2 million returned to landowners as stumpage in the most recent reporting period (LSU AgCenter 2017) and ash is a major part of this business. Due to the commercial importance of ash in Louisiana, we sought to better understand the impact EAB could have on hardwood timber receipts in this State.

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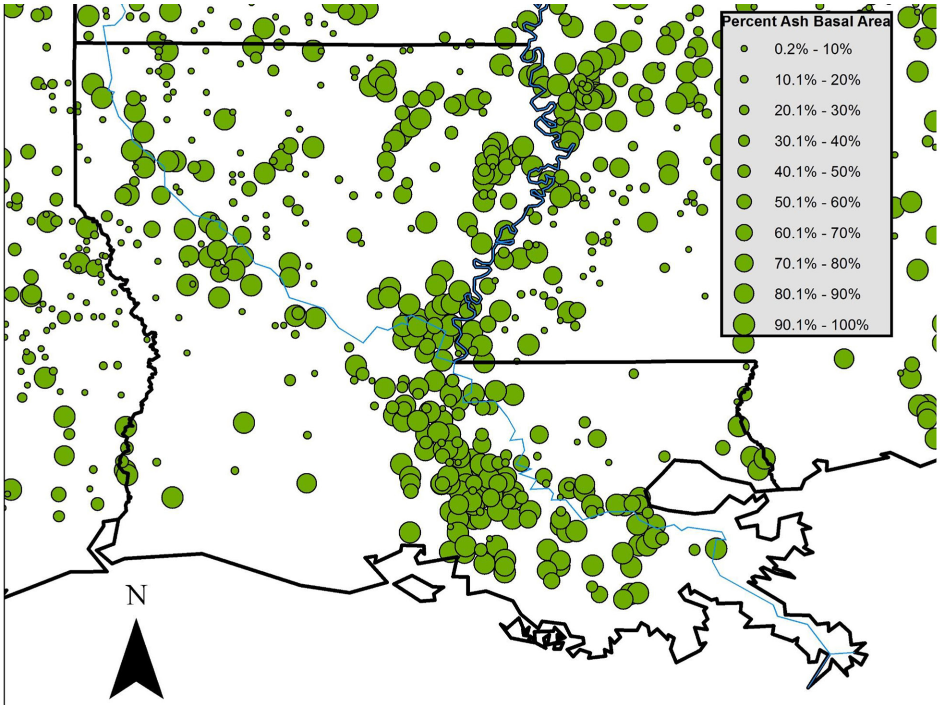

Figure 1—Basal area distribution of ash across Louisiana and portions of neighboring States (Source: USDA Forest Service, Forest Inventory and Analysis).

METHODS

Forested regions vary by a number of factors across the United States, thus our understanding of how EAB will propagate and spread in the southern forests of the Western Gulf region is incomplete. Furthermore, Louisiana's ash stocking is not at the levels observed in the northern United States where the infestation originated and ash was a significantly greater component of the forest (and ash depletion occurred rather rapidly). Therefore, we looked to determine how much timber (pulpwood and sawtimber) might be harvested annually under various management regimes and assumptions of EAB spread in Louisiana.

To do this, growing stock on timberland data in green tons were obtained from EVALIDator (USDA Forest Service 2018) and converted to cubic feet using standard conversions (Miles and Smith 2009). Ash mortality due to EAB was temporally assumed to follow a Beta distribution and to essentially kill all ash within a 25-year period (fig. 2). The Beta distribution is characterized by two shape parameters, alpha and beta. Alpha quantifies a "success" while beta quantifies a "failure." In the context of an EAB infestation, alpha illustrates a tree possessing an EAB presence, whereas beta describes trees absent of EAB.

We set alpha = 5.30 and beta = 2.00 for this initial scoping study following a program evaluation and review technique (PERT) outlined in VanderSchaaf (2018) that reflected our collective experiences and discussions with peers. This produced a mortality rate that was relatively slow at first, greatest occurring after the middle of the projection period, and was then followed by a rapid tapering off of mortality as the projection approached 25 years. We presumed a residual inventory of ash would remain in Louisiana's timberlands at the end of the projection period (5% of the existing ash inventory), which we determined to equal 33.9 million cubic feet. Annual ash growth was assumed to be a constant proportion of annual standing biomass, where the proportion is equal to the current rate as estimated using U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis data (USDA Forest Service 2017):

$$\frac{\text{Average annual net growth in cu ft}}{\text{Standing inventory at time present}} = \frac{12.4 \textit{ million cu ft}}{678.0 \textit{ million cu ft}} = 1.8288\% \qquad (1)$$

Figure 2 shows the projection of growth through time. All future ash mortalities were discounted to the present (2017) using the compound interest formula and summed to provide a present estimate of ash mortality volume.

Hardwood timber prices for Louisiana were obtained from the Louisiana State University AgCenter (Tanger 2017), which were based on quarterly market reports provided by TimberMart-South. Weighted annual average prices were calculated for stumpage and delivered logs using Louisiana Timber Product Output statistics for harvested hardwood sawtimber and pulpwood (Wall and others 2017). The weighted average prices were $74 per cunit (100 cubic feet) for stumpage and $164 per cunit for delivered logs. Receipts were calculated by multiplying present mortality volume, which assumed the dead timber would have otherwise been typical trees of average quality, times the weighted average prices.

A salvage arrangement using the double declining balance method coupled with a second Beta distribution depreciated the timber's value monthly over 1 year, as Louisiana's high heat and humidity rapidly degrade timber quality. Stumpage was assumed to "depreciate out" at a salvage price of $10 per cunit. The Beta cumulative distribution function was centered upon Louisiana's current 2.84 percent proportion of harvest volume (from the Louisiana timber product output report, Wall and others 2017) to timber inventory (from EVALIDator, USDA Forest Service 2018) using shape parameters of alpha = 4.33 and beta = 3.60. The monthly harvest volumes and values were then calculated over the year to estimated salvage values at 95 percent confidence intervals. Once benchmark and salvage values were calculated, the losses to hardwood timber receipts were determined by subtraction.

RESULTS AND DISCUSSION

We determined discounted future annual EAB mortalities summed to a volume that was equivalent to removing 2.13 million cubic feet currently comprising Louisiana's ash inventory. Total mortality summed to 657.5 million cubic feet over a 25-year projection period using the Beta distribution at our estimated shape parameters (fig. 3).

The current market values of 2.13 million cubic feet of ash timber in Louisiana, assuming it was otherwise healthy and representative, were $3.48 million at the mill gate and $1.57 million paid to landowners (table 1). Salvage of dying or dead inventory would temper any losses to hardwood timber receipts contributed by the

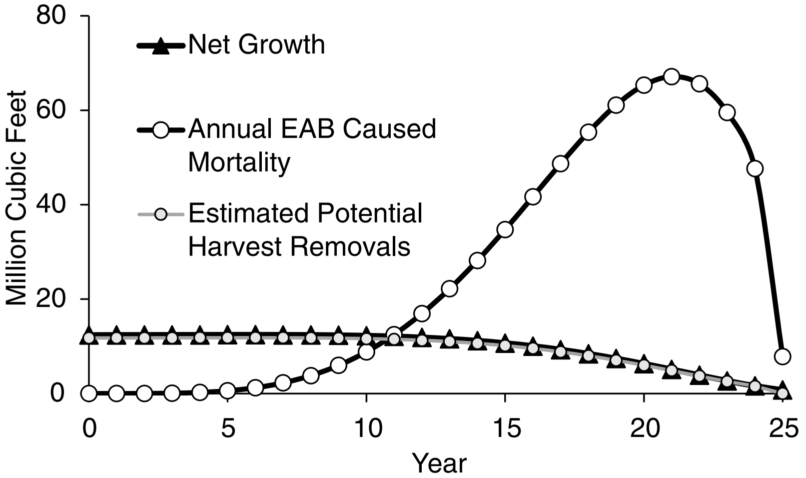

Figure 2—Simulated ash timber growth, removals, and mortality induced by emerald ash borer (EAB) spread and infestation for a 25-year test period.

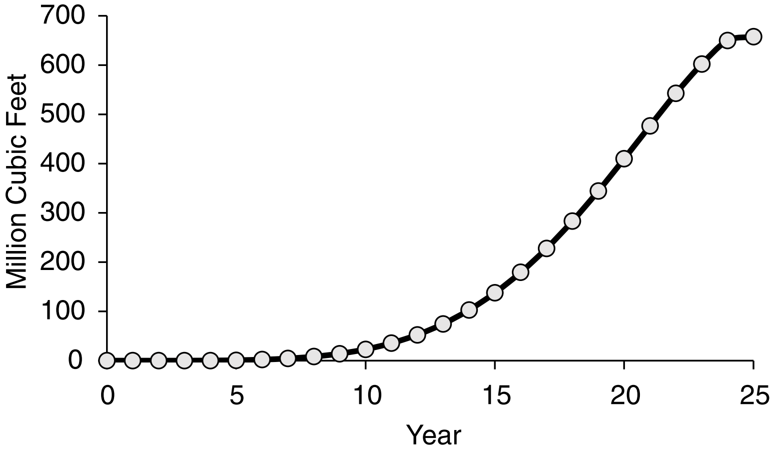

Figure 3—Cumulative losses over a 25-year projection period using a Beta distribution with shape parameters alpha = 5.3 and beta = 2.

Table 1—Annualized economic impacts to hardwood timber receipts assuming a 25-year period for emerald ash borer to eliminate ash from Louisiana's forest inventory

Source	Delivered	Stumpage
Discounted timber		
Lost value of dead timber (assuming typical trees of average quality)	-$3,483,000	-$1,571,000
Salvage		
Upper bound 95% CI	$79,400	$35,800
Mean	$71,800	$32,400
Lower bound 95% CI	$53,700	$24,200
Loss-no market value/left in woods		
Upper bound 95% CI	-$3,403,700	-$1,534,800
Mean	-$3,411,300	-$1,538,200
Lower bound 95% CI	-$3,429,400	-$1,546,300

CI = confidence interval.

ash resource but only to a relatively small degree at current harvest levels for the State. We found Louisiana landowners would receive an average of only $32,400 for stumpage, ranging from $24,200 to $35,800 at 95 percent confidence. Loggers would receive between $53,700 and $79,400 for deliveries. The economic impact to hardwood receipts after accounting for salvage operations averaged between -$3.40 million to -$3.43 million for the forest industry and -$1.53 million to -$1.55 million for forest landowners. This reduced hardwood receipts overall from $91.5 million to between $88.0 and $88.1 million.

Given current known infestation locations, figure 1 suggests landowners along the Red River in northwest Louisiana and Ouachita River in northeast Louisiana will be the first to experience these losses, followed later by those owning timberlands along the Mississippi and Atchafalaya Rivers. Offsetting these lost revenues would require market substitution of other species, such as another "white wood" like maple (*Acer* spp.), and/or mills will need to import deliveries from outside Louisiana. Both options will likely have additional multiplier effects with other industries that support forest sector activities (McConnell and others 2018, Tanger and Henderson 2014).

SUMMARY

The EAB is a relatively new invader to the forests of the South and the Western Gulf region. Establishing baselines, such as our effort here, can assist natural resources advocates and policymakers when making decisions that will have impacts across the forest value chain. Using a Beta distribution, we calculated the State's ash inventory would be impacted by mortality equivalent to 2.13 million cubic feet of the current ash inventory. Removing this amount of volume from the growing stock could decrease hardwood timber receipts by -3.81 percent if it were otherwise healthy and unaffected. Based upon current harvest levels, we determined only 2.06 percent of the timber's value would be recovered through salvage operations over one year. We concluded the impact to timber receipts would approximate 3.73 percent of current hardwood revenues.

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ECONOMIC IMPACTS OF PROJECTING HORIZONTAL ANGLES TO THE WRONG HEIGHT WHEN CONDUCTING POINT SAMPLING IN LONGLEAF PINE PLANTATIONS

Curtis L. VanderSchaaf

Abstract—Point-sampling selects sample trees by projecting horizontal angles. In many inventories, angles are to be projected to where diameter at breast height (d.b.h.) is measured (4.5 feet above the ground), but due to user error, angles are often projected to diameters at other heights. Thus, errors are made as to which trees should be sampled, probabilities of sampling individual trees are incorrect, and the basal area estimate does not truly correspond to d.b.h. The objective of this paper is to determine the potential economic impacts of projecting angles at heights other than d.b.h. when d.b.h. is the desired height. Projections at age 15 years for 200 surviving trees per acre on a low quality site (site index 50 feet at base age 25) and for 400 and 700 trees per acre on a higher quality site (site index 70 feet at base age 25) were examined. On all three sites, two ages (20 and 30) were used to establish virtual plantations and sampling was conducted using 10 and 20 basal area factor prisms by projecting horizontal angles to four heights: 4.5 feet, 5.0 feet, 5.5 feet, and 6.0 feet. A taper equation was used to estimate changes in diameter along the stem. For the stand conditions examined, incorrectly projecting angles to heights other than d.b.h. reduced timber appraisals by as much as 7.4 percent and up to $170 per acre. Across many acres and stands, this type of nonsampling error can result in serious errors in valuing stumpage.

INTRODUCTION

Horizontal point-sampling, often referred to as variable radius sampling, is commonly used to determine the amount of woody product and economic value of stands. The approach samples trees based on projecting horizontal angles. A tree is sampled whenever the cross-sectional area of a tree stem is larger than the projected angle. Rather than establishing actual angles in the field, instruments (such as prisms and angle-bars) are used that in effect project angles when viewing stem cross-sectional areas. More complete descriptions of horizontal point-sampling can be found in Shiver and Borders (1996), Iles (2003), and Avery and Burkhart (2002).

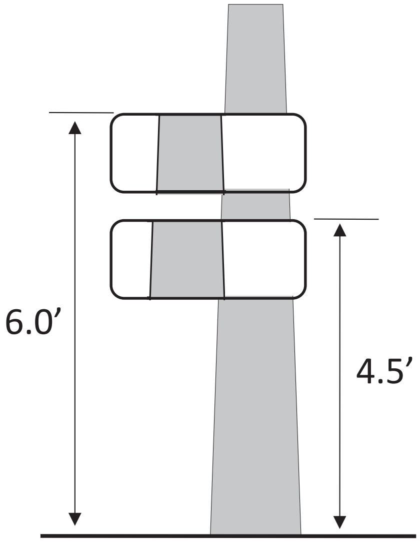

Figure 1—When viewing through a prism at 4.5 feet the tree is exactly borderline and would be sampled, but due to taper of the stem, at 6.0 feet the tree would be considered “out” and would not be sampled. If viewed at 6.0 feet, when 4.5 feet was desired, the tree would incorrectly be excluded from the sample.

When projecting horizontal angles, common errors include not holding a prism over the sample point (the vertex of angles are located within the prism) and projecting horizontal angles along slopes. Another common mistake is to view the cross-sectional area of tree stems at heights other than that desired (fig. 1). In most horizontal point-sampling inventory protocols, tree stems are to be viewed where diameter at breast height (d.b.h.) is measured, or 4.5 feet above the ground. However, because of user error, often stems are sampled at heights other than the desired d.b.h. Projecting horizontal angles to heights other than breast height is a valid sampling procedure. For example, in some cases

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angles are projected to 17.3 feet above the ground in the Western United States to account for thick understory vegetation (Husch and others 1982: 255; Iles 2003: 547, 548). The basal area per acre estimate obtained at a height of 17.3 feet is a legitimate estimate of basal area per acre, but it is not an estimate of basal area per acre at breast height.

One should be concerned about projecting angles to heights other than breast height when breast height is desired because:

1. As already mentioned, one cannot claim that the basal area per acre estimate is an estimate of basal area at breast height.
2. Viewing different tree stems within the same inventory at various heights will produce inconsistent probabilities (although not necessarily incorrect probabilities – see Iles 2003: 547-548) of sampling which can lead to incorrect basal area per acre estimates (as well as other variables). For example, when sampling on flat ground, projecting a horizontal angle to an 8-inch-d.b.h. tree at 6 feet above the ground while projecting a horizontal angle to another 8-inch-d.b.h. tree at 4.5 feet above the ground will lead to different sampling probabilities (and hence incorrect expansion factors to a per acre or per tract value) that can result in incorrectly sampling or not sampling the 8-inch-d.b.h. trees.
3. Even if a user projects horizontal angles to a constant height other than breast height for all non-borderline trees, determining whether borderline trees are to be sampled using limiting distances calculated for breast-height will produce inconsistencies among the probabilities of sampling trees (and hence incorrect expansion factors).

The objective of this paper is to determine potential economic impacts of viewing stems at heights other than breast height when breast height is desired. Although Iles (2003: 522, 523) presents estimates when one tree is incorrectly not sampled, I wanted to determine the impacts across an acre and for different stand conditions for two commonly used English (square foot) basal area factors (BAFs) in the Southern United States. To do this, I examined the potential economic impacts for unthinned longleaf pine (*Pinus palustris* Mill.) plantations in the Western Gulf region of the Southeastern United States.

METHODS

Data Used in Model Fitting and Prediction

A similar analysis was conducted for loblolly pine (*Pinus taeda* L.) plantations (VanderSchaaf and Jordan 2011). To determine potential economic impacts across a range of initial and current stand conditions, observations (table 1) from a yield table (Lohrey and Bailey 1977) were used to estimate diameter distributions, from which trees were established within 1-square-acre simulated plantations. For simplicity, all plantations were assumed to be established on level-ground (thus no need for slope correction factors, but in reality this is another consideration foresters should account for), all plantations were pure planted longleaf pine, spatial autocorrelation among individual trees was ignored (which could impact the d.b.h. of neighboring trees in our virtual plantations), all tree diameters were assumed to be perfect circles and are centered around the spatial location of a tree center, and all spacings were assumed square.

Stand Conditions

For the sake of brevity, only two site indices (SI) were used (50 feet and 70 feet at base age 25). On the SI 50 site, observations were obtained for combinations of planting density per acre (~1,075 seedlings per acre) and age (20 and 30). This planting density corresponded to surviving trees per acre at age 15 of 200 within the yield tables presented in Lohrey and Bailey (1977). On the SI 70 site, observations were obtained for combinations of planting density per acre (460 and 913) and age (20 and

Table 1—Stand-level variables and three-parameter Weibull distribution parameter estimates as obtained from Lohrey and Bailey (1977) to conduct simulations

Site index	Planting density	Surviving at age 15	Age	Trees	D_q	BAA	*a* Location	*b* Scale	*c* Shape
feet	*--number per acre--*		*years*	*number per acre*	*inches*				
50	1,075	200	20	190	6.3	40.9	0	6.66	3.61
			30	163	8.7	67.9	0	9.26	3.90
70	460	400	20	372	6.6	88.6	0	7.01	3.69
			30	295	8.8	125.6	0	9.39	3.87
70	913	700	20	630	6.0	123.3	0	6.33	3.26
			30	448	8.3	170.1	0	8.85	3.59

D_q is quadratic mean diameter and BAA is basal area in square feet per acre. For SI 50, age 30, a value for *b* of 9.26 was used rather than the reported 9.28. For SI 70, age 30, and 400 trees surviving at age 15, a value for *b* of 9.39 was used rather than the reported 9.38.

30). These planting densities correspond to surviving trees per acre at age 15 of 400 and 700, respectively, within the yield tables presented in Lohrey and Bailey (1977). Hence, average planted tree survival per acre, quadratic mean diameter at breast height, and parameter estimates of the three parameter Weibull diameter distribution were obtained for each combination of age and density.

An individual tree d.b.h. was then assigned using the predicted Weibull distribution to each grid point, and survival of that tree was determined by comparing the percent survival rate to a uniformly distributed random variable. For example, if the yield table reported percent survival as 35 percent for a particular planting density and age combination, a tree assigned a uniformly distributed random variable less than or equal to 0.35 indicated the tree survived. However, any tree assigned a uniformly distributed random variable greater than 0.35 indicated the tree died and the diameter was removed from consideration for sampling.

For surviving trees, individual tree height was estimated using an equation obtained from VanderSchaaf and McConnell (2020) that predicts total tree height (Ht, in feet) as a function of d.b.h. (in inches):

$$\mathrm{Ht} = \exp^{[2.6575 + 0.5666 \ln \textit{d.b.h.} + 0.00938/2]} \qquad (1)$$

After establishing a virtual plantation, a sample point was placed at the center of each square acre and sampling was simulated using 10 BAF and 20 BAF prisms. To determine the impacts of projecting horizontal angles to points along the stem other than breast height when breast height is desired, a taper equation was used to determine the change in diameter along each surviving tree stem (Baldwin and Polmer 1981). Parameters for crown ratios of less than 36 percent were used. Diameter was then predicted for four sampling heights: breast height—4.5 feet above the ground, 5.0 feet, 5.5 feet, and 6.0 feet.

The limiting distances for the predicted diameters of the four sampling heights for each tree were then determined using a BAF's plot radius factor (2.750 for a 10 BAF and 1.944 for a 20 BAF). Based on the location of a tree within a plantation, the Euclidean distance from the sample point to each tree was determined and compared to the tree's limiting distance for a particular sampling height. If the limiting distance for each tree was equal to or greater than the tree's Euclidean distance, the tree was sampled for that particular sampling height. However, the tree per acre expansion factor was calculated using d.b.h. for all four sampling heights.

Thus, for heights other than 4.5 feet, the probability of inclusion in the sample was based on the sampling height but the expansion factor was based on d.b.h.—leading to inconsistencies among the probability of sampling and the expansion factor. Recall, the concept of probability proportional to size is that smaller trees have a lower probability of inclusion. Thus, if the probability of inclusion for a particular tree size is small, yet a tree of that size is sampled, there must be many of them in the sampled population, leading to greater expansion factors for smaller trees when using the same BAF.

To examine variability among repeated cruises, for survival amount at age 15 (200 trees per acre for SI 50 and 400 or 700 trees per acre for SI 70), age (20 and 30 years), BAF (10 and 20), and sample size (number of sample points = 50 per repeated cruise) estimate, a total of 500 separate simulated plantations were established and a virtual cruise was conducted in each virtual plantation. Thus, it can be thought that for a particular combination of factors, 500 separate cruises were simulated, thus allowing us to examine sampling distributions of the timber cruise means. It is assumed that a sample point is established in the center of each square virtual acre thus eliminating any potential edge bias.

Individual tree weight and product weights (pulpwood, chip-n-saw, and sawtimber) were then estimated using equations found in Baldwin and Saucier (1983):

$$\mathrm{Wt}_{Tot} = 10^{(-0.66098 + 0.96407 \log[\textit{d.b.h.}^2 \textit{Ht}])} \qquad (2)$$

$$\mathrm{Wt}_{d} = 10^{\mathrm{Wt}_{Tot} * (1 - 6.80342[\textit{dm}^{2.97184} / (\textit{d.b.h.}^2 \textit{Ht})^{1.04751}])} \qquad (3)$$

where

Wt_{Tot} = total bole green weight, outside bark (in pounds),
Wt_{d} = outside bark green weight (in pounds) to upper stem diameter merchantability limit (in inches), and
dm = upper stem diameter outside bark merchantability limit (in inches).

Assumed merchantability standards for three product classes are presented in table 2. For simplicity, any tree meeting minimum merchantability standards for a particular product class was placed in that product class (thus no cull trees and no product degrades). If portions of trees met sawtimber merchantability standards, that tree was assigned to that product class, if portions of trees did not meet sawtimber merchantability standards but met chip-n-saw merchantability standards the tree was assigned to that product class, and so forth for the pulpwood class. Sawtimber and chip-n-saw trees were considered mutually exclusive. However, upper-stem portions of sawtimber and chip-n-saw trees were assigned to the pulpwood product class, sometimes referred to as topwood.

Table 2—Product merchantability limits in inches and product revenues per ton for a particular product class

Product class	Merchantability limits (inches) Minimum d.b.h.	Maximum d.b.h.	dm	Revenue per ton ($) Poor	Optimistic
Pulpwood	4.5	9.5	2	10	20
Chip-n-saw	9.5	11.5	6	18	30
Sawtimber	11.5	-	6	23	45

d.b.h. is diameter at breast height, dm is the upper stem diameter outside bark merchantability limit in inches. Upper-stem portions of chip-n-saw or sawtimber trees were assigned to the pulpwood product class (e.g., topwood).

Economic Impacts

To determine the economic value of an individual tree, all weight estimates were divided by 2,000 pounds to convert to tons, and then multiplied by two different sets of stumpage prices based on 2017 (Tanger 2018) market conditions for the Western Gulf region of the Southeastern United States (table 2). One set was considered "Optimistic," or highly desired stumpage prices by a landowner, and the second set was considered "Poor," or prices less desired by a landowner. Revenues of all sampled trees ("in" trees) were then summed by sample point and averaged across sample points (*n* = 50) for each of the 500 virtual cruises. Mean values from each of the 500 cruises were then averaged to determine the average economic value per acre for a particular BAF, sampling height, survival at age 15, and age combination.

RESULTS

Simulations of 200 Trees per Acre at Age 15 on Site Index 50 Sites (Base Age 25)

Based on basal area estimates, on average, for a 10 BAF, when projecting horizontal angles to a height of 6.0 feet at ages 20 and 30, around one-third of a tree at each sample point was incorrectly not sampled (table 3). Stated alternatively this equates to about one tree every three sample points. For a 20 BAF, around one-sixth of a tree was incorrectly not sampled. Stated alternatively this equates to about one tree every six sample points. Projecting angles to a height of 5.0 feet has a relatively minimal impact on economic value (percent differences ranged from 1.6 percent to 2.7 percent) but projecting angles to a height of 6.0 feet can have some meaningful impact (percent differences ranged from 4.6 percent to 7.4 percent) on appraisals.

Simulations of 400 Trees per Acre at Age 15 on Site Index 70 Sites (Base Age 25)

Based on basal area estimates, on average, for a 10 BAF, when projecting horizontal angles to a height of 6.0 feet at ages 20 and 30, more than half of a tree at each sample point was incorrectly not sampled (table 4). Stated alternatively this equates to about one tree every two sample points. For a 20 BAF, around one-third of a tree was incorrectly not sampled. Stated alternatively this equates to about one tree every three sample points. Projecting angles to a height of 5.0 feet had a relatively minimal impact on economic value (percent differences ranged from 1.5 percent to 2.4 percent) but projecting angles to a height of 5.5 feet can have some meaningful impact (percent differences ranged from 3.0 percent to 4.8 percent) on appraisals.

At ages 20 and 30, for the Optimistic prices and when projecting angles to a height of 6.0 feet, "missing" trees resulted in underestimating economic value close to $80 and $130 per acre, respectively. The reductions ranged from 4.5 percent to 7.1 percent of the correct economic value at breast height. These economic underestimates may not appear serious, but if a 30-year-old stand is 50 acres, economic value will be underestimated by about $6,450 (based on the yield tables used). Across 100 such stands, this underestimate would be $645,000. Thus, consistently projecting horizontal angles to heights other than breast height when breast height is desired (and thus is used to calculate expansion factors) across time can result in significant losses or gains (depending on your perspective) in timber valuation/appraisal.

Simulations of 700 Trees per Acre at Age 15 on Site Index 70 Sites (Base Age 25)

For a survival of 700 seedlings per acre at age 15, at ages of both 20 and 30, on average based on basal area estimates, close to one tree at each sample point for a 10 BAF prism was incorrectly not sampled while for a 20 BAF prism about half a tree was incorrectly not sampled when projecting horizontal angles to a height of 6.0 feet (table 5). Projecting angles to a height of 5.0 feet has a relatively minimal impact on economic value (percent differences ranged from 1.7 percent to 2.6 percent) but projecting angles to a height of 5.5 feet can have some meaningful impact (percent differences ranged from 3.4 percent to 5.1 percent) on appraisals.

At age 20, when using the Optimistic prices and when projecting angles to a height of 6.0 feet, "missing" trees resulted in underestimating economic value close to

Table 3—Impact on basal area and economic value per acre estimates when incorrectly projecting horizontal angles to a height of 5.0 feet, 5.5 feet, or 6.0 feet (rather than 4.5 feet) for two sets of product revenues at age 20 and 30 when 200 trees per acre are surviving at age 15

			Average revenue per acre ($)							
			Poor price				Optimistic price			
Age	Angle height (feet)	Average BAA estimate	Pulp	Chip	Saw	Total	Pulp	Chip	Saw	Total
						BAF 10				
20	4.5	41.5	232.55	32.96	1.97	264.01	465.10	54.93	3.86	517.10
	5.0	40.4	226.78	32.50	1.92	257.42	453.57	54.16	3.76	504.08
	5.5	39.3	221.47	31.96	1.90	251.13	442.95	53.27	3.72	491.69
	6.0	38.4	216.64	31.64	1.88	245.51	433.28	52.73	3.68	480.59
						BAF 20				
20	4.5	46.1	259.08	38.15	2.04	265.34	518.16	63.58	4.00	519.34
	5.0	45.2	253.74	38.01	2.04	258.33	507.48	63.35	3.99	505.45
	5.5	44.3	248.94	37.74	2.06	251.85	497.88	62.90	4.02	492.67
	6.0	43.6	244.63	37.57	2.03	245.91	489.26	62.62	3.97	480.91
						BAF 10				
30	4.5	67.6	248.88	268.97	244.20	761.23	497.76	448.28	477.78	1422.30
	5.0	66.3	243.56	264.62	241.35	748.71	487.12	441.04	472.21	1398.82
	5.5	65.1	238.57	260.60	238.83	737.09	477.15	434.33	467.27	1377.05
	6.0	64.0	233.57	256.72	236.35	725.66	467.13	427.87	462.42	1355.60
						BAF 20				
30	4.5	70.0	256.81	279.29	254.96	767.81	513.61	465.48	498.83	1434.49
	5.0	68.8	251.49	276.62	251.88	755.55	502.98	461.04	492.80	1411.17
	5.5	67.7	246.49	273.66	249.14	743.45	492.97	456.09	487.44	1388.27
	6.0	66.7	241.81	270.92	246.71	732.36	483.61	451.53	482.70	1367.29

BAA is basal area in square feet per acre. Site index (base age 25) is 50 feet.

Table 4—Impacts on basal area and economic value per acre estimates when incorrectly projecting horizontal angles to a height of 5.0 feet, 5.5 feet, or 6.0 feet (rather than 4.5 feet) for two sets of product revenues at age 20 and 30 when 400 trees per acre are surviving at age 15

			Average revenue per acre ($)							
			Poor price				Optimistic price			
Age	Angle height (feet)	Average BAA estimate	Pulp	Chip	Saw	Total	Pulp	Chip	Saw	Total
						BAF 10				
20	4.5	88.4	493.78	108.50	10.20	612.47	987.55	180.83	19.95	1188.33
	5.0	86.1	481.23	106.43	10.06	597.71	962.45	177.38	19.68	1159.51
	5.5	83.9	468.90	104.66	9.81	583.36	937.80	174.43	19.19	1131.42
	6.0	81.8	457.01	103.07	9.58	569.64	914.03	171.78	18.74	1104.51
						BAF 20				
20	4.5	88.5	489.73	111.82	10.50	611.17	979.47	186.37	20.54	1184.66
	5.0	86.2	477.09	111.41	10.29	597.78	954.18	185.68	20.14	1158.05
	5.5	84.0	465.56	110.67	9.98	585.07	931.13	184.45	19.52	1132.89
	6.0	81.9	455.07	108.83	9.83	572.51	910.14	181.39	19.23	1108.39
						BAF 10				
30	4.5	126.0	442.45	504.23	518.19	1464.86	884.89	840.38	1013.84	2739.12
	5.0	123.7	433.09	496.28	512.23	1441.60	866.18	827.14	1002.19	2695.50
	5.5	121.5	424.16	489.95	505.02	1419.13	848.31	816.58	988.08	2652.98
	6.0	119.4	415.06	484.10	497.82	1396.98	830.13	806.83	974.00	2610.96
						BAF 20				
30	4.5	126.1	442.85	502.36	521.42	1466.38	885.71	837.27	1020.17	2742.68
	5.0	123.8	432.11	498.83	513.88	1444.58	864.21	831.39	1005.41	2700.56
	5.5	121.6	422.07	495.20	505.84	1422.81	844.13	825.33	989.69	2658.61
	6.0	119.6	413.87	489.45	498.75	1401.73	827.73	815.75	975.82	2618.67

BAA is basal area in square feet per acre. Site index (base age 25) is 70 feet.

Table 5—Impacts on basal area and economic value per acre estimates when incorrectly projecting horizontal angles to a height of 5.0 feet, 5.5 feet, or 6.0 feet (rather than 4.5 feet) for two sets of product revenues at age 20 and 30 when 700 trees per acre are surviving at age 15

			Average revenue per acre ($)							
			Poor price				Optimistic price			
Age	Angle height (feet)	Average BAA estimate	Pulp	Chip	Saw	Total	Pulp	Chip	Saw	Total
					BAF 10					
20	4.5	123.6	668.95	91.51	7.92	768.38	1337.90	152.51	15.50	1505.91
	5.0	120.0	650.47	89.98	7.86	748.31	1300.93	149.97	15.38	1466.28
	5.5	116.5	633.09	88.60	7.79	729.49	1266.18	147.67	15.24	1429.10
	6.0	113.3	616.68	87.29	7.70	711.67	1233.36	145.48	15.07	1393.91
					BAF 20					
20	4.5	123.5	672.52	88.17	8.51	768.96	1345.05	146.95	16.65	1508.17
	5.0	119.8	655.88	87.09	8.44	751.14	1311.77	145.14	16.52	1472.90
	5.5	116.4	639.58	85.77	8.26	733.35	1279.16	142.95	16.17	1437.76
	6.0	113.2	624.41	84.75	8.21	717.08	1248.83	141.25	16.06	1405.58
					BAF 10					
30	4.5	170.7	666.82	628.96	536.13	1831.91	1333.64	1048.27	1048.95	3430.86
	5.0	167.3	652.10	618.17	530.28	1800.55	1304.20	1030.28	1037.50	3371.98
	5.5	164.0	638.00	607.34	524.91	1770.25	1276.00	1012.24	1027.00	3315.23
	6.0	160.9	624.13	597.55	519.24	1740.91	1248.25	995.91	1015.90	3260.07
					BAF 20					
30	4.5	170.0	671.27	608.40	543.27	1822.94	1342.55	1014.01	1062.91	3419.47
	5.0	166.6	657.07	598.20	536.40	1791.67	1314.15	997.00	1049.47	3360.62
	5.5	163.4	643.60	587.82	530.32	1761.74	1287.21	979.70	1037.58	3304.48
	6.0	160.4	630.88	577.63	524.69	1733.21	1261.77	962.72	1026.57	3251.06

BAA is basal area in square feet per acre. Site index (base age 25) is 70 feet.

$100 per acre while at age 30 the reduction resulted in underestimating economic value close to $170 per acre. The percent reductions ranged from 4.9 percent to 7.4 percent of the correct economic value at breast height. If a 30-year-old stand is 50 acres economic value would be underestimated by about $8,500 (based on the yield tables used). Across 100 such stands, this underestimate would be $850,000.

DISCUSSION

In practice, most foresters will not consistently project horizontal angles to 6.0 feet. However, even when projecting horizontal angles to 5.0 feet, across time, significant differences in economic values will be observed. For instance, at age 30, when using a 20 BAF and the Optimistic prices for a site with 400 seedlings per acre surviving at age 15 (table 4), across 100 such 50-acre stands, projecting horizontal angles to a height of 5.0 will produce a difference of around $215,000 as compared to projecting horizontal angles to breast height. For a stand with 700 seedlings per acre surviving at age 15 (table 5), and at age 30, a difference of around $295,000 would be observed.

Differences in stand-level estimates among the horizontal angle heights occur because some trees that should be sampled when projecting an angle to 4.5 feet are not, and because for those trees that are sampled when projecting horizontal angles to heights of 5.0, 5.5, and 6.0 feet, the corresponding trees per acre expansion factor is incorrect. Due to taper, and since all expansion factors in the sample are based on breast height, the expansion factors are smaller than what they should be based on the probability of sampling at heights of 5.0, 5.5, and 6.0 feet (resulting in underestimates). If the proper expansion factor is calculated for all trees sampled at heights of 5.0, 5.5, and 6.0 feet, the stand-level estimates are identical to those obtained at breast height. However, in the field, foresters are not going to measure the correct diameter for a particular horizontal angle height and thus in the field we foresters make the simplifying assumption that all horizontal angles are projected to breast height. The assumption that horizontal angles will always be projected to exactly breast height by a forester is rather ambitious. However, understanding the economic impacts of incorrectly projecting horizontal angles will help to ensure that trees are correctly sampled at the desired 4.5 feet height.

Longleaf pine plantations were chosen because they are relatively easy to project. Obviously, taper rates could have a substantial impact on economic values; in general we expect relatively low rates of taper in pine plantations (especially newer generation genetic stock), but in other stand types taper rates can differ substantially. Stand densities could have an impact, plantation rectangularity could be a factor, the presence of hardwoods or wildling pines would also be a factor, as well as the level of “clumpiness” in stands.

Substantial differences in stand-level variable estimates in the same stand due to the use of different BAFs have been observed (Husch 1955, Wiant and others 1984), most likely resulting from incorrectly determining whether a tree should be sampled. For this examination, it is assumed there is no error associated with correctly determining whether trees are “in” or “out” for a particular sampling height. However, in reality, foresters often do not correctly measure ground distances, sites are not on level ground and thus foresters fail to account for slope, and oftentimes foresters fail to check every borderline tree.

CONCLUSIONS

This present study demonstrates that failing to identify which trees to sample when conducting point-sampling can have a substantial impact on the valuation/appraisal of stands. These errors can lead to under/over bidding on timber tracts, can result in incorrect decisions about the economic feasibility of conducting various management practices, and can lead to making poor management decisions in general.

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PRELIMINARY EVALUATION OF PRICE PREMIUM REQUIRED FOR GROWING HIGHER QUALITY LOBLOLLY AND SLASH PINES ON EXTENDED ROTATION AGES

Arun Regmi, Donald L. Grebner, Robert K. Grala, and John L. Willis

Abstract—Pine (*Pinus* spp.) plantations in the Southeastern United States are managed intensively following even-aged silviculture. Trees are harvested at young ages resulting in inferior wood quality. We modeled two fast-growing southern pines using the Forest Vegetation Simulator to determine the price premium that forest landowners need to grow higher quality pines on longer rotation ages. Different management regimes were optimized using a land expectation value maximization approach. Results suggested that delaying final harvest by 10 years is financially obtainable, while a 20-year rotation extension depends on demand of higher quality sawtimber. In addition, rotation extension more than 30 years is financially undesirable. This study serves as a basic resource for primary forest product industries interested in purchasing higher quality pine sawtimber.

INTRODUCTION

The Southeastern United States has extensive pine plantations. These plantations are primarily managed with even-aged silviculture through extensive use of clearcutting (Allen and others 2005). Among southern pines, loblolly pine (*Pinus taeda* L.) is the most commercially dominant species, and this forest type has increased over time due to tree planting (South and Harper 2016). Over the past few decades, pine plantations have been harvested at shorter rotation ages—currently, most are generally less than 30 years—to ensure optimal economic returns (Jokela and others 2010, Miller and others 2009). The application of genetically improved seedlings along with advanced silvicultural treatments such as mechanical and chemical site preparation, herbicide treatment, fertilization, competition control, mid-rotation brush control, and thinnings are key reasons for the higher productivity of pine plantations (Allen and others 2005, Fox and others 2007). Higher productivity in short periods (Fox and others 2007, Zhao and others 2016) helps to successfully recover high establishment costs and other initial investments (Guldin 2019). In addition, short rotation harvests can generate large amounts of wood fiber, which is attractive to many forest landowners (Fox and others 2007).

But at what cost has this improved productivity come? Can this improved productivity fulfill the preferences of a diverse group of wood users (e.g., sawmill, veneers mills) who prefer larger, quality sawlogs? Although revenue from intensively managed forests has increased dramatically over time, it has adversely affected sawtimber quality (Zobel 1984), as shown by several past studies which reported the negative consequences of short rotation harvests on wood quality (Barbour and others 2003, Dobner and others 2018, Larson and others 2001, Zobel 1984). Shorter rotations have led to the production of relatively small sawlogs from smaller, younger trees (often 12-16 inches small-end diameter). Trees harvested earlier tend to have a higher proportion of juvenile wood compared to older, mature wood (Larson and others 2001). Larger, older trees can produce larger, higher quality sawlogs with a lower proportion of juvenile wood content (Bendtsen and Senft 2007, Biblis and Carino 2002, MacPeak and others 1990, Zobel and others 1972). Juvenile wood is considered relatively undesirable for manufacturing solid wood products because of lower stiffness and lower strength compared to mature trees (Bendtsen and Senft 2007, Clark and others 2007, Larson and others 2001).

Increasingly shorter harvest rotations have also resulted in shortages of large-diameter pine sawlogs in local solid wood markets. This may prove challenging, given that research shows that recent improvement in the housing sector has positively affected softwood lumber consumption (Howard and others 2017, Wear and others 2016). Since home construction requires higher grades of lumber, increasing construction may raise the demand for high value lumber in the future. In addition, continuous production of relatively small-sized sawlogs for wood fiber and woody biomass has increased overall

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wood supply, resulting in less demand and decreased prices for pine pulpwood. In this situation, many forest landowners may wait to cut their trees, expecting a higher price for their wood as sawtimber. Furthermore, there are still some landowners who are concerned over forest-derived ecological benefits and are interested in managing their forests for both ecological and economic benefits. Landowners often manage their forests to achieve multiple objectives including wildlife habitat, carbon sequestration, aesthetics, and recreational opportunities (Grebner and others 2015, Kluender and Walkingstick 2000). The increasing focus on timber production from short rotation pine plantations may adversely affect a variety of ecosystem services associated with older forests such as wildlife habitat, carbon sequestration, aesthetics, and water quality.

While managing forests for higher quality pine sawtimber can help achieve a landowner's multiple management objectives, there is a lack of information on the economic trade-off of postponing final harvest to grow higher quality pines. Although past studies have conducted financial analyses on longer rotation management, they were primarily focused on non-timber benefits. Few of these studies looked at economic trade-offs of managing pine plantations on longer rotation ages to produce higher quality wood. Several have focused on economic valuation of different management regimes of southern pines, using a land expectation value (LEV) maximization approach to identify the optimal regime. Research focusing solely on maximizing timber production suggests using shorter rotations for higher financial benefits (Jones and others 2010, Mills and Stiff 2013). Others have considered joint management of pine plantations for timber production and wildlife habitat and evaluated the economic trade-off of alternative management regimes (Barlow and others 2007, Davis and others 2017, Huang 2009). This research concluded that forest landowners need to be incentivized for the forgone timber revenue by adopting alternative management strategies, as wildlife-friendly management lengthened the rotation ages and reduced the LEV. Still others have evaluated economic trade-offs of managing pine forests for carbon sequestration (for example, Foley and Galik 2009, Sohngen and Brown 2008). Several have considered the impact of carbon payments in optimal harvest age or rotation ages (Alavalapati and Stainback 2005, Susaeta and others 2014, van Kooten and others 1995), while others have examined the financial profitability of pine plantations for carbon sequestration (Dwivedi and others 2009, Huang and Kronrad 2006). Their collective work suggests that a longer rotation is economically feasible for the joint management of timber and carbon sequestration, but forest landowners need carbon payments to lengthen the optimal final harvest age.

To address this knowledge gap, the objective of this study is to evaluate the price premium required to grow higher quality southern pines on longer rotation ages across the Lower Coastal Plain and flatwood regions of Southeastern United States.

MATERIALS AND METHODS

We used the Forest Vegetation Simulator (FVS) from the Forest Service, U.S. Department of Agriculture to simulate pine stands. Since the FVS model uses national forests as reference locations, we chose the Desoto National Forest in Mississippi as a study location. Desoto National Forest is in the "232" ecoregion (the Lower Coastal Plain and Coastal Flatwoods) (Bailey 1995). As this ecoregion spreads from South Carolina to eastern Texas, results from this study should be broadly applicable to other Southeastern States covered by the Lower Coastal Plain and Coastal Flatwoods ecoregion.

Management Scenarios

Two fast-growing southern pines, loblolly and slash (*Pinus elliottii* Engelm.), were simulated for different management regimes across a range of site indices and planting densities. Average site index (SI) for a study site was assumed to be 90 feet (base age 50 years). In addition, we used SI 80 and SI 100 to see the impact of site quality on analyses. Simulations were started from a "bareground" condition using initial planting densities (spacings) of 622 (7 feet by 10 feet), 544 (8 feet by 10 feet) and 435 (10 feet by 10 feet) trees per acre (TPA) (Londo and others 2008). We assumed bareroot seedling survival rate to be 90 percent, following chemical and mechanical site preparation and then a banded herbaceous weed control at 1 year post-planting.

All management regimes were thinned from below based on Reineke's Stand Density Index (SDI) target (Reineke 1933), which involved thinning stands to 35 percent of maximum SDI when they reached 55 percent of maximum SDI. This technique was applied to avoid possible density-dependent tree mortality after 55 percent of maximum SDI and maintain full site occupancy to promote the growth of quality trees and reduce unnecessary competition with unwanted species (Dean and Chang 2002). We assumed maximum SDIs of 450 for loblolly pine and 400 for other pines. Upper limits of SDI were set at 247 and 220 (55 percent of maximum SDI) where competition starts, and lower limits were set at 157 and 140 (30 percent of maximum SDI) to ensure full occupancy, for loblolly and slash pines, respectively. A maximum of two thinnings were used and the interval between two successive thinnings and final harvest was at least 5 years. Mid-rotation brush control was carried out 2 years post-thinning to limit competition of unwanted vegetation.

Financial Analysis

We used price data of pine products from TimberMart-South (2013-2018) (table 1). Table 2 presents costs (Maggard and Barlow 2017) for each management practice used in simulations. We used the LEV maximization method to determine financially optimal management regimes for each species. The structural form of the LEV equation (1) is:

$$\text{LEV} = \frac{\text{NFV}}{(1+r)^n - 1} \qquad (1)$$

where NFV is net future value at rotation age, *n* is the length of rotation, *r* is the real discount rate in decimal percent. The LEV difference between the optimal LEV and LEV at extended rotation ages were then calculated from equation (2):

$$\text{LEV Diff} = \text{Optimal LEV} - \text{LEV}_n \qquad (2)$$

where LEV_n is LEV at 10, 20 or 30 years beyond the optimal LEV. Periodic compensation (PC) was then converted into an annual compensatory rate for respective rotation extension periods (*n* = 10, 20, and 30 years):

$$\text{Annual compensatory rate} = \frac{\text{PC} \times i(1+r)^n}{(1+r)^n - 1} \qquad (3)$$

Sawtimber stumpage price (4) required at extended rotation ages (SP_E) to justify the final harvest delay was calculated using an equation further derived from equation (1):

$$\text{SP}_E\ (\$) = \frac{\text{LEV}[(1+r)^n - 1] + \text{FV}_C - \text{FV}_{R(\text{pulp+CNS})}}{\text{V}_{\text{sawtimber}}} \qquad (4)$$

where LEV at an optimal rotation age, *n* is extended rotation ages, FV_C is future value of costs at year *n*, FV_R is future value of revenues from pulp and chip-n-saw at *n*, and $\text{V}_{\text{sawtimber}}$ is sawtimber volume (tons) at year *n*. Price premiums for growing higher quality pines on extended rotation ages were determined by simply subtracting current market stumpage prices (SP_C) from SP_E (5):

$$\text{Price premium } (\$) = \text{SP}_E - \text{SP}_C \qquad (5)$$

The financially optimal management regimes with maximum LEV were identified for both pine species. LEVs at 10, 20 and 30 years beyond the financially optimal rotation age were then calculated for quantifying compensation rates and price premiums necessary to justify growing higher quality southern pines.

Sensitivity Analysis

A sensitivity analysis to assess the impact of different factors on LEV and price premium evaluation was calculated. We used three discount rates: 3 percent, 5 percent, and 7 percent; three different site indices; and three different planting densities for sensitivity analysis.

RESULTS AND DISCUSSION

To make this analysis simpler to understand, results for the average site at 3 percent discount rates are discussed in detail. Our results (table 3) from the financial analysis of loblolly and slash pine indicated that all combinations of site index and discount rates produced positive LEVs. On an average site of SI 90 with a 3 percent discount rate, the financially optimal rotation age was found at age 34 (LEV of $2133.54 per acre) for loblolly pine and at age 38 (LEV of $1534.52 per acre) for slash pine. Compensatory rates for delaying the final harvest by 10, 20, and 30 years for growing higher quality pines were $26.23 per acre, $39.68 per acre, and $48.16 per acre for loblolly pine, and $22.87 per acre, $30.19 per acre, and $36.69 per acre for slash pine, respectively. Similarly, required price premiums to justify the rotation extension were $2.89 per ton, $9.44 per ton, and $19.56 per ton for loblolly pine, and $3.39 per ton, $9.35 per ton, and $19.50 per ton for slash pine, respectively, for 10-, 20-, and 30-year rotation extensions.

Table 1—Specifications and average stumpage prices ($/ton) of pine products from 2013 through 2018 across the Southeastern United States

Product	d.b.h.	Price
	inches	*U.S.$/ton*
Pulpwood	6-7	9.93
Chip-n-saw	8-11	17.15
Sawtimber	12 & up	24.72

Source: TimberMart-South 2013-2018.

Table 2—Silvicultural practices, timing, and costs for all management scenarios of four pines

Practice	Cash flow (U.S.$/acre)	Year
Mechanical site preparation	140.99	0
Chemical site preparation	78.96	0
Site preparation burning	25.01	0
Per seedling cost	0.12	
Planting labor cost	60.41	0
Banded herbaceous weed control	57.11	1
Mid-rotation release	62.12	2 years post thin

Source: Maggard and Barlow 2017.

Table 3—Financially optimal LEV (U.S. $/acre), compensatory rates (U.S. $/acre/year) and price premiums (U.S. $/ton) for growing higher quality loblolly and slash pines on longer rotation ages on different site index and discount rates at planting density 544 trees per acre

Pine species	Site Index 100				Site Index 90				Site Index 80			
Discount rate	Optimal	10-year	20-year	30-year	Optimal	10-year	20-year	30-year	Optimal	10-year	20-year	30-year
Loblolly pine												
3%												
Harvest years	15, 22, 34	44	54	64	16, 24, 34	44	54	64	17, 25, 40	50	60	70
LEV	2585.91	2214.86	1806.95	1354.23	2133.54	1909.78	1543.22	1189.67	1604.34	1363.86	1099.64	797.96
LEV difference		371.05	778.96	1231.69		223.76	590.32	943.87		240.48	504.70	806.38
Compensatory rates		43.50	52.36	62.84		26.23	39.68	48.16		28.19	33.92	41.14
Price premium		4.24	10.95	23.27		2.89	9.44	19.56		4.05	10.42	22.38
5%												
Harvest years	15, 22, 32	42	52	62	16, 24, 33	43	53	63	17, 25, 35	45	55	65
LEV	912.37	693.84	459.25	265.52	672.85	531.10	327.53	175.89	434.48	336.92	184.92	57.27
LEV difference		218.54	453.12	646.85		141.74	345.32	496.95		97.57	249.56	377.21
Compensatory rates		28.30	36.36	42.08		18.36	27.71	32.33		12.64	20.03	24.54
Price premium		6.66	19.64	42.87		5.06	17.77	37.92		4.32	15.46	35.12
Slash pine												
3%												
Harvest years	15, 23, 35	45	55	65	17, 25, 38	48	58	68	19, 27, 41	51	61	71
LEV	2049.07	1728.99	1392.35	1056.15	1534.52	1339.40	1085.33	815.38	1109.32	978.11	773.88	566.10
LEV difference		320.09	656.72	992.92		195.12	449.18	719.14		131.21	335.44	543.23
Compensatory rates		37.52	44.14	50.66		22.87	30.19	36.69		15.38	22.55	27.72
Price premium		4.45	11.30	22.37		3.39	9.35	19.50		2.79	8.57	17.90
5%												
Harvest years	15, 23, 33	43	53	63	17, 25, 36	46	56	66	19, 27, 38	48	58	68
LEV	662.31	484.48	289.86	143.46	404.22	296.56	156.50	40.05	214.80	136.51	25.40	-61.38
LEV difference		177.83	372.45	518.85		107.66	247.72	364.17		78.29	189.40	276.18
Compensatory rates		23.03	29.89	33.75		13.94	19.88	23.69		10.14	15.20	17.97
Price premium		6.69	20.04	41.66		5.34	16.73	36.90		4.90	16.16	34.13

LEV = land expectation value.

As expected, LEV and compensatory rates increased as site index increased, which has been reported in previous studies (Barlow and others 2007, Carley and Grado 2000, Davis and others 2017). This trend holds true because higher productivity sites yield more wood than lower productivity sites. Therefore, the highest compensatory rates were found on high quality sites while lowest were found on lower quality sites. Consistent with previous studies, our results also indicated that the discount rate was another influential factor, as LEV and compensatory rates decreased as the discount rate increased (due to the time value of money). The effect of discount rates was higher on yield received in later years as it was discounted heavily compared to yield received earlier in rotation ages, and this effect increased with discount rates. Among three planting density levels, medium planting density (544 TPA) was financially optimal for all possible management regimes of both pine species.

Conversely, we found that price premium increased with an increase in discount rates. This could be due to the proportion of sawtimber volume, as we calculated the premium for sawtimber only. An increase in the discount rate led to a decrease in rotation age which resulted in production of lower sawtimber volume and higher chip-n-saw volume. Therefore, more premium was needed to justify the revenue loss. This implies that forest landowners could receive higher price premiums at higher discount rates with less revenue loss.

Our results indicated that, both loblolly and slash pines had nearly similar compensatory and price premium values for all site index and discount rates. For both species, price premium for a 10-year rotation extension ranged from $2.79 per ton to $6.69 per ton while it ranged from $8.57 per ton to $20.04 per ton for 20-year rotation extension. This shows that delaying the harvest age by 10 years is obtainable while more than 10 years may depend on buyers' interest. However, at lower interest rates, the price premium for delaying final harvest by 10 and 20 years was below $11 per ton, which may attract buyers. Given the discount rates and site index, a 30-year rotation extension might not be preferred by buyers because price premium rates are almost 100 percent and more than the existing market price for southern pine sawtimber.

CONCLUSIONS

Overall, the objective of this study was to evaluate the price premium that forest landowners required for growing higher quality loblolly and slash pines on longer rotation ages. The LEV maximization approach was used to conduct a comparative analysis of different management regimes. Our results suggested that growing higher quality pines by extending the harvest age is economically feasible; however, forest landowners would probably need to be incentivized to do so. Price premiums varied according to discount rates and rotation extension periods. Delaying the final harvest by 10 years required a considerably lower price premium, with significant increases realized by extending the rotation by another 10 or 20 years. Indeed, the price premium for 30-year rotation extension was 100 percent (or more) of the existing sawtimber stumpage price, suggesting a 30-year rotation extension may be financially undesirable for most. This study serves as a basic resource for primary forest product industries interested in acquiring higher quality pine sawtimber and forest landowners interested in the economic impacts of applying alternative management practices to their forests.

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A MIXED-EFFECTS HEIGHT-DIAMETER MODEL FOR LONGLEAF PINE PLANTATIONS IN NORTHERN FLORIDA AND GEORGIA

Curtis L. VanderSchaaf and T. Eric McConnell

Abstract—A mixed-effects height-diameter model is presented for longleaf pine (*Pinus palustris* P. Mill.) plantations in northern Florida and Georgia. After obtaining height-diameter measurements from a plot/stand of interest, this mixed-effects model can be calibrated to produce localized individual tree height estimates. Based on model calibration of independent data from South Carolina, the use of three or four longleaf pine trees from a plot to calibrate the model provides a reasonable compromise between predictive ability and field sampling time. If calibrated at the stand-level, three trees could be used, but larger sample sizes of 10 or 15 would likely produce more accurate estimates. To calibrate these models for specific plots/stands, an Excel spreadsheet is available on request.

INTRODUCTION

Height (H)-diameter (D) models are an integral component of forest inventories used to reduce sampling times. Mixed-effects H-D models have been developed for many species. The advantages and rationale behind using mixed-effects H-D models is provided in this publication and others (Calama and Montero 2004; Lynch and others 2005; Trincado and others 2007; VanderSchaaf 2012, 2013, 2014). Longleaf pine (*Pinus palustris* P. Mill.) plantations are an important forest type in northern Florida and Georgia. There are 593,267 acres of longleaf pine plantations, fairly evenly distributed among both States. To increase the efficiency of forest inventories in longleaf pine plantations in northern Florida and Georgia, an individual tree mixed-effects H-D model was developed.

METHODOLOGY

Data Used in Model Fitting

The data used in model development were obtained from the U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) annual surveys completed between 2011 and 2015. Survey data were obtained from all forested regions of Florida and Georgia. Data were obtained from the FIA database website (O'Connell and others 2017, USDA Forest Service 2017). Plots were clusters of four points arranged such that point 1 was central, with points 2 through 4 located 120 feet from point 1 at azimuths of 0, 120, and 240 degrees (Bechtold and Scott 2005). Each cluster point was surrounded by a 24-foot fixed-radius subplot where trees 5.0 inches in diameter at breast height (d.b.h.) and larger were measured. Combined, the four subplots totaled approximately 0.17 acres. Each subplot contained a 6.8-foot fixed-radius microplot where saplings (1.0-4.9 inches d.b.h.) were measured. The four microplots totaled approximately 0.01 acres. Each plot was only measured once; hence, there were no concerns about repeated measures or serial correlation.

Since trees with a d.b.h. of 5 inches or larger have a greater probability of being sampled, there is an increase in the number of trees relative to smaller diameters (fig. 1). Data from only those plots where longleaf pine comprised at least 60 percent of the total basal area were included in the model fitting dataset. A value of 60 percent basal area was selected to help reduce the inclusion of "wildlings," which are pine trees that were not planted, in the model fitting and validation analyses. Additionally, a value of 60 percent basal area reduces the impacts of hardwoods on the H-D relationships and hence produces more uniformity in H estimates when used operationally in appropriate plantations. Only H and D measurements of longleaf pine were modeled. Individual tree and plot-level summary data are presented in tables 1 and 2.

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Figure 1—Height-diameter relationship for the model fitting dataset (*n* = 818 trees).

Table 1—Tree-level summary statistics of trees used in model fitting and model calibration/validation

		Diameter (inches)				Height (feet)			
Model	*n*	Minimum	Mean	Maximum	SD	Minimum	Mean	Maximum	SD
Fit	818	1.1	6.7	17.9	2.04	10	44	88	13.9
Validation	938	1.2	6.5	20.1	1.84	9	40	83	9.9

SD is standard deviation, *n* is number of trees.

Table 2—Model fitting and validation plot-level means

		Species of interest			Other species		
Model	Number of plots	TPA	D_q	BAA	TPA	D_q	BAA
Fit	45	221	5.9	36	134	4.6	7
Validation	27	422	5.4	68	155	4.1	14

TPA = trees per acre, D_q = quadratic mean diameter (inches), and BAA = square feet of basal area per acre.

Species of interest refers to plot-level summary statistics for longleaf pine used in fitting the height-diameter equations. Other species refers to hardwoods as well as other conifers.

Model Development and Parameter Estimation

Total tree height was predicted as a function of diameter at breast height:

$$\ln H_{ki} = (\beta_0+u_{0k})+(\beta_1+u_{1k})\ln D_{ki} + \varepsilon_{ki} \qquad (1)$$

where

ln = natural logarithm,
H_{ki} = individual tree total height (feet) for tree *i* within plot (or stand) *k*,
D_{ki} = individual tree diameter at breast height (inches) for tree *i* within plot (or stand) *k*,
β_0, β_1 = parameters to be estimated,
u_{0k}, u_{1k} = plot/stand-specific random effects, assumed to be $N(0, \sigma^2_0)$ and $N(0, \sigma^2_1)$, respectively,
(β_0+u_{0k}) = plot/stand-specific intercept,
(β_1+u_{1k}) = plot/stand-specific slope, and
ε_{ki} = random error where it is assumed $\varepsilon \sim N(0, \sigma^2 I)$.

Additionally, a covariance, σ_{01}, can be assumed to exist between u_{0k} and u_{1k}. Linear mixed-effects models, in this particular case, produce an efficient estimate of plot/stand-specific parameters because only six parameters are estimated using the model fitting algorithm $(\beta_0,\beta_1,\sigma^2{}_0,\sigma^2{}_1,\sigma_{01},\sigma^2)$.

Based on the variance and covariance estimates, plot/stand-specific random effects (u_{0k}, u_{1k}) can be predicted and then added to the "population average" intercept and slope (β_0, β_1) estimates to obtain plot/stand-specific parameter estimates. Plot/stand-specific random parameters produce a more localized H-D equation since the random effects account for local site conditions such as soil type, genetic stock, site preparation, mid-rotation silvicultural practices, spatial and time-specific climatic conditions, etc. The prediction of plot/stand-specific random effects is conducted outside the model fitting algorithm and thus degrees of freedom are not lost due to specific plot/stand random effects. In terms of model fitting, a less efficient method of obtaining plot-specific parameter estimates would be to estimate parameters separately for each plot using ordinary least squares or weighted least squares.

Although the parameter estimation efficiency of mixed models is an advantage, the greatest advantage often is the ability to calibrate the model using data independent of those used in model fitting. Hence, for trees from plots/stands not in the model fitting dataset, plot/stand-specific H-D relationships can be produced if H and D observations have been collected from trees in that plot/stand.

When compared to the traditional means of developing local H-D equations, where H and D are measured and then a separate equation is fit for a stand (or in some cases a plot), a mixed-effects model analysis is efficient because a model can be calibrated without having to statistically fit a model and thus even small sample sizes can be used (Lynch and others 2005). In many cases, fixed-effects region-wide H-D equations are used to predict tree heights. To account for growing condition differences among stands for the same species, in addition to D, these models contain measures of site quality and/or stand density, among others. Studies have shown that a calibrated mixed-effects H-D model often produces better predictions than a region-wide H-D model containing stand-level regressors (Huang and others 2009, Temesgen and others 2008, Trincado and others 2007). Mixed-effects models fit using plot-level data can also be calibrated at the plot-level during operational inventories, providing more localized H-D relationships within a stand.

The objective was to measure H on every tree but occasionally due to various reasons, H was not directly measured. Only trees whose heights were actually measured (as opposed to visually estimated or predicted using equations) were used in model fitting. Parameters of equation (1) were estimated using SAS Proc MIXED (Littell and others 1996) which assumes random errors are normally distributed and subsequently estimates parameters using maximum likelihood. To reduce complexity in model application, no attempt was made to include spatial correlation in the models. The random error covariance-variance matrix was assumed to be $\sigma^2 I_{nk}$.

Data Used in Model Calibration

To gain insight into the optimal calibration sample size, independent FIA survey data from South Carolina obtained from 2012 to 2016 were used. Individual tree and plot-level summary data are presented in tables 1 and 2.

A minimum sample size of 10 trees per plot was selected. Hence, a plot had to contain at least 12 trees of longleaf pine to be included, in this case 10 trees would be used to calibrate the model and the 11th and 12th trees would be predicted; at least two predicted trees allows for calculation of the variance. Calibration sample sizes of 1, 2, 3, 4, 5, 8, and 10 were examined.

For consistency, the tree used to calibrate the model for a sample size of one was also the first tree for a sample size of two, the two trees used to calibrate the model for a sample size of two were the first two trees for a sample size of three, etc. Calibrations were conducted 50 times for each sample size to avoid the dependence of the calibration results on one particular sample.

Validation analyses follow those presented in Trincado and others (2007). The difference between the observed (H_{obs}) and predicted height (H_{pred}) of all trees (*i*) whose Hs were predicted for each individual plot (*k*) and for each of the 50 replications (r), or each plot (k) and replication (r) combination, was calculated ($e_{kri} = H_{obs\ kri} - H_{pred\ kri}$), trees used in calibration for a particular plot and replication combination were not included in the validation statistic calculations. The mean residual ($\bar{e}$) and the sample variance (v) of residuals were computed and considered to be estimates of bias and precision; respectively. An estimate of mean square error (MSE) was obtained for each combination by combining the bias and precision measures using the following formula:

$$\mathrm{MSE}_{kr} = \bar{e}^2_{kr} + v_{kr} \tag{2}$$

The 50 MSE, $\bar{e}$, and v values of a particular plot for a particular calibration sample size were then averaged to obtain an average value of the three calibration statistics for each plot and sample size. The average plot calibration statistics were then averaged for each calibration sample size to obtain final calibration statistics. To account for the transformation bias, the procedure recommended by Baskerville (1972) was used as described in the calibration example provided below.

RESULTS AND DISCUSSION

Based on the model fitting results (not presented for the sake of brevity), it is best to assume that both β_0 and β_1 are random (or, essentially, that each plot (or stand) has their own intercept and slope) and that a covariance (σ_{01}) exists between u_{0k} and u_{1k}. Table 3 contains parameter estimates and model-fitting statistics. In terms of choosing an optimal model calibration sample size at the plot- or stand-level, a reasonable trade-off between statistical measures (precision and accuracy) and sampling times (e.g., costs) is three or four trees (fig. 2).

Table 3—Population average (β_0 and β_1) and random effects variance (σ^2_0, σ^2_1) and covariance (σ_{01}) parameter estimates

Parameter	Estimate	Standard error
β_0	2.6575	0.08188
β_1	0.5666	0.03464
σ^2_0	0.2475	-
σ^2_1	0.03844	-
σ_{01}	-0.09177	-
-2LL	-1249.3	
AIC	-1241.3	
σ^2	0.009380	
n	45	

-2LL = twice the negative log-likelihood (smaller is better), AIC = Akaike's Information Criterion (smaller is better), σ^2 = estimated mean square error, and n = the number of clusters, or plots.

In a sense, using one tree in calibration allows for the "population average" curve to be moved up and down based on that tree's relationship to the "population average" curve. Figure 3 helps to provide context. The use of two trees in calibration essentially allows for the curve to be moved up and down, as well as a reshaping of the curve, whereas the use of three or more trees will in a sense refine the movement and reshaping of the "population average" curve.

Studies have shown that even the use of only one tree in calibration substantially improves height estimates (Calama and Montero 2004; Huang and others 2009; Temesgen and others 2008; Trincado and others 2007; VanderSchaaf 2012, 2013, 2014). Thus, when calibrating at the plot-level, one tree may suffice. However, if calibrating at the stand-level it may be feasible to use larger sample sizes of 10 or 15 trees.

EXAMPLE OF MODEL CALIBRATION

For clarity and ease of application, the methodology to predict random effects is presented. Nomenclature is based on Schabenberger and Pierce (2002: 431). The expression used to predict random effects, Estimated Best Linear Unbiased Predictors (EBLUPS), is:

$$\hat{\boldsymbol{\mu}}_k = \hat{\mathbf{D}}\mathbf{Z}_k^{\mathbf{T}}(\hat{\mathbf{R}}_k + \mathbf{Z}_k\hat{\mathbf{D}}\mathbf{Z}_k^{\mathbf{T}})^{-1}(\mathbf{y}_k - \mathbf{X}_k\hat{\boldsymbol{\beta}}) \tag{3}$$

where

$\hat{\boldsymbol{\mu}}_k$ = predicted random effects of plot/stand k, a 2 x 1 vector where 2 is the number of predicted random effects,

$\hat{\mathbf{D}}$ = estimated covariance-variance matrix (2 x 2) of the random effects,

$\mathbf{Z}_k$ = random effects matrix (n_k x 2) containing observed values of tree diameter (natural log transformed) from plot/stand k, and a column of 1s,

$\hat{\mathbf{R}}_k$ = estimated covariance-variance random error matrix expressed as $\sigma^2\mathbf{I}_{nk}$ since the variance is assumed constant across all plots/stands and tree heights are assumed temporally and spatially uncorrelated within a plot/stand,

$\mathbf{y}_k$ = n_k x 1 vector of observed heights (natural log transformed) from plot/stand k,

$\mathbf{X}_k$ = regressor matrix (n_k x 2) consisting of a column of 1s and the observed values of tree diameter (natural log transformed) from plot/stand k, and

$\hat{\boldsymbol{\beta}}$ = 2 x 1 vector of estimated fixed-effects parameters.

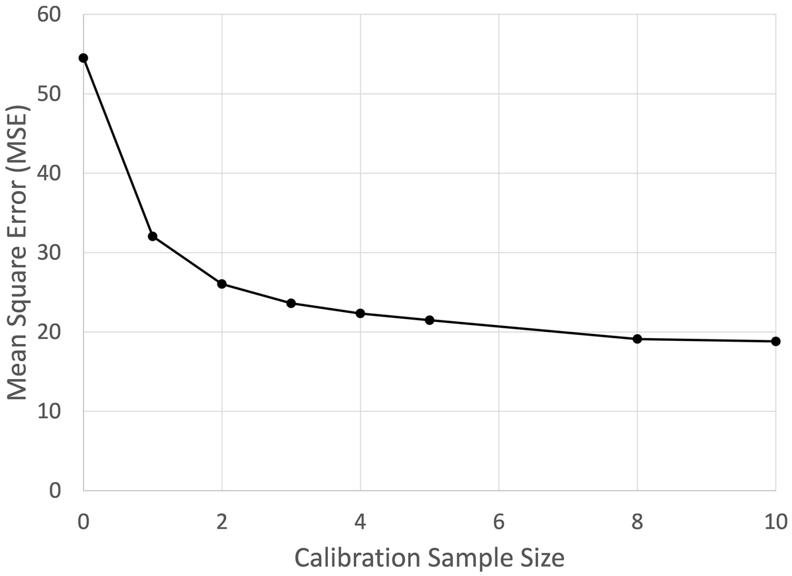

Figure 2—Model calibration mean square error (MSE) results. Calibration sample sizes are the number of trees used in calibration ($n = 27$ plots).

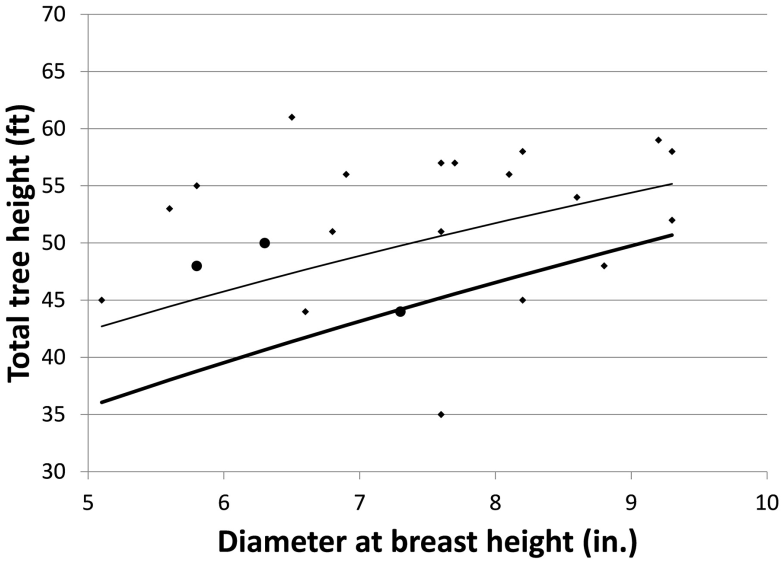

Figure 3—Observed total tree height and diameter at breast height for $n = 22$ trees. This plot resides in Charleston County, SC. The bold solid line is the “population average” estimate obtained by not calibrating equation (1), and the lighter solid line is the estimate following calibration of equation (1) producing equation (6). Black diamonds and black circles are paired height-diameter observations. Black circles were trees used to calibrate equation (1).

To demonstrate model calibration, three individual trees were randomly selected from an individual plot (or stand) to be used in calibration. Heights for the three trees were 48, 50, and 44 feet and the corresponding Ds were 5.8, 6.3, and 7.3 inches, respectively.

$$\mathbf{Z} = \begin{bmatrix} 1 & \ln(5.8) \\ 1 & \ln(6.3) \\ 1 & \ln(7.3) \end{bmatrix} = \begin{bmatrix} 1 & 1.757858 \\ 1 & 1.840550 \\ 1 & 1.987874 \end{bmatrix},$$

$$\mathbf{X} = \begin{bmatrix} 1 & \ln(5.8) \\ 1 & \ln(6.3) \\ 1 & \ln(7.3) \end{bmatrix} = \begin{bmatrix} 1 & 1.757858 \\ 1 & 1.840550 \\ 1 & 1.987874 \end{bmatrix}$$

Besides the column of 1s, all numerical values are lnD (naturally log transformed value of D in inches) for the three observations randomly selected from this particular plot (or stand).

$$\mathbf{y} = \begin{bmatrix} \ln(48) \\ \ln(50) \\ \ln(44) \end{bmatrix} = \begin{bmatrix} 3.871201 \\ 3.912023 \\ 3.784190 \end{bmatrix}$$

$$\hat{\boldsymbol{\beta}} = \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix} = \begin{bmatrix} 2.6575 \\ 0.5666 \end{bmatrix}$$

$$(\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}}) = \begin{bmatrix} 3.871201-(2.6575+0.5666[\ln(5.8)]) \\ 3.912023-(2.6575+0\ 5666[\ln(6.3)]) \\ 3.784190-(2.6575+0.5666[\ln(7.3)]) \end{bmatrix} =$$

$$\begin{bmatrix} 3.871201-3.653502 \\ 3.912023-3.700355 \\ 3.784190-3.783830 \end{bmatrix} = \begin{bmatrix} 0.217699 \\ 0.211668 \\ 0.000360 \end{bmatrix}$$

$$\hat{\mathbf{D}} = \begin{bmatrix} \sigma_0^2 & \sigma_{01} \\ \sigma_{01} & \sigma_1^2 \end{bmatrix} = \begin{bmatrix} 0.2475 & -0.09177 \\ -0.09177 & 0.03844 \end{bmatrix}$$

$$\hat{\mathbf{R}} = \begin{bmatrix} \sigma^2 & 0 & 0 \\ 0 & \sigma^2 & 0 \\ 0 & 0 & \sigma^2 \end{bmatrix} = \begin{bmatrix} 0.00938 & 0 & 0 \\ 0 & 0.00938 & 0 \\ 0 & 0 & 0.00938 \end{bmatrix}$$

All numerical values for $\hat{\mathbf{D}}$, $\hat{\mathbf{R}}$, and $\hat{\boldsymbol{\beta}}$ were obtained from table 3 and were obtained from the model fitting results of equation (1). The dimensions of $\hat{\mathbf{R}}$, $\mathbf{Z}$, $\mathbf{X}$, $\mathbf{y}$, and $(\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})$ will change based on the number of observations used in model calibration.

When performing matrix operations as seen in equation (3), the following predictions of the random effects, EBLUPS, for β_0 and β_1 of this particular plot (or stand) were obtained:

$$\hat{\boldsymbol{\mu}} = \begin{bmatrix} \mu_{0k} \\ \mu_{1k} \end{bmatrix} = \begin{bmatrix} 0.3977 \\ -0.1404 \end{bmatrix}$$

These predicted random effects for this plot (or stand) are added to the "population average" parameter estimates, $\hat{\boldsymbol{\beta}}$, to obtain plot/stand-specific parameter estimates for this particular plot/stand, $\hat{\boldsymbol{\beta}}_{Calibrated}$:

$$\hat{\boldsymbol{\beta}}_{Calibrated} = \begin{bmatrix} \beta_0 + \mu_{0k} \\ \beta_1 + \mu_{1k} \end{bmatrix} = \begin{bmatrix} 2.6575+0.3977 \\ 0.5666-0.1404 \end{bmatrix} = \begin{bmatrix} 3.0552 \\ 0.4262 \end{bmatrix}$$

It is well known that logarithmic transformations often linearize data and produce homogeneity of variances; however, a transformation bias occurs since additive errors in log-log models become multiplicative when transformed back to the original scale. To account for the transformation bias, the procedure recommended by Baskerville (1972) should be used when predicting heights:

$$\ln H_{ki} = (\beta_0+u_{0k}) + (\beta_1+u_{1k})\ln D_{ki} + \sigma^2/2 \qquad (4)$$

where

σ^2 = mean square error (or residual variance) from the model fit (see table 3).

To obtain height predictions in the original units (feet), equation (5) should be used:

$$H_{ki} = \exp^{[\beta 0k + \beta 1k \ln D_{ki} + \sigma 2/2]} \qquad (5)$$

where

$\beta_{0k} = (\beta_0+u_{0k})$ = plot/stand-specific intercept,
$\beta_{1k} = (\beta_1+u_{1k})$ = plot/stand-specific slope, and
all other variables as previously defined.

For the example above, equation (5) would be expressed as:

$$H_{ki} = \exp^{[3.0552 + 0.4262 \ln D_{ki} + 0.00938/2]} \qquad (6)$$

Assuming a tree has a D of 7.1 inches, the predicted H would be 49 feet. Use of the simplified, "population average" curve, on the other hand, provides a predicted height of 43 feet, a 12 percent difference.

Figure 3 clearly demonstrates that calibrating equation (1) using observed Hs and Ds from a particular plot (producing equation (6)) vastly improved predictive ability, consistent with many other studies (e.g., Calama and Montero 2004; Huang and others 2009; Lynch and others 2005; Temesgen and others 2008; Trincado and others 2007; VanderSchaaf 2012, 2013, 2014). Relative to the "population average" curve, for a given D, most Hs for this particular plot were greater (perhaps due to genetic stock, stand-level species composition, aspect, soil type, site productivity, etc.). Hence, equation (6), through the calibration process, provided an H-D curve that reflected this behavior. However, using the so-called "population average" trend failed to recognize the behavior of trees in this individual plot relative to the average behavior across all plots.

CONCLUSIONS

A mixed-effects H-D model is presented for longleaf pine plantations in northern Florida and Georgia. By obtaining H-D measurements from plots/stands of interest, equation (1) can be calibrated to local site conditions. In most cases, model calibration will result in better H predictions relative to a fixed-effects region-wide model (Huang and others 2009; Temesgen and others 2008; Trincado and others 2007; VanderSchaaf 2012, 2013, 2014). Calibration of equation (1) will often be advantageous to fitting local H-D equations (or plot- or stand-specific equations) because calibration can be appropriate and have acceptable model fit statistics with small sample sizes (Lynch and others 2005). To calibrate these models for specific plots/stands, an Excel spreadsheet is available on request.

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3. Fire

Moderator:

Rebecca Kidd

THE DEVELOPMENT OF A SOUTHERN APPALACHIAN MOUNTAIN FUELS PHOTO SERIES

T. Adam Coates, Thomas A. Waldrop, Helen H. Mohr, and Todd F. Hutchinson

Abstract—The use of a fuels photo series to characterize potential combustibles and adequately anticipate and predict potential wildfire and prescribed fire behavior and effects in a given area is a practice that began nearly 50 years ago. These photo series are regional in nature and have tended to characterize the variability in Western United States fuel complexes in finer detail than Eastern United States fuel complexes. Managers and practitioners have long expressed great interest in a more site-specific, Southern Appalachian Mountain fuels photo series. In this article, we present the developmental framework for a new Southern Appalachian Mountain fuels photo series that was created in 2019 (Coates and others 2019).

INTRODUCTION

Prescribed fire is a forest management practice used extensively throughout the Southeastern United States to accomplish a variety of landowner objectives, such as hazardous fuel reduction, slash and debris reduction for site preparation, wildlife habitat enhancement, vegetative control of less-desired species, and ecosystem restoration (Waldrop and Goodrick 2012). It is well documented that wildland fire has been part of the Appalachian region for centuries (Lafon and others 2017), but much of the scientific understanding needed to utilize fire for the accomplishment of long-term management in this region is still emerging. Many managers and scientists in the region have desired a reference tool to aid in the determination of Appalachian-specific fuel loads as a means to better predict and anticipate potential fire behavior.

Fuels photo guides for the Eastern United States have included ones specific for estimating fuel loads as a result of clearcut harvesting (Sanders and Van Lear 1988) or post-hurricane damage in southern pine forests (Wade and others 1993). Also, a photo guide was specifically created for loblolly (*Pinus taeda*) and longleaf pine (*P. palustris*) plantations in the upper Coastal Plain region (Scholl and Waldrop 1999). Other photo guides have included managed and unmanaged stands. For northern hardwood and oak-hickory (*Quercus* spp.-*Carya* spp.) forest types, Wilcox and others (1982) developed a guide for each forest type, also grouped by site, class, and harvest history. A more recent guide developed for the Mid-Atlantic States gives users pre- and post-prescribed fire data arranged by differing levels of fuel types including leaf litter, ericaceous shrubs, and logging slash (Brose 2009). No fuels photo guide has been developed specifically for long-unburned stands in the Southern Appalachians. It is our goal with the production of this guide to take the first step in that direction.

METHODS

The new Southern Appalachian Mountain fuels photo guide was developed using photographs, site descriptions, and forest fuels inventories obtained from 705 research plots located on portions of the following Federal lands: Great Smoky Mountains National Park (Tennessee) and the Andrew Pickens (Sumter National Forest, South Carolina), Chattooga River (Chattahoochee National Forest, Georgia), and Nantahala (Nantahala National Forest, North Carolina) Ranger Districts (Waldrop and others 2007). All plots were located in areas where prescribed fire might be utilized to achieve forest management objectives.

Field Data Collection

In the field, fuels inventories were conducted using Brown's Planar Intersect Method (Brown 1974), as modified by Stottlemyer (2004) (fig. 1). Using this technique, down and dead woody debris 0–1/4 inch, 1/4–1 inch, 1–3 inches, and >3 inches in diameter was tallied as 1-, 10-, 100-, and 1,000-hour timelag size classes, respectively, along three 50-foot transects established at a 45° angle. Timelag refers to how each individual fuel-size class responds to changes in relative humidity (Brown 1974). Using this method, 1-hour and 10-hour fuels were tallied within the first 6 feet of each

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transect, 100-hour fuels were tallied within the first 12 feet, and 1,000-hour fuels were tallied along the entire 50-foot transect. A quality rating (sound or rotten) was additionally recorded for 1,000-hour fuels.

Estimates of fuel loading in tons per acre (W) were derived for each fuel-size class based upon these equations (Brown 1974):

For material $\leq$3 inches: $W = (11.64)(n*d^2*s*a*c) / N*L$ (1)

For material >3 inches: $W = (11.64)(\Sigma d^2*s*a*c) / N*L$ (2)

where

11.64 = conversion factor of volume to tons per acre;
n = the number of woody fuels tallied per timelag-size class;
d = quadratic mean diameter of particles (inches);
s = specific gravity of fuels (s = 0.70, 0.58, 0.58, and 0.30 for 0–1/4-inch, 1–3-inch, >3-inch sound, and >3-inch rotten material, respectively) (Anderson 1978);
a = non-horizontal angle correction factor;
c = slope correction factor;
N = number of transects at each plot (N = 3); and
L = length (feet) of sampling plane (L = 6 for 1- and 10-hour fuels; L = 12 for 100-hour fuels; and L = 50 for 1,000-hour fuels).

Litter depth, duff depth, and fuel bed height (defined as the distance from the top of the litter layer to the top of any coarse woody debris crossing the transect) were measured at three locations along each 50-foot transect: 12–13 feet, 24–25 feet, and 40–41 feet (fig. 2). Thus, plot averages for each variable were based upon nine individual measurements.

Ericaceous shrub (*Rhododendron maximum* or *Kalmia latifolia*) cover was calculated by measuring the canopy dimensions of each shrub using 50-foot measuring tapes within the 0.025-acre fixed-area plot. Ground cover vegetation <1 foot tall was visually estimated in the same 0.025-acre fixed-area plots (fig. 3).

The range pole in the photographs was 6 feet tall and was placed at the 40-foot mark along the

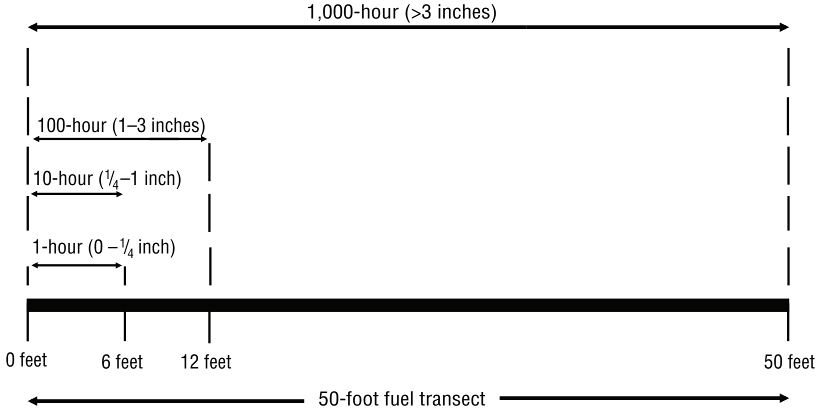


Figure 1—Sampling parameters along each 50-foot transect for the tally of woody fuel components (Stottlemyer 2004).

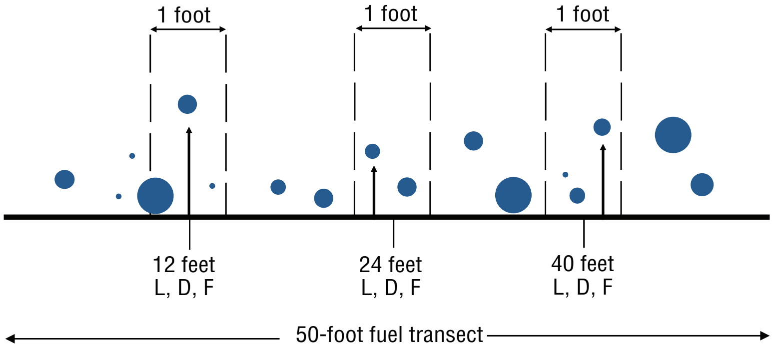


Figure 2—Sampling locations for litter (L) and duff (D) depth and fuel bed height (F) along the 50-foot transects (Stottlemyer 2004). The spheres above represent woody debris of differing diameters intersecting the sampling transects.

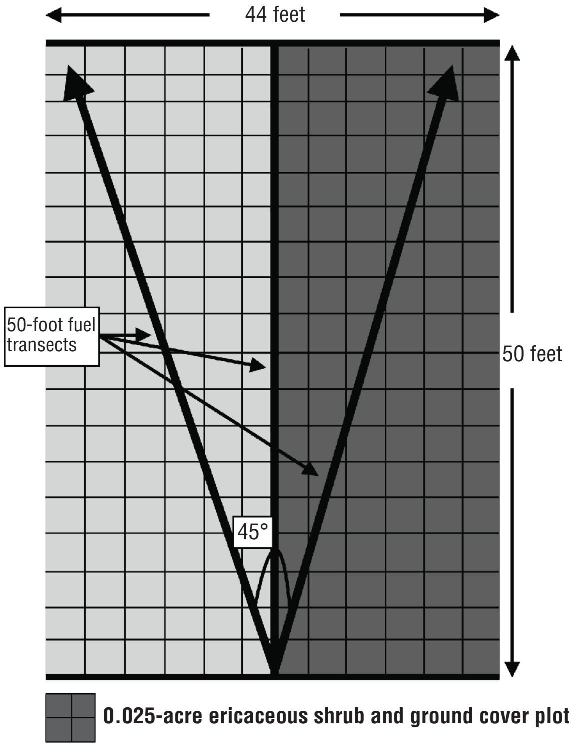


Figure 3—The orientation of ericaceous shrub and ground cover sampling utilized at each plot (Stottlemyer 2004).

Table 1—Combinations of aspect and elevation used to organize the Southern Appalachian Mountain fuels photo guide

Aspect	Elevation
degrees	*feet*
46–135	1,000–1,999
	2,000–3,499
	≥3,500
136–225	1,000–1,999
	2,000–3,499
	≥3,500
226–315	1,000–1,999
	2,000–3,499
	≥3,500
316–45	1,000–1,999
	2,000–3,499
	≥3,500

center sampling transect. The camera was placed approximately 5 feet above ground when the photographs were taken.

Development of the Guide

Unlike other guides, we chose to group sites by aspect and elevation instead of forest types or fuel models. Aspect and elevation, alone or in combination, are known to affect forest composition and fuel loading in the study area (McNab 1991, Simon and others 2005). Based upon 12 combinations of aspect and elevation relevant for land managers in the region, 74 photographs were selected for presentation in this guide. In general, the selected photographs were taken in the dormant season. All sites/photographs chosen for the guide are from stands that have had no active management for at least 10 years based on visual indicators and landowner records. Fuel loads represented in these 74 photographs included no logging residues and assumed coarse woody debris inputs from background levels of insects and diseases.

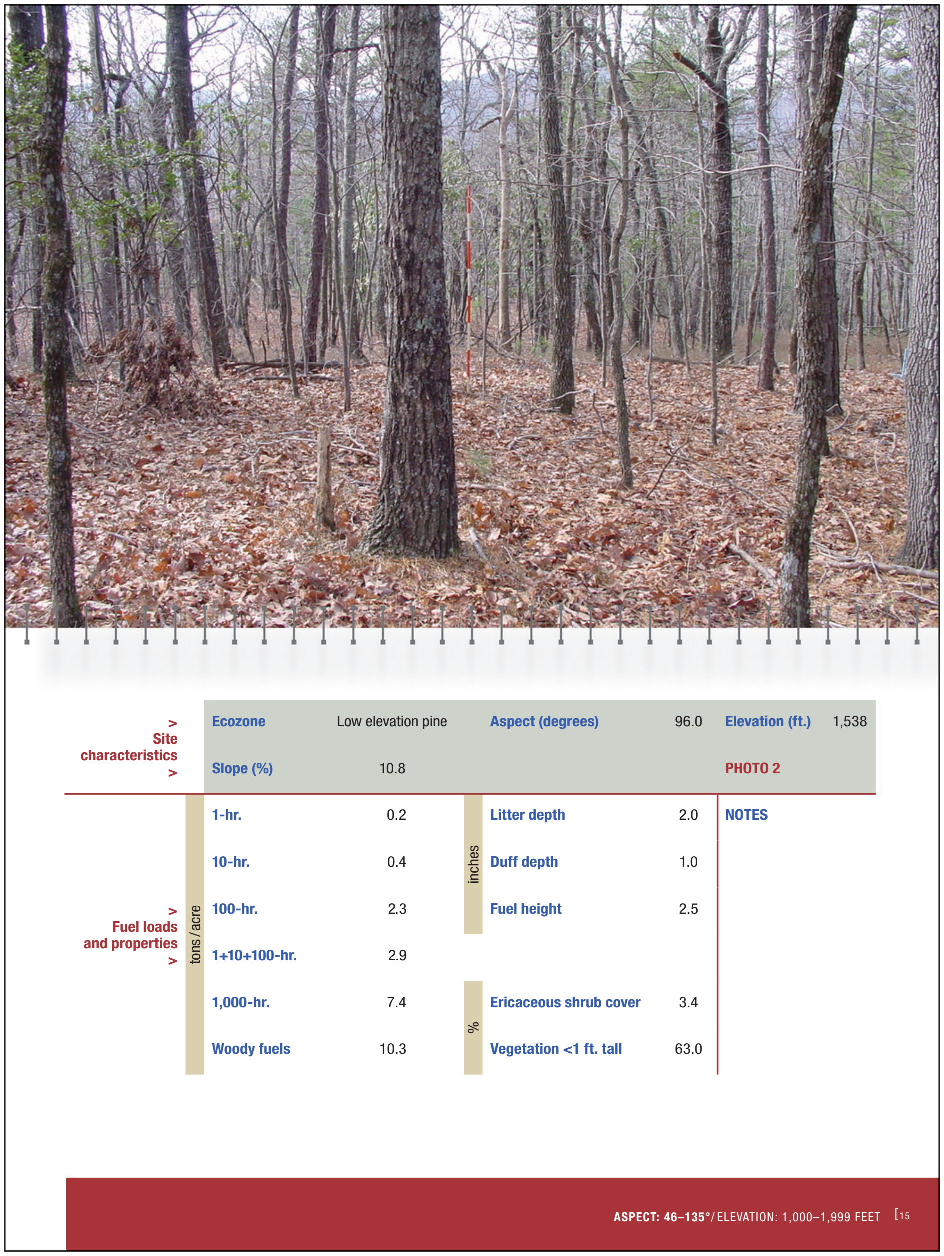
The aspect-elevation combinations are found in table 1. Using these aspect-elevation combinations as a basis for differentiation, specific photographs were then selected to display a fairly wide range of accumulated coarse woody debris ≤3 inches in diameter. If the amount of these materials was similar between locations at a given aspect-elevation combination, ecozone, stand density, and ericaceous shrub cover were evaluated to highlight site variability.

Using the Guide

This guide contains 74 photographs and accompanying data obtained at each depicted location. These photographs and data are differentiated by combinations of aspect and elevation. Sections of the guide are designated with these combinations in mind, as noted in the table of contents. They are arranged so that when the guide is opened and turned horizontally, the image will be on the top and the information table will be on the bottom (fig. 4).

To utilize the guide, users should select an aspect and elevation combination represented at the larger scale of the area to be managed with prescribed fire. Based on site conditions of an area representative of the fuel conditions of the larger area to be managed with prescribed fire, determine which photograph(s) from the aspect and elevation combination appear most similar to your area. In order to select one image when multiple photographs appear suitable, it may be necessary to narrow the selection based upon differences in ericaceous shrub cover, slope percentage, or 1,000-hour fuels.

While this tool may prove valuable to estimate fuel loading in specific locations of interest within the



> **Site characteristics** >		**Ecozone**	Low elevation pine		**Aspect (degrees)**	96.0	**Elevation (ft.)**	1,538
		Slope (%)	10.8				**PHOTO 2**	
> **Fuel loads and properties** >	tons/acre	**1-hr.**	0.2	inches	**Litter depth**	2.0	**NOTES**	
		10-hr.	0.4		**Duff depth**	1.0		
		100-hr.	2.3		**Fuel height**	2.5		
		1+10+100-hr.	2.9					
		1,000-hr.	7.4	%	**Ericaceous shrub cover**	3.4		
		Woody fuels	10.3		**Vegetation <1 ft. tall**	63.0		

ASPECT: 46–135°/ELEVATION: 1,000–1,999 FEET [15

Figure 4—Photos and data are arranged by aspect and elevation combinations, followed by 1+10+100-hour fuel loads (from least to greatest).

Southern Appalachian region, the limitations of the guide must be considered. These photographs and fuels inventories are based upon specific observations in specific locations generally during the dormant season and will not necessarily be an exact representation of the overall landscape in every situation.

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EIGHT YEARS LATER, DID A WILDFIRE IN SOUTHWESTERN VIRGINIA ACCOMPLISH FIRST-ENTRY PRESCRIBED FIRE TREE REGENERATION OBJECTIVES?

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Carolyn A. Copenheaver, and Melissa A. Thomas-Van Gundy

Extended abstract—In the early 20th century, fire exclusion policies had unforeseen consequences on the forests of the Appalachian Mountains, including fuel accumulation and a shift in composition to more fire-intolerant species (Nowacki and Abrams 2008, Waldrop and others 2016). The failure to regenerate desirable fire-adapted species, such as oaks (*Quercus* spp.) and Table Mountain pine (*Pinus pungens*), led scientists and managers to consider the use of prescribed burning as a management tool to restore these species (Brose and others 2013).

The application of prescribed burning to promote oak reproduction has led to conflicting results (Brose and others 2013, Keyser and others 2019). Several reasons have been posited as to why differences occur, including differences in burn season or frequency and overall fire behavior (Brose and others 2013). Generally speaking, wildfires are of higher intensity and consume more duff than prescribed fires (Hahn and others 2019). Also, prescribed fires are ignited with management intentions and goals in mind. Objectives are targeted under specific constraints of weather and desired fire behavior (Waldrop and Goodrick 2012). In contrast, wildfires typically result from unplanned natural (in other words, lightning ignitions) or human (for example, arson, carelessness, etc.) causes. The dormant season has been the preferred burn season of choice for prescribed fires in the Southern and Central Appalachian Mountain regions for a host of reasons, including concerns for specific wildlife species and their habitat, avoidance of western United States wildfire seasons when personnel and resources might already be utilized, and potentially hazardous burning conditions (Keyser and others 2019).

Over the past 15 years, the size of wildfires in Virginia and West Virginia has been increasing (National Interagency Fire Council 2019). This has led some forest managers and researchers to consider wildfire-related regeneration dynamics, particularly when compared to those generated by prescribed fires. Black and others (2018) used the Composite Burn Index (CBI) to correlate wildfire burn severity to vegetation effects on the Daniel Boone National Forest in Kentucky. As fire severity increased, so did overstory mortality and oak and pine sapling density and recruitment. Hagan and others (2015) examined vegetation response following two wildfires in the Linville Gorge Wilderness Area, NC, and found that oak and Table Mountain pine seedlings increased post-fire alongside a more diverse herbaceous layer. These studies suggested that fires of higher intensity might be needed to achieve oak and pine regeneration objectives.

During research activities in the summer of 2018, researchers at Virginia Tech visually observed suspected differences in tree regeneration in two adjacent forested areas (fig. 1) of the Fishburn Forest in southwest Virginia. Both of the forested areas were on eastern aspects, but one was affected by a wildfire in November 2010, and the other had not been affected by any type of fire in at least the last 20 years.

To investigate potential regeneration differences, the abundance of tree regeneration was measured in a total of 63 0.02-acre plots. Eighteen plots were located in the wildfire-affected area, and 45 plots were located within a non-burned portion of the Fishburn Forest. Differences in sample size were simply based upon the affected acreage. Within these plots, all stems <2 inches diameter at breast height (d.b.h.) were counted. The species was

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recorded, and height class was assigned based upon the following classifications: Class 0 = <1 foot; Class 1 = 1–3 feet, Class 2 = 3.1–4.5 feet; Class 3 = >4.5 feet. Species were placed into two groups: a xeric group, which consisted of chestnut oak (*Quercus montana*), scarlet oak (*Quercus coccinea*), and hickories (*Carya* spp); and a mesic group, which consisted of red maple (*Acer rubrum*), blackgum (*Nyssa sylvatica*), tulip-poplar (*Liriodendron tulipifera*), sourwood (*Oxydendron arboreum*), and sassafras (*Sassafras albidum*).

Preliminary analyses of the data (Wilcoxon test for non-parametric data, $\alpha = 0.05$) suggested:

- Total tree regeneration (all height classes included) was significantly ($p < 0.0001$) greater in the wildfire-affected portion of the Fishburn Forest.
- Regeneration of the xeric group (<1 foot) was significantly ($p < 0.0001$) greater on the wildfire-affected portion of the Fishburn Forest.

Using this data and data collected from additional prescribed fire and wildfire locations in the Appalachian region (Thompson and others 2019), we hope to better understand how long-term forest restoration goals might be accomplished in long-term non-burned forests. Two 2018 Virginia wildfire locations and one 2018 West Virginia wildfire location are being measured similarly to develop a more comprehensive understanding of potential wildfire impacts on tree regeneration.

Figure 1—Comparison of regeneration on the Fishburn Forest, Montgomery County, VA, in non-burned (left) and wildfire-affected (right) areas (Thompson and others 2019).

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ASSESSING POTENTIAL LONG-TERM CHANGES IN SOUTHERN APPALACHIAN MOUNTAIN FOREST SOIL CHEMISTRY FROM REPEATED USE OF FUEL REDUCTION TREATMENTS

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W. Michael Aust, Thomas A. Waldrop, and Dean M. Simon

Extended abstract—In 1999, the national Fire and Fire Surrogate study was undertaken to address concerns regarding wildfire hazard reduction and the restoration of forest structure and function in many fire-excluded locations nationwide (Coates and others 2010, Schwilk and others 2009). Thirteen regions were included in this nationwide project, including the Southern Appalachian Mountains, with study sites located on the Green River Game Lands near Hendersonville, NC. As fuel reduction treatments were implemented across the country, a broad array of ecosystem properties and processes were measured and monitored to determine potential treatment effects, including soil chemistry.

The fuel reduction treatments implemented for the Southern Appalachian Mountains Fire and Fire Surrogate study included prescribed burning only, cutting only, and a combination of cutting and burning. Three replications of each treatment and three untreated controls were established in 2001. The initial cutting operation was conducted from December 2001–March 2002. All trees >1.8 m tall and <10.2 cm diameter at breast height (d.b.h.) were felled by chainsaw crews. All shrubs were cut and piled (piles <1.3 m high). The initial prescribed burns for the burn-only and combination treatments were conducted in March 2003 and consisted of strip headfires and spot fires that produced mean flame lengths of 2 m or less (Tomcho 2004).

Soils (Cliffield and Evard series, Ultisols) were sampled within the treated areas and adjacent controls in 2005 to determine short-term post-treatment forest soil responses (Coates and others 2010). This included assessments of O horizon and mineral soil (0- to 10-cm depth) carbon (C), nitrogen (N), and C:N ratios; and mineral soil bulk density, pH, aluminum (Al), boron (B), calcium (Ca), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), phosphorus (P), potassium (K), soluble sulfur (S), sodium (Na), zinc (Zn), N mineralization, nitrification, and proportional nitrification. Briefly, Coates and others (2010) determined that a few soil properties and processes were affected 3 to 4 years post-treatment in 2005. Mean soil pH differed significantly ($p = 0.0457$) between the cutting-only treatments (pH = 4.60) and the control (pH = 4.72). Soil Fe for the combination treatment (93.38 mg kg^{-1}) and control (113.36 mg kg^{-1}) differed significantly ($p = 0.0143$) in 2005 (note that soil Fe values were highly variable prior to treatment and between the replications). Although statistically significant, these results were thought to have little biological meaning (Coates and others 2010).

Since that time, additional treatments have been conducted: prescribed fire only in 2006, 2012, and 2015; cutting only in 2012; and a combination of cutting and burning in 2012. Long-term treatment impacts on overstory and understory vegetation and fuels have been evaluated (Oakman and others 2019, Waldrop and others 2016), but soils have not been re-assessed. Few long-term soils research studies have been implemented in the Southern Appalachian Mountains, particularly ones that address potential long-term impacts of repeated prescribed fire (Callaham and others 2012). This lack of knowledge comes in light of an increase in prescribed fire acreage goals within portions of the Appalachian region (Brose and others 2001, Lorber and others 2018, Melvin 2018).

Wildland fires may impact forest soils, but potential impacts are difficult to characterize and are uniquely site specific. Soil responses to wildland fire may be related to aboveground vegetation, fire intensity and severity, time since fire when sampling occurs, method of soil sampling, soil sampling depth, and other factors (Alcañiz and others 2018, Coates and others 2018, Fairchilds and Trettin 2006, Hahn and others 2019). As a result of this lack

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of knowledge, soils were re-sampled at this site in summer 2018. O horizon and mineral soil C, N, and C:N and mineral soil Ca, Mg, K, P, and pH will be assessed to determine if there were significant chemical changes from 2001 to 2018.

With this research, we hope to better understand how soils respond to long-term implementation of fuel reduction treatments in the Appalachian region. This will ensure that soil conservation is incorporated into long-term management strategies. Additionally, we hope to distinguish potential relationships between vegetation, fuels, and soil properties that might better inform restoration goals and objectives in light of prescriptions and recommendations.

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SPATIAL AND SEASONAL FLAMMABILITY COMPARISONS OF NATIVE AND EXOTIC PLANTS IN THE POST OAK SAVANNAH, BLACKLAND PRAIRIE, AND PINEYWOODS ECOREGIONS OF TEXAS

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Abstract—Greater knowledge of plant flammability can improve prescribed fire effectiveness and wildfire mitigation strategies by improving fire behavior predictions in physics-based fire models and supplementing Firewise plant listings with flammability indices. Seasonal and regional changes in flammability parameters were estimated for yaupon (*Ilex vomitoria*), Chinese privet (*Ligustrum sinense*), greenbrier (*Smilax* spp.), and Chinese tallow (*Triadica sebifera*) within the Post Oak Savannah, Blackland Prairie, and Pineywoods Ecoregions of Texas. Foliage (yaupon, privet, and greenbriar) and wood (tallow) samples were collected in the dormant (February) and growing (August) seasons. Wood samples were collected from Chinese tallow due to dormant season leaf-off. Samples were evaluated using thermogravimetric analysis to estimate relative spontaneous ignition temperature (RSIT) and gas-phase maximum mass loss rate (GP-MMLR). RSIT and GP-MMLR are estimates of plant ignitability and combustibility. Yaupon was the most ignitable species during both seasons and across all three ecoregions. Chinese privet dormant season ignitability was similar to yaupon in the Post Oak Savannah and Blackland Prairie. Greenbrier exhibited the greatest growing season combustibility combined with moderate ignitability. Chinese tallow wood exhibited substantially greater ignitability and combustibility in the growing season. Collectively, all species exhibited seasonal and ecoregion variances in ignitability, while combustibility varied little relative to season and ecoregion. These data provide insight into potential species-specific contributions to fire behavior that may aid in more informed fire management planning.

INTRODUCTION

Hazardous fuels reduction and restoration and maintenance of fire-adapted ecosystems in Texas continue to be management priorities. Texas' year-round fire season adds to fire management complexity in terms of wildfire suppression in both dormant and growing seasons (Texas A&M Forest Service 2012). Prescribed fire continues to play an important role in reducing woody fuel loads in forest and grassland ecosystems. Subsequent reductions in fuel loads reduce fire intensity and spot fire potential leading to improved fire containment, decreased heat exposure to desired species, and less ignition risk to adjacent residential and commercial buildings. Therefore, improved knowledge of wildland fuel flammability could aid fire managers in meeting prescribed fire prescriptions and potentially reduce losses associated with wildfires.

Active fire suppression and passive and poor management have allowed prolific growth and expansion of invasive and weedy native species that contribute to increased regional fuel loads. For example, yaupon (*Ilex vomitoria*) is considered a weedy native often found in great densities in unmanaged forests and pine (*Pinus* spp.) plantations (Shadow 2011), as well as mixed grass woodland ecosystems, especially the Post Oak Savannah (Mitchell and others 2005). Chinese privet (*Ligustrum sinense*) and Chinese tallow (*Triadica sebifera*) are exotic invasive species that exhibit prolific growth, vigorous resprouting when damaged, high reproductive capacity, and are abundant along waterways, fence lines, and forest edges (Greene and Blossey 2012, Pile and others 2017). Greenbrier (*Smilax* spp.) has been known to outcompete native grasses in oak woodlands, and is often targeted by prescribed burning in prairie and savannah restoration projects (Sparks and others 2012).

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The objective of this study was to estimate spatial and seasonal ignitability and combustibility trends for yaupon, greenbrier, Chinese privet, and Chinese tallow in three east Texas ecoregions for the purpose of quantifying key plant flammability indices for possible inclusion into Firewise plant listings, and identifying potential risks or opportunities associated with prescribed burn programs. To our knowledge, flammability estimates have not been conducted on Chinese privet or Chinese tallow, and new insight into their spatial and seasonal flammability could be useful for improving prescribed fire effectiveness and hazard classification. Since flaming combustion is the primary driver of fire spread, our study focused on estimating ignitability and gas-phase combustibility. Thermogravimetric analysis (TGA) was used to evaluate oxidative thermal degradation profiles to estimate ignitability and combustibility parameters for select species.

METHODS

Study Sites

Regional flammability influences were based on selection of ecoregions where two exotic invasive species, Chinese privet and Chinese tallow, and two native species, yaupon and greenbrier, were present. All species have naturalized populations within the Pineywoods, Post Oak Savannah, and Blackland Prairie ecoregions of Texas (Diggs and others 1999, Diggs and George 2006, Oswalt 2010, Wang and Grant 2014). Pineywoods sample sites were on the Stephen F. Austin State University campus and Stephen F. Austin Experimental Forest near Nacogdoches, TX. Post Oak Savannah sites were located at the Texas A&M University Equine Center and Veterans Park in College Station, TX. Blackland Prairie sites were located at the Trinity River Audubon Center and White Rock Lake in Dallas, TX.

Pineywoods sites consisted of mixed pine and hardwood forests on Alfisol and Inceptisol soils with little topographic relief. Post Oak Savannah sites consisted of mixed post oaks (*Quercus stellata*) and live oaks (*Quercus virginiana*) on Alfisol and Inceptisol soils with gently rolling terrain. Blackland Prairie sites exhibited a mix of live oak, cedar elm (*Ulmus crassifolia*), sugarberry (*Celtis laevigata*), and eastern red cedar (*Juniperus virginiana*) on Alfisol, Mollisol, Inceptisol, and Vertisol soils with flat rolling terrain.

Sampling

Chinese privet, yaupon, and greenbrier foliage samples were collected from the same five plant specimens in each ecoregion ranging from 0 to 2 m in height during both seasons, and Chinese tallow wood samples were collected using the same parameters. Samples were collected in the dormant (February) and growing (August) season. Seasonal sampling was coordinated across three study ecoregions to account for spatial influences on flammability. Foliage samples were flash frozen with liquid nitrogen and ground using a standard coffee grinder, while wood samples were ground in a standard Wiley mill. Ground samples were dried in an air convection oven at 40 °C for 48 hours and passed through a standard series of sieves to obtain the 35 mesh fraction for TGA analysis.

Processing

Thermogravimetric analysis is a common method used to estimate plant flammability through the use of ground samples that focus on chemical composition, while reducing combustion variability associated with plant physical properties (White and Zipperer 2010). Anderson (1970) defines ignitability as the time-to-ignition and combustibility as the rapidity of combustion. Thermogravimetric estimates of ignitability are based on relative spontaneous ignition temperature (RSIT) in an air atmosphere under a predetermined linear heating rate up to 650 °C, with higher RSITs representing lower pilot ignition temperatures and flash points and are therefore more ignitable (Liodakis and others 2008, Liodakis and Kakardakis 2008). Combustibility estimates are a function of maximum mass loss rates (MMLR), meaning samples with greater MMLR are more combustible.

Thermogravimetry was conducted using a Perkin Elmer Simultaneous Thermal Analyzer (STA) 6000. Samples were weighed to ~20 mg and placed in a porcelain crucible. Heating range was 35-650 °C with a 10 °C min^{-1} linear heating rate. Purge gas was air (~21% O_2) set at 20 ml min^{-1}. Differential thermogravimetric (DTG) peaks were evaluated by measuring the mass loss as a function of temperature and time at the onset, maxima, and endset peaks to yield flammability parameters using Pyris 13.2 software. Second derivative peaks were also used to inform onset and endset reaction peaks corresponding to the first derivative (DTG). Five individual species samples underwent TGA analysis according to the above specifications. Descriptive statistics were used to compare seasonal and regional differences in RSIT and GP-MMLR.

RESULTS

Mean dormant season foliage RSIT yielded an ignitability ranking order of yaupon, Chinese privet, and greenbrier, with yaupon exhibiting greater ignitability (fig. 1). Interestingly, yaupon and Chinese privet had similar ignitability in the Post Oak Savannah and Blackland Prairie. Mean growing season foliage RSIT produced an ignitability ranking order of yaupon, greenbrier, and Chinese privet (fig. 2). Yaupon had the greatest growing season ignitability; however, greenbrier exhibited a considerable increase in ignitability, while Chinese privet had a moderate decrease. Substantial mean seasonal

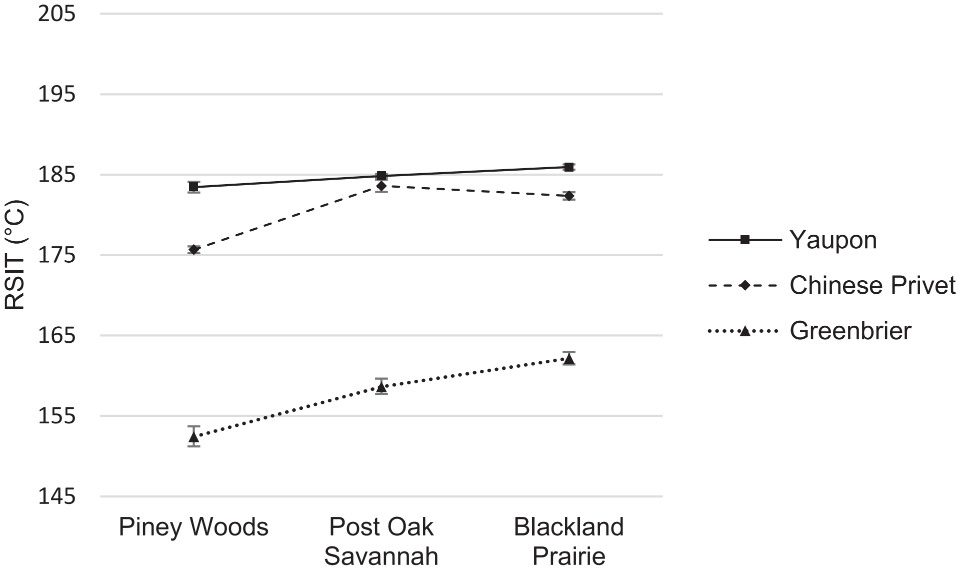

Figure 1—Mean dormant season relative spontaneous ignition temperature (RSIT) for yaupon, Chinese privet, and greenbrier foliage in the Piney Woods, Post Oak Savannah, and Blackland Prairie.

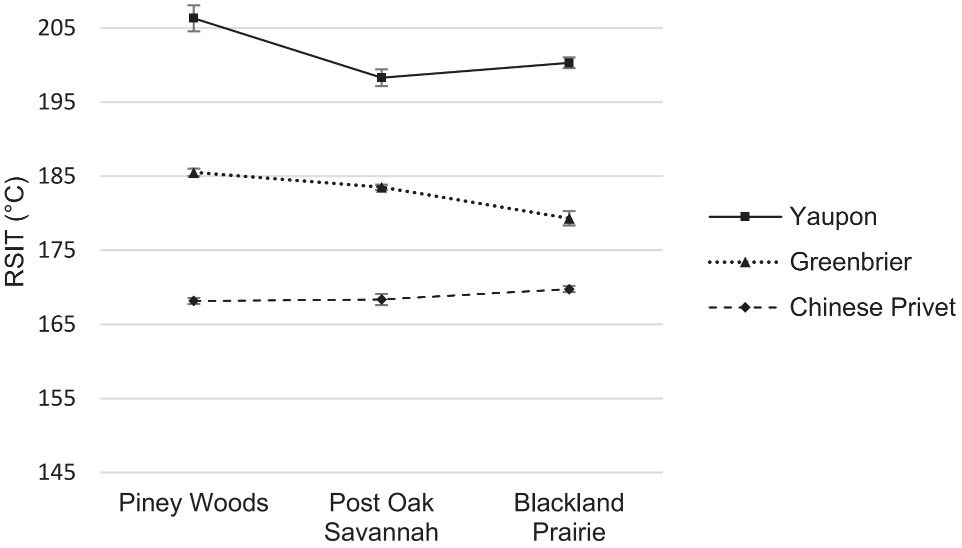

Figure 2—Mean growing season relative spontaneous ignition temperature (RSIT) for yaupon, Chinese privet, and greenbrier foliage in the Piney Woods, Post Oak Savannah, and Blackland Prairie.

differences in RSIT existed among species ranging from 11.8 to 25.0 °C (table 1). In contrast, mean regional differences in RSIT were greater in seasons associated with greater species-specific ignitability (table 2).

Mean dormant season foliage GP-MMLR yielded a combustibility ranking order of yaupon, greenbrier, and Chinese privet, with yaupon exhibiting greater ignitability (fig. 3). Pineywoods species yielded the greatest differences in combustibility. Mean growing season foliage GP-MMLR produced a combustibility ranking order of greenbrier, yaupon, and Chinese privet (fig. 4). Greenbrier produced substantially greater growing season combustibility compared to yaupon, especially in the Pineywoods. Mean seasonal effects among species foliage combustibility produced little variance (table 1). Likewise, mean regional species foliage GP-MMLR slightly differed (table 2).

Mean seasonal RSIT for Chinese tallow wood exhibited substantially greater ignitability in the growing season as opposed to the dormant season (fig. 5). The Blackland Prairie yielded the greatest range in Chinese tallow wood ignitability, with the least dormant and greatest

Table 1—Mean seasonal differences in relative spontaneous ignition temperature and gas-phase maximum mass loss rate within ecoregions by species

Source/species	RSIT (°C)	GP-MMLR (%/min)
Foliage		
Yaupon	16.96 (5.26)	0.18 (0.03)
Chinese privet	11.80 (3.94)	0.15 (0.12)
Greenbrier	25.04 (7.98)	0.93 (0.42)
Wood		
Chinese tallow	22.91 (4.80)	2.28 (1.13)

Figures in parentheses are standard deviations.

RSIT = relative spontaneous ignition temperature and GP-MMLR = gas-phase maximum mass loss rate.

Table 2—Mean ecoregion differences in relative spontaneous ignition temperature and gas-phase maximum mass loss rate among species with respect to season and ecoregion

Source/season/species	RSIT (°C)	GP-MMLR (%/min)
Foliage		
Dormant		
Yaupon	1.67 (0.74)	0.39 (0.24)
Chinese privet	5.29 (3.56)	0.23 (0.19)
Greenbrier	6.50 (3.11)	0.32 (0.18)
Growing		
Yaupon	5.35 (3.05)	0.35 (0.24)
Chinese privet	1.07 (0.77)	0.37 (0.28)
Greenbrier	4.14 (2.10)	0.49 (0.41)
Wood		
Dormant		
Chinese tallow	0.62 (0.27)	1.71 (0.80)
Growing		
Chinese tallow	5.76 (2.55)	2.03 (1.58)

Figures in parentheses are standard deviations.

RSIT = relative spontaneous ignition temperature and GP-MMLR = gas-phase maximum mass loss rate.

growing season RSIT. Similarly, Chinese tallow exhibited greater growing season combustibility compared to dormant season GP-MMLR (fig. 6). Chinese tallow exhibited the greatest GP-MMLR range in the Blackland Prairie. Differences in mean seasonal RSIT's were much greater as compared to GP-MMLR (table 1). Regionally, Chinese tallow exhibited greater differences in RSIT in the growing season, while differences in GP-MMLR remained relatively similar (table 2).

DISCUSSION

Thermogravimetic analysis yielded similar mass decomposition profiles from past studies conducted in air atmospheres, which represent two distinct thermogravimetric peaks linked to gas- and solid-phase combustion (Jones and others 2015, Liodakis and Kakardakis 2008, Munir and others 2009). Analysis of gas-phase combustion peaks yielded reasonable ignitability and combustibility estimates relative to species respective RSIT and MMLR indices.

As expected, yaupon was the most ignitable species among foliage samples, and was consistent with previous studies and anecdotal accounts (Long and others 2006). Additionally, yaupon exhibited relatively high combustibility and was readily ignited; therefore, fire managers should exercise caution when prescribed burning and actively suppressing fires in fuel beds with dense yaupon. Dormant season Chinese privet ignitability was also comparable to yaupon in the Post Oak Savannah and Blackland Prairie, and may allow for more effective control using prescribed fire. Conversely, greater Chinese privet densities may contribute to greater wildfire intensity, potentially leading to larger and more severe wildfires (Wang and others 2016). High growing season combustibility associated with greenbrier warrants caution during late dormant season prescribed burns. Greenbrier may also present a greater risk of torching and crown fire initiation in woodlands and forest stands where vines extend into the canopy, thus acting as a readily combustible ladder fuel.

Chinese tallow continues to be a regionwide problem in forests, grasslands, and riparian corridors. High growing season ignitability and combustibility of Chinese tallow wood may allow for more integrated management options using prescribed fire. Although ignitability and combustibility of Chinese tallow wood is quite variable, prescribed burning of growing season masticated wood residue may be an effective control for resprouting trees and seed bank management (Pile and others 2017).

Substantial differences in species ignitability with respect to season were potentially influenced by annual variation in photoperiod, temperature, and moisture regimes, as well as edaphic and minor topographic variation. In contrast, species combustibility did not appear to be greatly influenced by season or region. Regional ignitability results for yaupon, Chinese privet, and Chinese tallow exhibited greater differences in

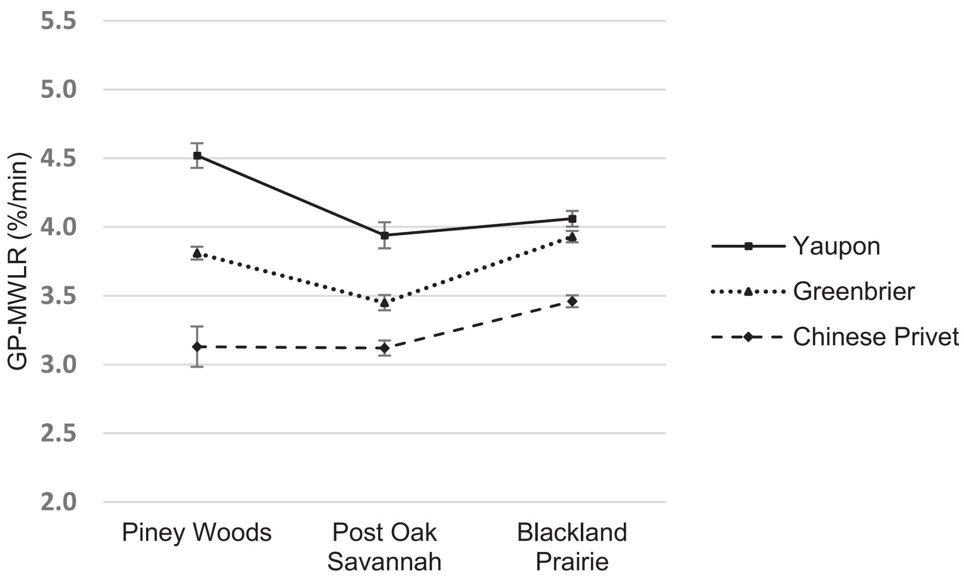

Figure 3—Mean dormant season gas-phase maximum mass loss rate (GP-MMLR) for yaupon, Chinese privet, and greenbrier foliage in the Piney Woods, Post Oak Savannah, and Blackland Prairie.

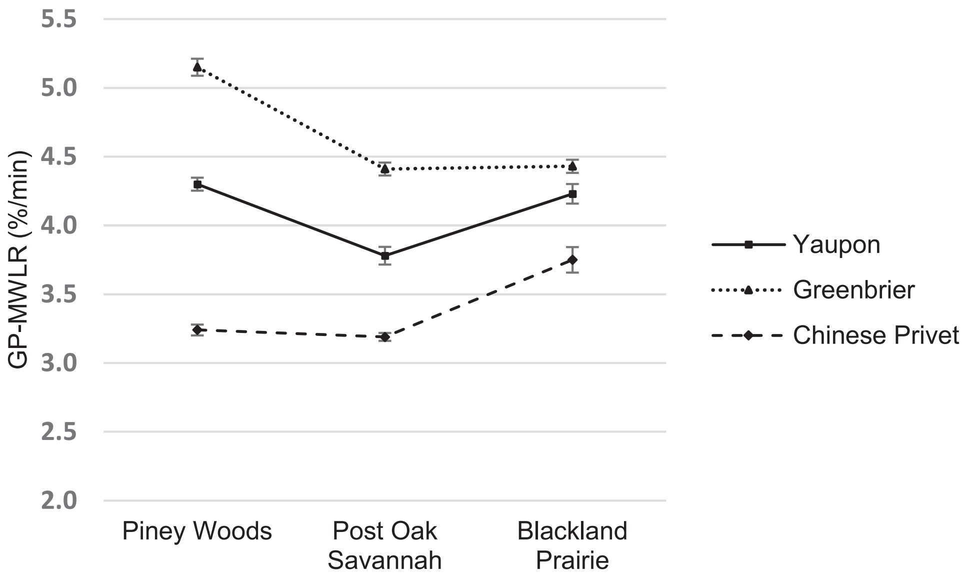

Figure 4—Mean growing season gas-phase maximum mass loss rate (GP-MMLR) for yaupon, Chinese privet, and greenbrier foliage in the Piney Woods, Post Oak Savannah, and Blackland Prairie.

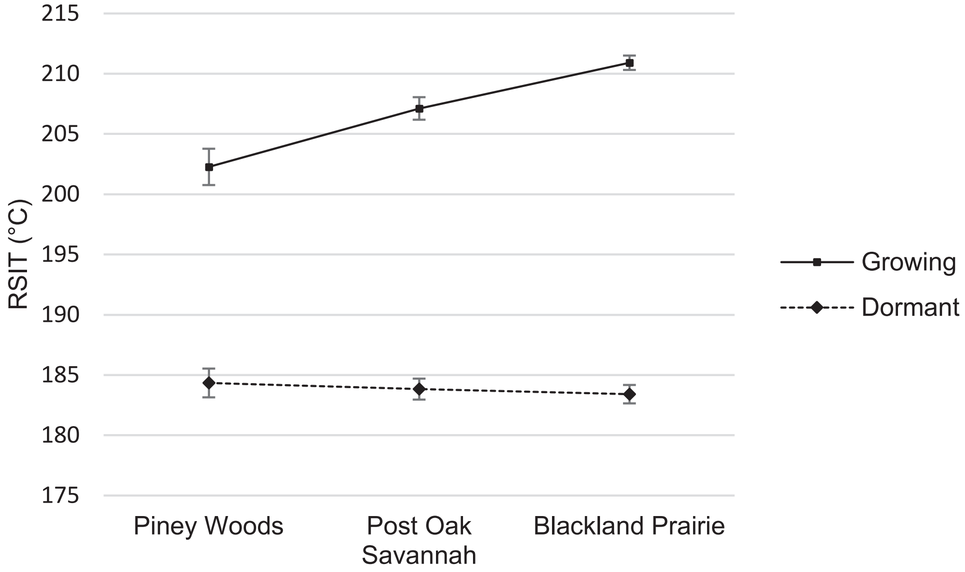

Figure 5—Chinese tallow wood mean dormant and growing season relative spontaneous ignition temperature (RSIT) for the Piney Woods, Post Oak Savannah, and Blackland Prairie.

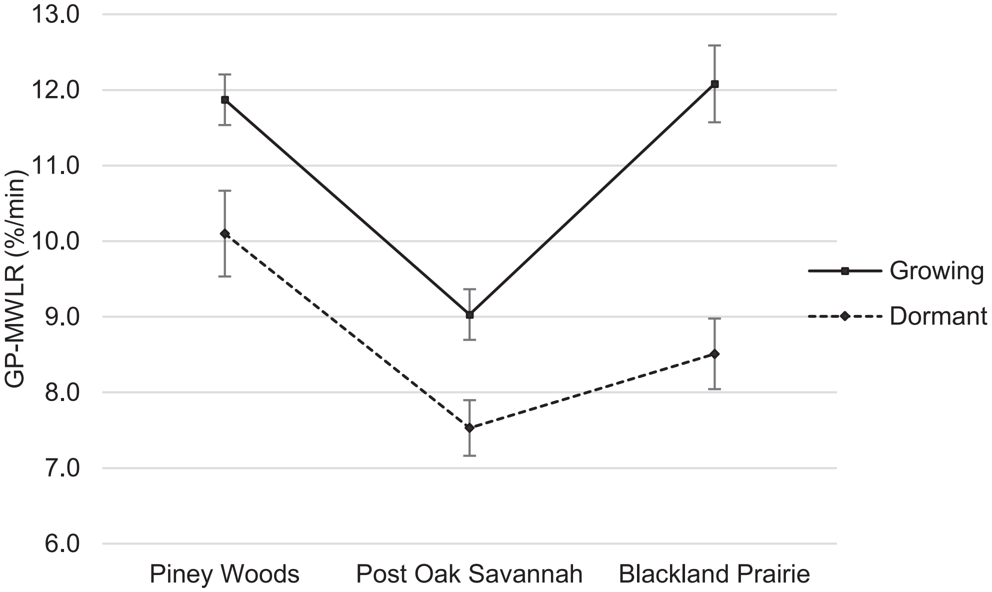

Figure 6—Chinese tallow wood mean dormant and growing season gas-phase maximum mass loss rate (GP-MMLR) for the Piney Woods, Post Oak Savannah, and Blackland Prairie.

ignitability associated with their respective season of greatest ignitability. Yaupon and Chinese tallow exhibited greater growing season ignitability across all three ecoregions suggesting greater differences in live fuel moisture or production of volatile compounds maybe linked to active growing conditions. Conversely, Chinese privet exhibited greater differences in dormant season ignitability suggesting active growth and subsequent changes in live fuel moisture or volatile compound production may occur opposite of its native associates. Greenbrier exhibited relatively high variation in ignitability with respect to region and season, suggesting ignitability maybe further influenced by associated cover type and edaphic conditions.

CONCLUSIONS

This study focused on estimating spatial and seasonal flammability trends of four east Texas plant species. Thermogravimetric analysis was used to estimate ignitability and combustibility parameters by evaluating oxidative thermal decomposition curves associated with species foliage and wood samples. Mean seasonal and ecoregion RSIT estimates for ignitability varied considerably for all species, while mean seasonal and ecoregion combustibility estimates for GP-MMLR exhibited little variation among species, with the exception of Chinese tallow. These findings provide a preliminary estimation of spatial and seasonal trends in species-specific flammability, which may aid in greater prescribed fire effectiveness and improve species hazard classifications aimed at reducing wildfire risk. However, bench-scale flammability testing using TGA is limited to small ground samples, thus further large-scale flammability testing is needed to validate flammability estimates. Furthermore, ignitability estimates based on higher RSIT values require further testing and validation to confirm the accuracy of this methodology.

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STAND DYNAMICS 12 YEARS AFTER PRESCRIBED FIRE TO RESTORE DEGRADED UPLAND OAK-HICKORY FORESTS IN THE OZARK-ST. FRANCIS NATIONAL FOREST, ARKANSAS

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Abstract—Prescribed fire, when applied at an appropriate frequency and intensity, has proven to be an effective management tool to promote and enhance upland oak (*Quercus* spp.) regeneration, particularly on xeric sites. Relatively thick protective basal bark, strong resprouting capabilities, and flammable leaf litter are fire-adapted traits that more fire-tolerant upland oaks possess, providing a competitive advantage over more fire-sensitive, mesophytic species (for example, red maple, *Acer rubrum*; blackgum, *Nyssa sylvatica*; black cherry, *Prunus serotina*). This study quantified the effects of prescribed fire on long-term changes in overstory (≥4.5 inches diameter at breast height, d.b.h.), sapling (0.6 to less than 4.5 inches d.b.h.), and seedling (>6 inches height, <0.6 inches d.b.h.) dynamics 12 years after burn treatments. Fires were implemented across three sites that experienced significant red oak (Section *Lobatae*) overstory mortality following severe drought (1998 to 2000) and a red oak borer (*Enapalodes rufulus*) outbreak (early 2000s). Twelve years after a single-dormant season burn, overstory basal area had been reduced across all sites with red oaks comprising the majority of mortality. In the no-burn control, an increase in overstory basal area was observed due to non-oak ingrowth. Densities of oak and non-oak seedlings increased 2 years post-dormant burn, but then began to decline as a result of these seedlings growing into saplings or being outcompeted. After 12 years, oak and non-oak sapling densities had rebounded, substantially, over pre-burn levels with red and white oaks (Section *Quercus*) present in greater densities and at competitive heights, positioning them to be recruited into the overstory.

INTRODUCTION

Oak (*Quercus* spp.) species are ecologically and economically important. Oaks are a major component in 68 percent of North American hardwood forest cover types (Stein and others 2003). They provide hard mast to numerous wildlife species such as white-tailed deer (*Odocoileus virginianus*) and eastern wild turkey (*Meleagris gallapavo*) (Brose and others 2014, Dersal 1940, Miller and Lamb 1984, Stein and others 2003). Large contiguous blocks of upland oak-hickory (*Carya* spp.) forests characterize the Ozark Plateau in southern Missouri and northwestern Arkansas, dominating the Central Hardwoods region of the United States (Chapman and others 2006, Guyette and others 2006, McShea and Healy 2002). These forests developed under frequent, low-intensity fires. Many of these fires were ignited by Native Americans and early European settlers, oftentimes extending past the natural fire season (Hicks and others 2004, Van Lear 2004). Through repeated exposure to fire disturbances, oaks evolved adaptations including thick basal bark protecting the cambium from heat damage and the ability to resprout following disturbance (Alexander and others 2008, Brose and others 2014). However, after long periods of fire suppression, decreases in oak regeneration potentials and recruitment of oak into the mid- and overstory strata has allowed for an increase of more shade-tolerant, fire-sensitive species (Heitzman and others 2007, Nowacki and Abrams 2008, Vickers and others 2014). "Mesophication," or the positive feedback in which closed canopy conditions favor shade-tolerant, fire-sensitive species, by maintaining cool, damp conditions, has further complicated oak regeneration and recruitment problems (Keyser and others 2017, Nowacki and Abrams 2008). In addition to oak regeneration problems, the absence of fire has allowed for over-mature, dense, even-aged closed canopy forests, increasing stress on overstory trees making them more susceptible to climatic and forest health disturbances such as drought, insect outbreaks, and pathogens (Haavik and others 2015, Vander Yacht and others 2018).

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In the early 2000s, increased overstory mortality was noticed in northwestern Arkansas following a period of significant drought and an outbreak of red oak borer (*Enapalodes rufulus*). In this region, red oak (Section *Lobatae*) species experienced increases in mortality with northern red oak (*Quercus rubra*) and black oak (*Q. velutina*) experiencing the greatest mortality (~126 trees per acre). White oaks (Section *Quercus*; *Q. alba, Q. stellata*) affected by the drought demonstrated severe crown dieback and in most cases when affected, failed to rebound (Fan and others 2008, Spetich 2004). Mortality events were attributed to oak decline or effects of pre-disposing (for example, advanced tree age; shallow, rocky soils; and dense forest conditions), inciting (for example, drought), and contributing (for example, red oak borer and hypoxylon canker (*Biscogniauxia atropunctatum*)) factors (Heitzman and others 2007, Johnson and others 2002, Manion 1990). These forest health disturbances were coupled with documented decreases in oak regeneration and failed recruitment of oak species following mortality events (Bendixsen and others 2016, Larsen and others 1997) Decreases in regeneration and increases in mortality caused by red oak borer and drought prompted the investigation of the use of prescribed fire as a restoration tool on these sites in northwestern Arkansas. This study evaluated the long-term effects of prescribed fire on the stand dynamics in degraded upland forests and the interactions with forest health and climatic disturbance events. To do this, the objectives of this study were to characterize changes in overstory basal area and species composition; sapling density and composition, diameter, and height; and seedling density and composition.

MATERIALS AND METHODS

Study Area

This study was conducted on the Big Piney Ranger District in the Ozark-St. Francis National Forest in northwestern Arkansas. Sites were located in Johnson and Pope Counties, Arkansas, and were within the Boston Mountains Ecoregion. Early Pennsylvanian sandstones and shale with a minor limestone component made up the parent material and Nella-Enders, Nella, and Mountainburg soils were found on the sites (USDA NRCS 2018). This region was classified as a humid subtropical climate receiving an average of 49.5 inches of rainfall and 2.1 inches of snowfall annually. The average high temperature was 92 °F (July to August) and average low temperature was 28 °F (January to February). The overstory was an upland oak-hickory cover type with northern red oak, white oak, black oak, post oak (*Quercus stellata*), mockernut hickory (*Carya tomentosa*), and bitternut hickory (*C. cordiformis*) as the dominant species (Eyre 1980, McWilliams and others 2002). Surveys indicated over 295,000 acres were moderately to severely affected by oak decline events in this region (Starkey and others 2004).

Treatments

Three sites (Pilot Knob, Meadows Knob, and Falling Water) were located near ridge tops on south to southwest facing slopes of 20 to 40 percent and were characterized by increased stand age and density (Booker 2008). Each site was divided into two treatments: a dormant season burn and no-burn control treatment. A single dormant season fire was implemented at Pilot Knob in February 2006 and at Falling Water and Meadows Knob in early March 2007. Within each treatment, six to nine plots were randomly located (Booker 2008). To characterize the overstory, a 10 basal area factor (BAF) prism plot was located over each plot center. Each plot also contained five subplots, one located at plot center and four at a distance of 30 feet in each cardinal direction (north, south, east, and west). Each subplot contained a sapling plot (0.005 acres) and a nested seedling plot (0.001 acres).

Field Methods

Overstory, sapling, and seedling data were collected at each site at the end of the growing season (late July/early August) 1 year prior to treatment (pre-burn), 2 years following treatments (post2), and 12 years following treatments (post12). Overstory was classified as a living tree with a d.b.h. of 4.5 inches and greater. Variables collected for the overstory strata were d.b.h., species, and crown dieback and transparency. Saplings were considered living stems with a d.b.h. ranging from 0.6 inches to 4.5 inches and seedlings were greater than 2 feet in height and less than 0.6 inches d.b.h. Within each sapling plot species, height, and d.b.h. were determined. For seedlings, species, height, basal diameter, and vigor were recorded.

Data Analysis

Overstory basal area (square feet per acre) mean values were determined for each species group (red oak, white oak, hickory, and other, non-oak) in each treatment for the pre-burn, post2, and post12 measurement periods. Mean change in basal area from pre-burn to post2 (post2 minus pre-burn) and pre-burn to post12 (post12 minus pre-burn) were calculated for each species group by treatment. The same calculations were conducted for the sapling strata for red oak, white oak, red maple (*Acer rubrum)*, and other species groups using change in mean stems per acre from pre-burn to post2 and pre-burn to post12. Mean height and d.b.h. were determined for saplings to indicate post-burn changes in competitive status for species groups. Mean seedling stems per acre were determined and changes were summarized for pre-burn to post2 and pre-burn to post12 periods for each species group.

RESULTS AND DISCUSSION

Overstory

Basal area decreased for all species groups except other 2 years following treatments (table 1). Overstory oaks, affected by oak decline events, continued to experience mortality as illustrated by continued decreases in basal area. Red oak species, which were most negatively impacted by oak decline associated events, experienced a similar rate of decrease in basal area (12 to 13 percent) 2 years following both the no-burn control and dormant treatment. While mortality continued for red oaks in the control treatment (19 percent decrease in basal area), a greater decrease in basal area (43 percent) was observed from pre-burn to post12 in the dormant treatment. White oak basal area decreased 2 years following both treatments (2 to 4 percent). Twelve years following the control treatment white oak basal area continued to decrease (10 percent), whereas in the dormant treatment, white oak stems had begun to grow into the overstory strata as demonstrated by a 1 percent increase in basal area. Treatments appeared to have little impact on hickory basal area. The other species group experienced an initial decrease in basal area 2 years following the dormant treatment (15 percent), but began to increase in basal area (3 percent) by 12 years post dormant treatment. In the control, the other species group increased in basal area both 2 (7 percent) and 12 (15 percent) years post treatment (table 1).

Across our three study sites, basal area was reduced for the white and red oak groups across treatments due to the combined effects of oak decline and a single prescribed fire (table 1). Areas in the Boston Mountains are highly susceptible to decline-associated events due to stands being composed of dense, mature oaks. Spetich and He (2008) suggested that under the current low frequency fire regime, the potential for oak decline events would remain high within the Boston Mountains in northwest Arkansas until the older cohort died out. In contrast, under a more historical regime characterized by increased frequency of fires, oak decline events would impact a smaller portion of the landscape overall as a result of more frequent removal of physiologically weak and mature overstory trees. Understanding the impact of frequency of intermediate disturbances (such as prescribed burns) can impact vulnerability to oak decline may help project future stand compositions. Events remove older, wounded and diseased trees from the overstory increasing available light to the forest floor and thus, light reaching the regeneration strata. This should favor growth and development of oak reproduction while reducing mesophytic competitors (Brose and others 2014).

Saplings

Sapling densities (stems per acre) decreased 2 years following treatments for all species except the others species group, which increased in density in the control (table 2). The single dormant season treatment initially reduced densities for all sapling species groups as a result of topkill. Sapling densities were reduced by 94 percent for red oaks, 72 percent for white oaks, 74 percent for red maple, and 70 percent for other species groups 2 years following the dormant burn treatments. The majority of these reductions was attributed to topkill by the dormant season burn. As a result of resprouting

Table 1—Summary of mean overstory (≥4.5 inches d.b.h.) basal area prior to (Pre-burn) burn treatments and change in basal area 2 (Post2) and 12 years (Post12) following treatments across Pilot Knob, Falling Water, and Meadows Knob sites

		Basal area		
Species group	Treatment	Pre-burn	Post2 change	Post12 change
		square feet per acre		
Red oaks	Control	26.7 (7.6)	-3.3 (1.4)	-5.0 (2.5)
	Dormant	46.1 (5.1)	-6.1 (1.6)	-20.0 (4.0)
White oaks	Control	43.9 (7.7)	-1.1 (0.8)	-4.4 (2.8)
	Dormant	33.5 (4.5)	-1.3 (0.7)	+0.4 (2.1)
Hickory	Control	19.4 (6.4)	-1.7 (1.2)	0.0 (2.7)
	Dormant	6.1 (2.3)	-0.4 (0.4)	-1.3 (0.9)
Other	Control	15.0 (2.9)	+1.1 (1.8)	+2.2 (2.5)
	Dormant	11.7 (3.5)	-1.7 (1.2)	+0.4 (1.6)

Red oaks: northern red oak, black oak; white oaks: white oak, post oak; and other: blackgum, black cherry (*Prunus serotina*), red maple, etc.

Standard error presented in parentheses.

Table 2—Summary of mean sapling (0.6 to < 4.5 inches d.b.h.) density prior to (Pre-burn) burn treatments and change 2 (Post2) and 12 years (Post12) following treatments across Pilot Knob, Falling Water, and Meadows Knob sites

		Sapling density		
Species group	Treatment	Pre-burn	Post2 change	Post12 change
		stems per acre		
Red oaks	Control	6 (4)	0 (0)	+9 (4)
	Dormant	52 (21)	-49 (20)	+223 (71)
White oaks	Control	44 (17)	-11 (5)	-18 (11)
	Dormant	43 (17)	-31 (13)	+35 (14)
Red maple	Control	29 (10)	-2 (2)	+80 (25)
	Dormant	89 (24)	-66 (24)	+270 (71)
Other	Control	173 (23)	+16 (17)	+104 (47)
	Dormant	195 (29)	-136 (26)	+285 (70)

Red oaks: northern red oak, black oak; white oaks: white oak, post oak; red maple; and other: hickory, blackgum, black cherry, sassafras (*Sassafras albidum*), etc.

Standard error presented in parentheses.

responses, 12 years following the dormant season fires all species groups demonstrated an increase in sapling density (table 2). Twelve years following the dormant burn, red oak densities had increased by 428 percent over pre-burn, representing the greatest relative increase from pre-burn to post12 conditions. Twelve year increases in sapling density red oaks were followed by red maple (303 percent), other (146 percent), and white oak (81 percent) species groups. Sapling density increased slightly for red oak (150 percent), red maple (275 percent), and other (60 percent) species groups after 12 years in the control treatment. White oak was the only group to experience an overall decrease (41 percent) in sapling density in the control after 12 years (table 2).

Prior to the dormant season treatment, red (2.0 inches) and white (2.2 inches) oak saplings had a slightly greater d.b.h. when compared to competing red maple (1.8 inches) and other species (1.5 inches) groups. Two years following both treatments, sapling diameter increased for all species groups. In the dormant treatment, increases were likely due to the greater topkill occurrence in the smaller diameter stems. Survival of seedlings and saplings was also found to be related to larger basal diameter stems with stems less than 6 inches being damaged by fire in the Missouri Ozarks (Dey and Hartman 2005). As recruitment into the sapling strata occurred for nearly all species groups 12 years following the dormant treatment, sapling diameter decreased for all species groups. Twelve years after the dormant burn treatment, the average d.b.h. was 1.3 inches for all species groups. Pre-burn diameters for species groups in the control were similar to those in the dormant treatment. Decreases in sapling d.b.h. also occurred after 12 years in the control treatment due to the ingrowth of a few smaller saplings (table 2). Similar trends were observed for changes in sapling height. In the dormant treatment, prior to burning, red (18.2 feet) and white (18.1 feet) oaks were taller than red maple (17.8 feet) and other (14.7 feet) species groups. Twelve years following the dormant season treatment, red maple (18.0 feet) was taller than red oak (16.8 feet), white oak (13.0 feet), and other species (16.9 feet) groups. Height rankings among species groups likely changed due to differences of inherent rate of growth (for example, red maple is a faster growing species than upland red and white oaks).

Canopy gaps created by mortality events appear to have benefited the oak regeneration potential in these stands. Newly formed gaps create areas with intermediate-light levels required for oak regeneration and the use of prescribed fire reduces the shade-tolerant, fire-sensitive non-oak competitors (Greenler and Saunders 2019). Vander Yacht and others (2018) found that burning under a heavily disturbed canopy resulted in a negative effect on mesophytic species and had a greater benefit for the more shade-intolerant, fire-adapted species (Vander Yacht and others 2018). Our findings demonstrated the benefits of prescribed fire after canopy disturbance on red oak sapling densities (table 2), particularly at the Pilot Knob site. Increases in non-oak competitor species following the dormant season treatment at the other sites may be attributed to the sites having been in various stages of mesophication prior to burning. In another study conducted in the Missouri Ozarks, it was found that 50 percent of stems, despite species, were damaged by a single dormant season fire (Dey and Hartman 2005). Further, after three or more burns blackgum (*Nyssa sylvatica*) demonstrated increases in mortality while white oak and hickory species had relatively low mortality (14 to 22 percent; Dey and Hartman 2005). Repeated fires may increase the density of oak species compared to more shade-tolerant, fire-sensitive species due to selective mortality caused by the repeated burns. Other studies in the Central Hardwoods region have found that repeated burning reduced non-oak competitors by 60 to 70 percent compared the effect on oak densities (28 to 54 percent) (Fan and others 2008).

Seedlings

Prior to treatments, the other species group comprised over half of all seedlings (table 3). Seedling densities (stems per acre) increased for all species groups 2 years after treatments. In the dormant treatment, red maple (259 percent) illustrated the greatest rate of increase in seedling density, followed by white oak (191 percent), other (170 percent), and red oak (160 percent) species groups. Increases in seedling densities, although to a lesser extent, also occurred for all species groups 2 years after the control treatment. Following initial increases in seedling densities in the dormant treatment, seedling densities had decreased from 2 years post treatment to 12 years post treatment for all species groups except other. This is likely a result of initial seedling sprouts growing into the sapling strata as seedling densities continued to increase after 12 years in the control treatment (table 3).

An important physiological trait of oak seedlings is the storage of carbohydrates in their root tissue, which contributes to the survival and persistence of these species following a disturbance such as fire (Brose and others 2014). Storage of carbohydrates in the root stock by oaks is important because it supports sprouting following a top-killing fire. This, along with higher drought tolerance than mesophytic species on the more xeric sites in the Ozarks and the increased light levels due to overstory mortality, can increase oak advanced reproduction (Brose and others 2014). In our study, the effects of the dormant season prescribed fire in combination with reduced basal area likely increased the sunlight available to lower strata. This allowed seedling-sized stems to grow in height and basal diameter to be more competitive, thus increasing recruitment into the sapling class (Alexander and others 2008, Dey and Hartman 2005). Alexander and others (2008) quantified the effects of prescribed fire on upland oak and non-oak competitor seedlings in the Daniel Boone National Forest in Kentucky and found that on unburned sites, white oaks declined around 6 percent annually when compared to red maple and red oaks (which declined at about 5 percent annually); white oaks also exhibited the highest mortality on sub-mesic sites. In our study, white oak seedling densities increased following treatments, but in agreement with Alexander and others (2008) at a much slower rate than for the other, red oak, and red maple species groups.

Table 3—Summary of mean seedling (>2 feet in height and <0.6 inches d.b.h.) density prior to (Pre-burn) burn treatments and change 2 (Post2) and 12 years (Post12) following treatments across Pilot Knob, Falling Water, and Meadows Knob sites

		Seedling density		
Species group	Treatment	Pre-burn	Post2 change	Post12 change
		stems per acre		
Red oaks	Control	211 (71)	+78 (54)	+444 (198)
	Dormant	330 (91)	+530 (228)	+270 (98)
White oaks	Control	33 (18)	+22 (36)	+144 (75)
	Dormant	96 (63)	+183 (112)	+113 (84)
Red maple	Control	578 (178)	+100 (54)	+656 (270)
	Dormant	339 (139)	+878 (314)	+852 (300)
Other	Control	1222 (219)	+33 (59)	+189 (220)
	Dormant	748 (125)	+1278 (361)	+1348 (243)

Red oaks: northern red oak, black oak; white oaks: white oak, post oak; red maple; and other: hickory, blackgum, black cherry, sassafras, etc.
Standard error presented in parentheses.

CONCLUSIONS

Declines in overstory health due to oak decline events and low regeneration potentials of oaks in the understory suggested the need for management intervention. A single dormant season prescribed fire continued to reduce the basal area of the red and white oak overstory. As basal area was reduced, canopy gaps were created, allowing seedling sprouts regenerated by the fire treatments to receive more light and grow into advanced regeneration. The reduction of basal area in the overstory and increases in oak saplings and seedlings observed in this study shows the potential effect of adaptations to fire and gap-utilization that oaks possess. Although oak seedling and sapling densities increased in our study, so did the density of non-oak competitors. Variation was observed across our three sites (although not reported in this paper) in the degree to which oak versus mesophytic competitor sapling and seedling densities increased. This variation may be attributed to the different level of mesophication that existed prior to burning across the three sites as well as, topography and fire intensity. After only a single dormant season fire, red maple and other non-oak species remained competitive, which suggests additional management intervention(s) may be required.

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SOME FIRST-YEAR WILDFIRE EFFECTS ON TREE AND STAND CHARACTERISTICS ON THE CUMBERLAND FOREST, TENNESSEE

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Abstract—The summer and early fall of 2016 were characterized by an extended period of drought in Tennessee with as little as 3.8 inches of precipitation from August 1 through November 28. Subsequently, the fall fire season was exceptional in numbers of fires, the intensity with which they burned, and the severity of their impacts. One such wildfire burned 500 acres on the University of Tennessee's Cumberland Forest near Coalfield, TN, in late November. A study comparing the impact of this wildfire on the burned forest with the adjacent forest was initiated the following June. In the unburned forest, 3.5 percent of trees were estimated as recent mortality (<1 year old mortality) at the time of plot establishment. First-year results in the burn area indicated 87.6 percent of measured trees sustained some damage and 14 percent were top-killed by the fire. Chestnut oak (*Quercus montana*), the most common tree (n = 135), experienced 8.1 percent aboveground mortality, followed by yellow-poplar (*Liriodendron tulipifera*, n = 47) with 12.8 percent, and red maple (*Acer rubrum*, n = 125) with 16.8 percent. Mean scorch height was 2.95 feet, 2.05 feet, and 2.04 feet for these species, respectively. Basal burn was 76.1 percent, 68.0 percent, 46.0 percent for chestnut oak, red maple, and yellow-poplar, respectively. Red maple located in plots categorized as burned by high-severity fire experienced 37.2 percent top-kill and another 39.5 percent were experiencing significant decline by the end of the first growing season. Plots with 15-year-old legacy shortleaf pine (*Pinus echinata*) stumps had a mean fire severity of 3.7 (1-5 scale: low to high severity); plots without stumps had a mean fire severity of 2.8.

INTRODUCTION

Major wildfire events are often perceived as a western phenomenon because of the prevailing weather conditions and fuel types that make dramatic, large-scale, high-severity fires a relatively common occurrence. This frequency allows ample opportunity to investigate the ecological impacts of these stand-replacing events on western forests. For example, numerous reports spanning more than 60 years document ponderosa pine (*Pinus ponderosa*) mortality in high-severity burn areas and subsequent natural regeneration shortfalls rangewide (Ffolliot and others 2008, Lynch 1959, McHugh and Kolb 2003, Pearson 1950, Schmidt 1988, Schubert 1974).

While major mixed-severity wildfires can occur in the hardwood forests of the Eastern United States, regional climatic conditions are typically less favorable for major conflagrations. Additionally, fuel types and structure generally lend themselves to less dramatic surface fires of variable intensity and lower severity. The resulting lack of major wildfires in the Eastern United States has led to a dearth of literature on the effects of high-severity wildfire in this region. For example, the authors are aware of only one published source looking at postfire mortality in high- and low-severity fires of upland hardwoods of Virginia (Regelbrugge and Smith 1994). Most literature on fire in the East reports on effects of prescribed fire such as in the synthesis of fire-oak literature by Brose and others (2014).

However, there may be problems with inferring wildfire impacts from prescribed fire effects. For instance, major wildfires generally occur outside the prescriptive windows allowed by State permitting agencies. As such, not only would fuel moisture typically be lower at these times but soil moisture would be as well, especially during extended dry periods. Both points are important to consider as lower fuel moisture would contribute to higher burn intensity (all other factors being equal). With depressed soil moisture during extended dry periods, trees become stressed as xylem sap water pressure is decreased throughout its conductive tissue. As a result, these trees may be less capable of convective dissipation of heat by distributive movement of heated sap water (Michaletz and others 2012) and therefore potentially more susceptible to cambial necrosis, historically accepted as the cause of tree mortality

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(Dickinson and Johnson 2004). But the above decrease in sap pressure and susceptibility to heating has also been shown to cause xylem conduit deformation and transport cavitation (Lodge and others 2018, Michaletz and others 2012, Midgley and others 2011). This cavitation and deformation could contribute to the likelihood of top-kill from fire.

The summer and early fall of 2016 was characterized by an extended period of drought in Tennessee. Subsequently, the regional fall fire season was exceptional in number of fires, the intensity with which they burned, and the severity of their effects. A notable example was the 17,000-acre Chimney Tops 2 wildfire that burned into Gatlinburg, TN, at the end of November. At the same time as the Chimney Tops 2 wildfire, the Little Brushy wildfire burned 500 acres on the University of Tennessee's Cumberland Forest near Coalfield, TN. Beginning in June 2017, a study was begun using a paired stand approach investigating the impacts of this fire on the burned area in comparison to 500 acres of adjacent unburned but drought-impacted stands. This paper reports on some of the first-year findings.

MATERIALS AND METHODS

Location and Drought Conditions

The University of Tennessee's Cumberland Forest is located in Morgan County, TN. Particularly, the wildfire burned on Little Brushy Mountain located on the southernmost ridge of the Cumberland Mountain level III ecoregion (Griffith and others 1998). This elongated highland ridge runs east and west with a base elevation of under 1300 feet, a high point over 2100 feet, and is underlain by horizontal Pennsylvanian rocks of the Pottsville series. These strata are composed of fine-grained sandstone layers alternating with beds of shale, siltstone and coal (Wilson and others 1956). The wildfires extended from near the base of both the north and south sides and over the top of the mountain ridge (fig. 1).

Forests of this region are characterized as Appalachian mixed mesophytic with a highly diverse species composition. Past disturbance included mining and

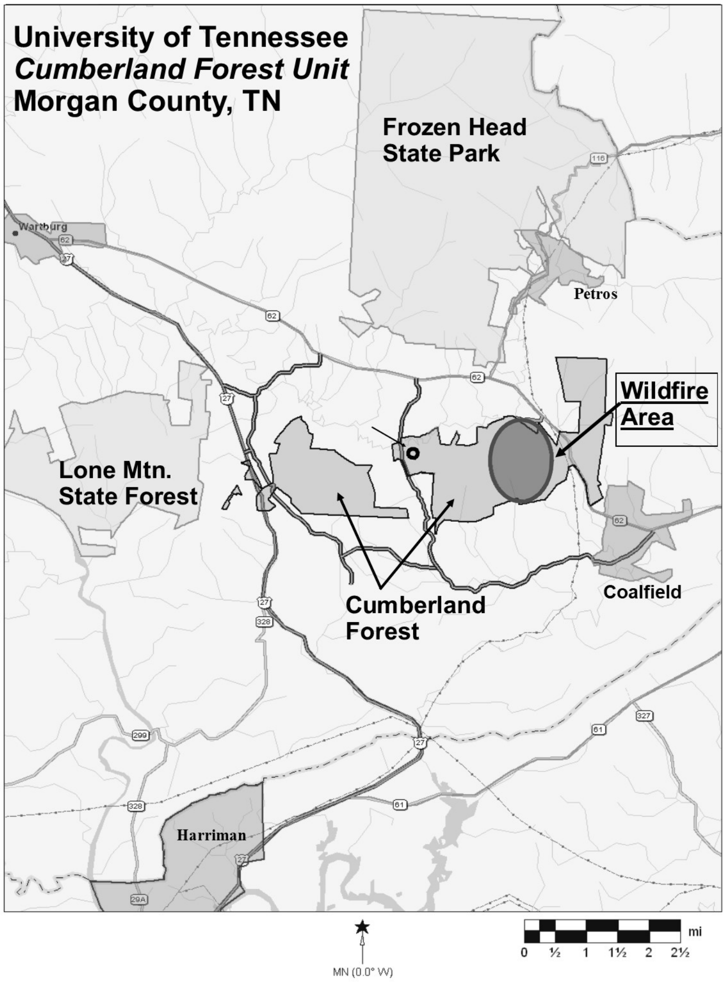

Figure 1—General location map of the University of Tennessee, Forest Resources Research and Education Center's Cumberland Forest Unit in Morgan County, TN, with the wildfire area highlighted.

extensive high-grading prior to University ownership in 1936. Some contour mining persisted through 1964 and pine afforestation trials were conducted on mined and cutover lands. Wildfire occurred regularly on the property prior to 1950 (Kring 1950). Subsequently, the area experienced little to no widespread disturbance until a southern pine beetle epidemic removed the overstory pine component from 1999-2002. One 53-acre clearcut regeneration harvest was conducted in the area in 2011.

From August 1 through November 28, 2016, only 3.8 inches of precipitation were recorded at the Cumberland Forest's weather station (normal 4-month mean precipitation at this site through November is 17.4 inches (Logan and others 1990)). The drought by the end of November 2016 (according to the Standardized Precipitation-Evapotranspiration Index (SPEI)) was of near-record severity (fig. 2). The 1000-hour fuel moisture was a record minimum value of 15 percent on November 22 (USDI 2017). On November 23, wildfire was reported on the Cumberland Forest and burned through November 28.

Plot Design

In the summer of 2017, 30 0.10-acre, fixed-radius permanent plots were established in the 500-acre wildfire area and 30 plots were placed in adjacent unburned forest on an 860-foot by 860-foot grid. Each plot had a 0.01-acre, nested revegetation circular micro-plot located at 90 degrees and 18.6 feet from plot center.

Plot Measurement Variables

Plot center was marked with a heavy gauge iron pin. Plot level parameters collected included slope (percent), aspect (degrees), overstory crown density (percent) using a densiometer, shortleaf pine (*Pinus echinata*) stump hole presence (True/False), and plot burn severity (0-5; 0 = unburned, 1 = surface fire (<5 percent replacement of upper canopy layer from top-kill), 2 = low severity fire (6-25 percent top-kill), 3 = moderate/mixed severity fire (26-75 percent top-kill), 4 = high severity fire (76-95 percent top-kill), and 5 = replacement fire (>95 percent top-kill)). These burn severity categories followed a hybrid of LANDFIRE fire severity classes (LANDFIRE 2013) and the Fire Effects Information System term definitions (USDA FS 2020) and the authors' additional upper- and lower-end delineations. These modifications

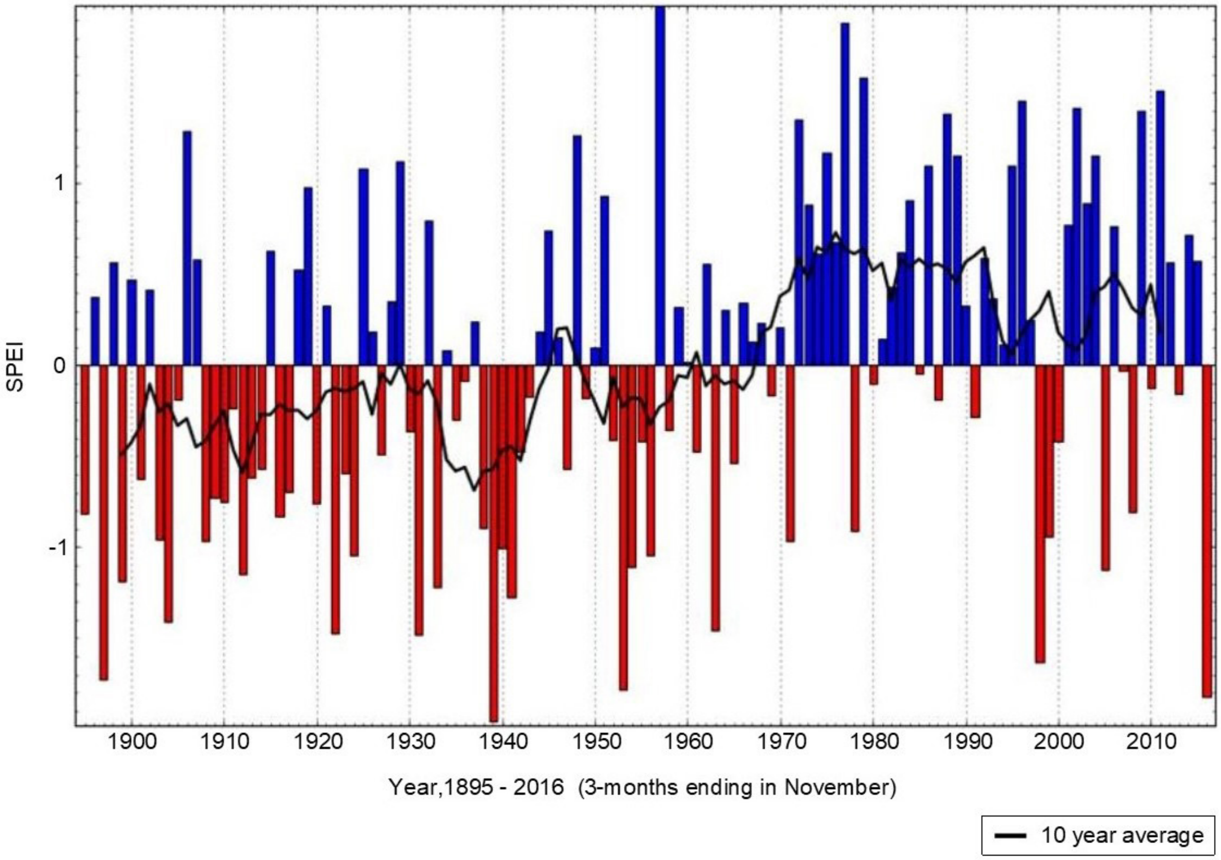

Figure 2—Standardized Precipitation-Evapotransporation Index (SPEI) for Tennessee. SPEI is a multiscalar drought index (Beguería and others 2014) which, in this case, used data sourced from the Western Regional Climate Center (https://wrcc.dri.edu/). Bars extending below 0 indicate annual moisture deficiency with the 2016 bar representing 11-month negative surpassed only by 1939.

were made to accommodate the paired unburned area of the study (0 = unburned) and to distinguish them from plots that may have experienced only partial burns on the lower end of the scale (1 = surface fire). The inclusion of the upper-scale category, the stand-replacement burn severity (index class 5), allowed for a finer-grain data capture of extreme fire effects achieved by these wildfire conditions in contrast to fire behavior under normal prescribed fire conditions in the Eastern United States.

Tree Variables

Each stem 5 inches or greater in diameter at breast height (d.b.h.) in the 0.10-acre plot was tagged with a uniquely numbered aluminum tag attached near the base-facing plot center. In the case of multiple sprouts, each individual stem (ramet) was measured and recorded distinctly and the clump (genet) was numbered. The tree species was identified, and d.b.h. (inches and tenths) and total height (feet) were measured and recorded. A TruPulse® laser clinometer was used to measure tree height. Crown class was noted (1-5; 1 = dominant, 2 = codominant, 3 = intermediate, 4 = suppressed, 5 = dead). Mortality rank was given on a 1-3 scale (1 = assumed survival, 2 = significant decline, 3 = dead). In unburned plots, mortality was estimated to be >3 years old, about 2 years old, and <2 years old at measurement. Physical characteristics such as remaining presence of attached dead leaves, enduring fine twigs, and presence and quantity of intact bark were used as most recent mortality indicators. Acknowledgement of general fire damage (True/False) was noted on burn plots and specifically, scorch height was recorded (feet and tenths) as well as the percentage of the circumference of the base that was burned. Finally, acknowledgement of burned out shortleaf pine stump holes within 10 feet of the tree was noted (True/False).

Micro-Plot Variables

In the micro-plot, seedlings taller than 1 foot but less than 1 inch in d.b.h. were tallied. Height and d.b.h. for saplings between 1 inch and 5 inches in d.b.h. were measured and recorded. Finally, percent cover was estimated and categorized (vines, grasses, shrubs, forbs).

Analysis

The wildfire effects on plot and tree variables were analyzed using the Real Statistics Resource Pack software Release 6.8 (Zaiontz 2020) with supplementary graphics generated by R package '*ggplot2*' (R Core Team 2017, Wickham 2016).

For the plot-level data, we investigated the relationships between shortleaf pine stump presence and burn severity and slope. After verifying normal distribution of the data with Shapiro-Wilk's test, we used 2-sample t-tests to look for differences between burn severity and slope of plots with stumps present and absent.

We restricted our tree-level analyses to red maple (*Acer rubrum*), yellow-poplar (*Liriodendron tulipifera*), and chestnut oak (*Quercus montana*). Tree species differences in normally distributed variables (mortality) were investigated with one-way analysis of variance followed by pairwise t-tests. Differences among tree species for variables not normally distributed (mortality index, scorch height, base burn, and burn severity) were explored with nonparametric Kruskal-Wallis tests, followed by pairwise Mann-Whitney exact tests.

The unburned plot data were used in this analysis only as a contrasting reference to fire induced top-kill. It is recognized that this unburned mortality likely represents a process of tree decline in their entirety (above- and belowground) and over a period of time rather than the crown replacement more prevalent in this disturbance event. Only recent mortality in the unburned plots (estimated dead <2 years) was used for comparison.

RESULTS

Plot Variables

Every plot established in the wildfire area had been burned through, confirming the almost complete coverage of the fire within the 500-acre area. Percent slope for the plots ranged from a low of 4 percent to a high of 65 percent with two-thirds having slopes greater than 31 percent. Aspect did not appear to influence burn severity except potentially in the lowest severity class (1) where only two plots were north-by-northwest facing (336 and 344 degrees). Distribution of plot burn severity (1-5) had a bell shape slightly weighted to the severe end with a third of the plots ranked at a 3 and 23 percent ranked both as 2 and 4. Thirteen percent of the plots experienced high severity fire.

Plots with burned-out shortleaf pine stumps (n = 12) had a mean burn severity of 3.7. Plots without stumps (n = 18) had a mean severity of 2.8 and similar variance ($F_{11,17} =$ 1.281, $p < 0.345$). This significant difference ($p < 0.033$) in mean severity might be due in part to the historical occurrence of shortleaf pine in areas topographically predisposed to more extreme fire behavior; mean aspect of plots with shortleaf pine was 197.3 degrees and 216.5 degrees without shortleaf pine. However, 13 of the 18 plots with historical shortleaf pine absent had a northerly aspect (270 – 360 degrees; 0 – 90 degrees). Ten of the 12 plots with legacy shortleaf pine stumps had a southerly aspect (>90 and < 270 degrees). Average slope for plots without legacy shortleaf pine was 40 percent and were not significantly different ($p < 0.247$) from plots with stumps (32 percent) and similar variance ($F_{11,17} =$ 0.785, $p < 0.317$).

Tree Variables

The three most prevalent species in the burn area were chestnut oak (31.3 percent; *n*=135), red maple (29.0 percent; *n*=125) and yellow-poplar (10.9 percent; *n*=47) (table 1). Mean tree d.b.h. of these species ranged from 14.4 inches for yellow-poplar and 13.5 inches for chestnut oak to 8.5 inches for red maple. Fire damage was observed on 87.6 percent of all trees measured in the wildfire area. Fourteen percent of all trees were recorded as top-killed during the first growing season after the fire. Only 3.5 percent of measured trees were estimated to have died within 1 year in the adjacent unburned forest. Chestnut oak, yellow-poplar, and red maple experienced 8.1 percent, 12.8 percent, and 16.8 percent mortality. The means of the ranks of the three species mortality index significantly differed between groups ($p < 0.002$; $\alpha = 0.05$). Chestnut oak mortality index value was 1.27 and similar to yellow-poplar's 1.47 ($p = 0.140$). Red maple mortality index was 1.56, significantly higher than chestnut oaks ($p = 0.005$) but not yellow-poplar ($p < 0.556$). The index value accounted for trees experiencing dramatic aboveground die-back, but were not top-killed.

Mean scorch height among the three species were 2.95 feet for chestnut oak, 2.04 feet for red maple, and 2.05 feet for yellow-poplar. There were significant differences in the means of the ranks of scorch heights among the three species ($p < 0.001$). Chestnut oak scorch height was greater than both red maple ($p < 0.001$) and yellow poplar ($p < 0.001$). Red maple and yellow poplar were similar ($p < 0.113$). Maximum scorch heights for the three species were 12 feet, 20 feet, and 13.5 feet respectively. Chestnut oak experienced significantly greater base burn damage (76.1 percent) than both yellow-poplar (46.0 percent) ($p < 0.001$) but not red maple (68.0 percent) ($p = 0.463$) (ranked base burn group differences $p = 0.001$). Red maple and yellow-poplar base burn damage was significantly different ($p = 0.003$). The interaction of scorch height to base burn only became positively correlated above 75 percent basal burn (fig. 3).

Table 1—Occurrence (*n*), percent mortality, mortality index value, scorch height, base burn, and burn severity by species

Species	*n*	Mortality	Mortality index	Scorch height	Base burn	Burn severity
		percent		*feet*	*percent*	
Red maple	125	16.8	1.56 ± 0.8 b	2.04 ± 2.9 a	68.0 ± 38.2 b	3.6 ± 1.2 b
Yellow-poplar	47	12.8	1.47 ± 0.7 b	2.05 ± 3.1 a	46.0 ± 47.2 a	2.6 ± 1.5 a
Chestnut oak	135	8.1	1.27 ± 0.6 a	2.95 ± 2.8 b	76.1 ± 28.8 b	3.5 ± 1.1 b

Means (± standard deviation) in mortality index, base burn, and burn severity columns followed by the same letter are not significantly different ($p < 0.05$).

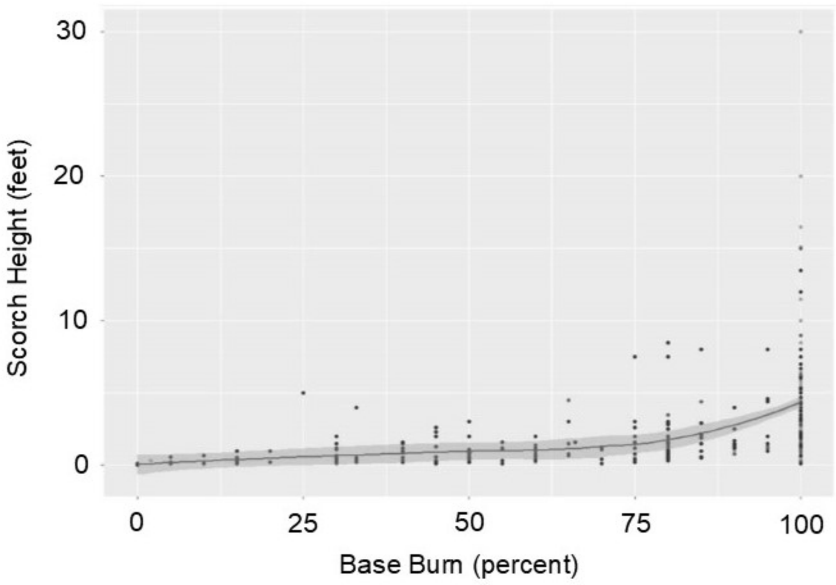

Figure 3—Correlation of scorch height (feet) by basal burn (percent). Increasingly positive correlation of scorch height begins past 75 percent basal burn.

Chestnut oak and red maple were fairly evenly distributed across burn severities while yellow-poplar was heavily skewed in numbers of occurrences in the low-severity plots. High-severity fire impacted every yellow-poplar with 42.9 percent mortality and the remaining 57.1 percent in decline. Red maple mortality was 37.2 percent with another 39.5 percent in decline. Chestnut oak mortality was 6.6 percent with another 33.3 percent in decline. (table 2).

DISCUSSION

Chestnut oak was the most prevalent species in the burn area. Surprisingly, it had the highest percentage of basal burn damage but had the lowest mortality rate. This corresponded with a significantly higher burn severity index measure than yellow-poplar, indicating its occurrence in areas with greater fire effects. Although previously existing fire scars were not measured as part of this study, given the age of the chestnut oak and frequency of historical fires known to have been common on the property prior to the 1950s (Kring 1950), it is likely that old fire scars also inflated the basal burning reported in this study. The ability of chestnut oak to compartmentalize damage explains how it remained on site despite previous scarring and corresponded with these mortality results.

Yellow-poplar followed the pattern reported by Nelson and others (1933) of being more resistant to basal damage than chestnut oak. Despite this resistance, mortality of poplar was greater than chestnut oak. When wildfire-caused mortality was exclusively considered, red maple had the highest number of stems top-killed. Initial top-kill and significant decline estimations of red maple may be overstated, however, as continued visitation to the plots revealed heavily damaged stems but many with full crowns persisting at the end of the second growing season. This may be indicative of a high tolerance for stem damage as a result of its diffuse-porous stem architecture that would prevent or prolong decline and mortality. Yellow-poplar had the highest rate of top-kill in areas of mixed/moderate, high, and replacement severity fires. Regelbrugge and Smith (1994) reported scorch height accounting for 93 percent of the variation in fire-killed basal area and 96 percent of variation in tree number measured 2 years after a wildfire in Virginia. Interestingly, scorch heights measured in this study were similar for the three most prevalent species. Yellow-poplar's frequency in low-severity plots should have low scorch heights reported and in fact there was a significantly lower mean basal burn percentage then chestnut oak.

Variability in scorch height for yellow-poplar may be attributed to topographical features and their effects on fire behavior. More specifically, this is indicative of

Table 2—Species occurrence (*n*), percent of total species population, percent mortality, and significant decline by burn severity class and percent of plots in burn class

Burn severity class	Plots in burn class	Species	Occurrence		Mortality	In decline
	percent		*n*	*percent*	*percent*	*percent*
1	6.6	CHO	0	0.0	-	-
		REM	6	4.8	-	-
		YEP	19	40.4	10.5	5.3
2	23.3	CHO	30	22.2	6.7	13.3
		REM	16	12.8	12.5	12.5
		YEP	2	4.3	-	-
3	33.3	CHO	44	32.6	2.3	-
		REM	45	36.0	4.4	8.9
		YEP	14	29.9	14.3	-
4	23.3	CHO	31	22.9	12.9	12.9
		REM	15	12.0	6.7	20.0
		YEP	5	10.7	20.0	60.0
5	13.3	CHO	30	22.2	6.6	33.3
		REM	43	34.4	37.2	39.5
		YEP	7	14.9	42.9	57.1

CHO = chestnut oak, REM = red maple, YEP = yellow-poplar a "chimney effect" on fire behavior impacting yellow-poplar occupying narrow drains on upland sites. These steep, narrow topographical features which are typically mesic sites with a thick duff layer and coarse woody debris under normal conditions, dried under the drought conditions experienced in 2016. The three sides of these features can funnel air upslope much like a chimney, creating strong convective currents and cross radiation between the three sides, concentrating the fires heat and preheating the existing heavy fuels. This environment may have created high flame fronts that scorched yellow-poplar as the fire burned uphill in drains occupied by these trees, compensating for the yellow-poplar that experienced little fire behavior at the low-severity plots.

CONCLUSIONS

These data may be too early to accurately determine top-kill and correlate mortality to an indicator variable(s) like scorch height or basal burn. Repeated measures are needed to track any shift in successional trajectories as caused by the fire. The large percentages of declining trees, especially yellow-poplar, may indicate ongoing mortality for the next few years. Mature yellow-poplar appeared more susceptible to mortality in the drought-fueled fall wildfire than red maple. Based on these preliminary results, wildfire effects may vary primarily by species in a mature upland eastern hardwood forest.

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EVALUATING THE INFLUENCE OF FEDERAL PRESCRIBED FIRE REGIMES IN EAST TEXAS ON WHITE-TAILED DEER BODY CONDITION AND ANTLER SIZE

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Abstract—The physiological impacts of Federal prescribed burn regimes on white-tailed deer (*Odocoileus virginianus*) body weight and antler size was investigated in east Texas National Forests. Burn history was provided by the U.S. Department of Agriculture, Forest Service, National Forests and Grasslands in Texas. Many State wildlife management areas overlapped the National Forest boundaries; therefore, the burn histories were used in combination with Texas Parks and Wildlife Department deer harvest records to investigate the relationships between white-tailed deer physical attributes and prescribed fire. Deer antler beam and inside mean spread were significantly greater at 2 years post-burn than at less than 1 year post-burn. These results indicate that frequent prescribed fire is physiologically beneficial to white-tailed deer.

INTRODUCTION

Prescribed fire is a commonly used silvicultural practice deployed by the U.S. Department of Agriculture, Forest Service (USFS), National Forests and Grasslands in Texas (NFGT) for habitat management and ecosystem restoration (Wall and others 2019). The ecoregion in eastern Texas known as the Pineywoods occurs across the Davy Crockett, Angelina, Sabine, and Sam Houston National Forests. These forests have evolved alongside growing season fires and are host to many endangered, fire-dependent plants and animals such as Texas trailing phlox (*Phlox texensis*), red-cockaded woodpeckers (*Picoides borealis*; RCW), and Louisiana pinesnakes (*Pituophis ruthveni*) (Agee and Skinner 2005, Conner and others 1995, Diamond and others 1997). In 2010, the Pineywoods was listed as one of the most endangered ecoregions in the United States, with fire suppression considered one of the predominant contributing factors (Weakley and others 2019). Expansive and biologically diverse “open and park-like” longleaf pine (*Pinus palustris*) had an estimated pre-settlement range of 37 million hectares in the Southeastern United States (Jose and others 2006, Outcalt 2000, Van Lear and others 2005). In the early 1990s, less than 3 percent of the longleaf pine savanna was still intact, down to approximately 1.2 million hectares (Frost 1993, Landers and others 1995, Van Lear and others 2005). Some more contemporary estimates following restoration efforts of longleaf pine ecosystems suggest approximately 2.1% currently remaining (Jose and others 2006, Kush and others 2004)

The many well-recognized benefits of prescribed burns include reducing fuel accumulations, cycling nutrients, promoting the growth of herbaceous grasses and forbs, reducing hardwood and shrub stem encroachment, promoting browse availability for wildlife, and increasing anthropogenic access (Agee and Skinner 2005, Boyles and Aubrey 2006, Brown and Smith 2000, Ryan and others 2013).

The NFGT has implemented a standardized protocol for monitoring both long- and short-term effects of their prescribed fire programs and consists of randomized, permanently placed fuel plots within compartments of the National Forests (McWhorter 2012, Wall and others 2019) This program is a derivative of methods outlined in the U.S. Department of the Interior, National Park Service’s Fire Monitoring Handbook as well as the Brown method for understory fuels analysis and aims to facilitate a uniform method of data collection and outline minimum monitoring standards associated with prescribed fire (Brown 1974, USFS 2014, USDI NPS 2003). The rationale behind the fire-monitoring program includes the use of the long-term data collection for comparative analysis of vegetation changes and fuel

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reduction treatments in connection to quantified burn plan and ecosystem-specific objectives to increase interagency knowledge of fire effects, improve fire regime condition classes, and evaluate progress toward meeting those objectives (McWhorter 2012, Wall and others 2019)

Although the USFS prescribed burn objectives focus mainly on vegetation, fuel, and habitat trends, we wanted to investigate the direct physiological effects of the prescribed burn treatments on wildlife species. White-tailed deer (*Odocoileus virginianus*) is an appropriate species to measure physiological impacts in relation to fire because many management practices that are beneficial to the RCW likewise benefit white-tailed deer. Frequent growing season fires, thinning of overstory trees, and mosaics of burn treatments have shown to improve habitat composition for both species, evidencing the fire-evolved dependency and interconnectedness of these ecosystems (Lyons and Ginnett 2017, Masters and others 1996, Sparks and others 1998). Using deer harvest records provided by Texas Parks and Wildlife Department (TPWD) in combination with Federal historical prescribed fire archives for burn years, we correlated the effects of burn treatments on white-tailed deer body weight and antler measurements.

METHODS

Burn history information was attained from the Interagency Fuel Treatment Decision Support System (IFTDSS), Fuel Treatment Effectiveness Monitoring (FTEM), and personal communication with USFS personnel. Texas Parks and Wildlife Department provided deer harvest records from Alabama Creek, Bannister, Moore Plantation, and Sam Houston National Forest wildlife management areas (WMA). The data were recorded between 2010 and 2017 on the opening day of deer rifle hunting season and consisted of body weight, total antler points, and antler base, beam, and inside spread measurements. IFTDSS and FTEM were used to correlate burn years as the WMAs were nested within the National Forests.

Statistical Analysis

The white-tailed deer body condition variables were correlated to burn years and quantified using one-way analysis of variance followed by post-hoc comparisons (Tukey) for any significant variables. Due to the proximity of the WMAs to one another, combined with similar white-tailed deer management protocols, we assumed relative genetic homogeneity of the data and did not block by WMA. Burn years ranged from 0 to 3 years since the last prescribed fire. A 90 percent confidence level was used to test significance for all body weight and antler measurements ($p = 0.10$). All nubbin bucks, spikes, and male deer younger than 1.5 years of age were removed from the antler analyses to prevent juvenile antler measurements from skewing the data. Body weight analyses include both male and female deer.

RESULTS AND DISCUSSION

The majority of deer (64 percent) were harvested within Moore Plantation and Sam Houston National Forest. Eighty percent of deer were between 1.5 and 3.5 years of age at the time of harvest, with the most common age class being 2.5 years (29 percent). Sex composition consisted of 71 percent male and 29 percent female. More than 55 percent of deer ($n = 144$) were harvested in areas that had been burned the same year and dropped significantly as years since the last burn increased, bottoming at seven deer harvested 3 years post-burn. We hypothesize that the drop in harvests as years since the last burn increases may be attributed to either deer preference for more open areas or anthropogenic aversion to hunting in denser vegetation. As succession increases vegetation density over time, hunters may simply prefer to hunt in areas that are more easily accessible. Vegetation growth may also decrease visibility, making the deer more difficult to harvest. Likewise, deer may prefer less dense ecosystems consistent with literature in regards to predator-prey behavior exhibited in other cervid species (Henderson and others 2018, Wall 2018, White and others 2003).

Average field-dressed body weight (34 kg, standard error = 0.6) did not differ significantly ($p = 0.218$) among years since last burn. Mean total antler points ranged from 5.75 to 6.75 and did not differ among years ($p = 0.584$). Antler base measurement means ranged from 62 to 75 mm and were also similar among years ($p = 0.134$). Antler beam length ($p = 0.079$) and inside spread ($p = 0.099$) differed among years since last burn (fig. 1). Antler beam length and inside spread were greater than at 2 years post-burn than the year immediately following a burn.

Results suggest a beneficial link between prescribed fire and white-tailed deer physiology, where deer body weight and antler measurements increased after burns, peaking 2 years after the last prescribed fire. This analysis quantifies promising evidence and contemporary justification for the continued use of prescribed fire as a beneficial management tool to improve both habitat quality as well as overall white-tailed deer health, body condition, and antler size. Furthermore, the beneficial pattern displayed in deer condition in response to frequent burns likewise evidences the necessity of fire in these ecosystems (Wall 2018).

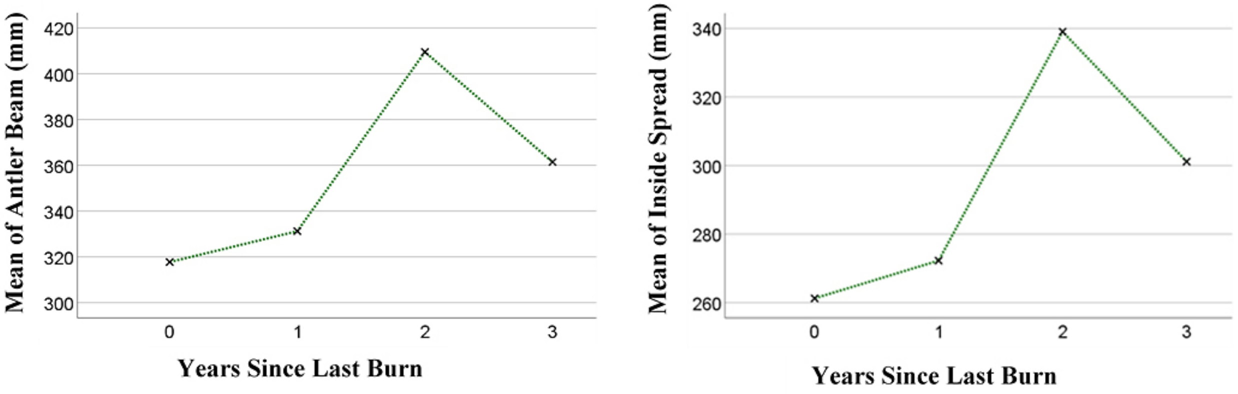

Figure 1—Least squares means for antler beam length (A) and inside spread (B) for white-tailed deer ≥1.5 years of age in relation to year since last burn.

CONCLUSIONS

Due to the infancy of research investigating direct physiological effects of fire on white-tailed deer, future research is imperative. Research involving increasing the sample size and fire return interval data in combination with adding browse surveys analyzing vegetative composition would be beneficial. It seems that the fire rotations native to these ecosystems improve overall deer health and hunter success. Continuing prescribed burn regimes on 2-4 year rotations may promote body weight and antler improvements while providing hunters with better access to game.

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4. Longleaf Pine

Moderator:

Brian Oswald

EARLY IMPACTS OF MIDSTORY HARDWOODS AND OVERSTORY DENSITY ON LONGLEAF PINE SEEDLING ESTABLISHMENT ON XERIC SITES

Jacob Henry, John L. Willis, David K. Schnake, Scott D. Roberts, Heather D. Alexander, and Heidi Renninger

Abstract—Competition has long been considered a constraint on longleaf pine (*Pinus palustris* Mill.) regeneration. However, observational evidence suggests that neighboring vegetation may facilitate longleaf pine seedlings on xeric sites. To explore this notion, we established a manipulative experiment across a gradient of overstory basal area (9 to 25 m^2/ha) with or without a hardwood midstory in the North Carolina Sandhills. After 2 years, seedling survival averaged 80 percent, differed significantly among overstory density groupings (p = 0.0006), and was lowest (73 percent) under high overstory density (greater than 18 m^2/ha). Seedling survival also varied significantly among midstory treatments (p = 0.0261), with the highest survival occurring beneath an intact midstory (84 percent). Seedling biomass averaged 10.5 g, varied significantly among overstory groupings (p = 0.0007), and was greatest (10.9 g) under low overstory density (less than 12 m^2/ha). The presence of a hardwood midstory did not significantly impact seedling growth.

INTRODUCTION

Decades of silvicultural research have highlighted competition as a contributing factor to longleaf pine (*Pinus palustris* Mill.) regeneration failures. Multiple studies have demonstrated that grass stage longleaf pine seedlings compete poorly for resources with established mature trees, midstory hardwoods, and herbaceous vegetation (Brockway and others 1998, McGuire and others 2001, Pecot and others 2007). Consequently, natural regeneration prescriptions for longleaf pine typically involve reducing overstory density through harvesting and applying low-intensity prescribed fire or herbicides to control understory competition prior to seed fall (Kush and others 2004, Menges and Gordon 2010). Collectively, these treatments are thought to provide longleaf pine with the optimal high resource environment needed to expedite development out of the grass stage.

In some situations, however, longleaf pine regeneration must be accomplished within the structure of additional natural resource objectives, thus preventing the use of established silvicultural techniques. For example, managing mature longleaf pine stands for red-cockaded woodpecker (*Picoides borealis* Viellot) (RCW) habitat has become a common natural resource objective (Walters 1991). RCW is an endangered bird found in the longleaf pine ecosystem that prefers large diameter trees for cavities (Rudolph and Conner 1991) and extensive longleaf forests for foraging (Henry 1989). When managing for RCW, overstory trees are maintained at a target density of 12 to 18 m^2/ha to provide sufficient cavity trees and the open canopy that is preferred by RCW (U.S. Fish and Wildlife Service 2003). This target density is, however, a potential impediment to longleaf pine seedling development (Croker and Boyer 1975).

Following the traditional model of longleaf regeneration also may not be appropriate for all sites. Many of the studies documenting the effects of intense understory competition on longleaf pine seedlings have been conducted on mesic sites, where resource competition is magnified. In contrast, on more xeric sites, seedling persistence under stressful growing conditions may be more important than resource competition. Moreover, on xeric sites, neighboring vegetation may facilitate longleaf pine seedling development by providing partial shade (Allen 1954) or redistributing water in the upper soil profile (Espeleta and Donovan 2002). Evidence of facilitative effects of competing vegetation on longleaf pine seedlings on xeric sites has been accumulating

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(Hiers and others 2014, Loudermilk and others 2016, Wahlenberg 1946), potentially bringing into the question our understanding of stand dynamics on xeric sites. However, little information exists detailing whether understory facilitation interacts with overstory density, or the processes through which longleaf pine seedlings are being facilitated.

To explore these questions, we established a stand-level manipulative experiment examining the growth and survival of planted seedlings across a gradient of overstory density in both the presence and absence of midstory hardwoods on a xeric site in the Sandhills Ecoregion. Specifically, we were interested in how the survival and growth of longleaf pine seedlings respond to (1) overstory density, (2) the presence of midstory hardwoods, and (3) the interaction of overstory density and midstory hardwoods. Clarifying the contributions of overstory density and midstory hardwoods to longleaf pine seedling performance will refine our understanding of competitive interactions on xeric sites and provide land managers with information to help improve regeneration prescriptions.

MATERIALS AND METHODS

Site Description

Our experiment was conducted in the Sandhills Ecoregion of North Carolina (35° 03’ 34.6932” N, 79° 22’ 22.0872” W) on the McCain Tract, managed by the Research Stations Division of the North Carolina Department of Agriculture and Consumer Services. Average monthly temperatures in Raeford, NC, (1981 to 2010) ranged from highs of 11.1 °C (January) to 32.1 °C (July) to lows of -1.7 °C (January) to 20.6 °C (July) (Arguez and others 2010). Average monthly rainfall (1981 to 2010) ranged from 77 mm (November) to 138 mm (July) (Arguez and others 2010), with an average annual total precipitation of 1182 mm. All experimental plots were established within mature longleaf pine stands growing on the Candor soil series (USDA NRCS 2019). The relevant characteristics of this series are that it has rapid permeability with no flooding frequency and is sandy throughout the entire soil profile while somewhat clayey and loamy at the deepest soil horizons (1.5 to 2.0 m). Longleaf pine was the dominant overstory species at the site, with basal areas ranging from 2 to 41 m^2/ha. The midstory (6,228 stems/ha) was dominated by turkey oak (*Quercus laevis* Walter; 82.3 percent) with admixtures of blackgum (*Nysssa sylvatica* Marsh; 9.1 percent) and sassafras (*Sassafras albidum* (Nutt.) Nees; 6.6 percent). Across the site, hardwood heights ranged from 0.1 m to 6.7 m, with an average height of 1.2 m. The herbaceous layer was dominated by wiregrass (*Aristida stricta* Michx.). The site was primarily managed to maintain RCW habitat with a secondary objective being longleaf pine regeneration. To accomplish both objectives, the stand was treated with a dormant season (December to February), low-intensity prescribed fire on a 3-year return interval.

Experimental Design

The experiment was established as a randomized complete block design. In February 2016, 15 experimental blocks (0.10 ha) were established across a gradient of longleaf pine overstory density (2 to 41 m^2/ha). Nine plots (0.002 ha) were nested within each block. Overstory basal area was determined at the plot level with a 10-basal area factor prism, and plots were then placed into one of three groups of overstory density based on RCW management guidelines (Costa 1992): less than 12 m^2/ha (low), 12 to 18 m^2/ha (prime), and greater than 18 m^2/ha (high). Each plot was planted with 16 containerized, 1-year-old longleaf pine seedlings spaced approximately 1 m apart. Midstory hardwoods were controlled by treating prior to planting (R0), treating after 1 year (R1), or left untreated (UN) for the entirety of the experiment (2 years, 2016 and 2017). Plot treatments consisted of cut stump treatment of midstory hardwoods following mechanical removal with brush saws in one-third of the plots with Brushtox Brush Killer herbicide (61.6 percent Triclopyr, Ragan and Massey, Inc., Gig Harbor, WA) mixed with methylated seed oil in a ratio of one part oil to nine parts herbicide each year in May with the goal of eliminating the hardwood midstory. For any hardwood sprouts that survived the cut stump treatment, the foliage was sprayed with the same herbicide the following summer. Plots with lowest oak densities were selected as (R0) in order to ensure adequate and less variable midstory hardwood stocking in the remaining plots. All other treatments were randomly assigned to remaining plots. To eliminate potential edge effects, each plot was separated by at least one buffer plot that received the same treatment as its nearest planted plot.

Sampling Design

Seedling survival and growth were measured in October 2017 at the end of the second growing season. Seedling survival was recorded for every seedling and averaged at the plot level. Growth was assessed through aboveground dry biomass (g) obtained from a random subsample of four seedlings per plot. Seedlings sampled for biomass were cut at the ground-line, stored in sealed plastic bags in a cooler with ice packs, transported to Mississippi State University, dried in an oven for 48 hours at 70 °C, and subsequently weighed.

Statistical Analysis

Linear mixed models were utilized to explore the impacts of overstory basal area, midstory hardwood presence, the interaction between overstory density and midstory hardwoods, and block on longleaf seedling growth and survival. Overstory basal area and midstory treatments were considered fixed effects, while block was considered a random effect. The response variables of longleaf pine seedling survival and growth were averaged at the plot level (*n* = 135). Mixed model selection was accomplished through backwards selection, where all effects were placed in the model, and subsequently removed when results of Type 3 tests were nonsignificant. Significant fixed effects were then further explored with Tukey-Kramer multiple comparison tests, to identify significant differences between midstory treatments or overstory groupings. Use of the variance components covariance structure was required for model convergence. All tests were evaluated at α = 0.05 level. Residuals were evaluated for all models to ensure assumptions of normality, equal variance, and independence were not violated. All analyses were performed in SAS 9.4 (SAS Institute Inc., Cary, NC).

RESULTS

Seedling Survival

Seedling survival was best explained by a model containing the fixed effects of midstory treatment and overstory groupings, and the random effect of block. Seedling survival differed significantly among overstory groupings (p = 0.0006), with seedlings growing beneath a low density overstory (86 ± 11 (SE) percent) having greater survival than those growing beneath high overstory density (73 ± 16 percent) (p = 0.0001) (fig. 1). Seedling survival in midstory treatments differed significantly (p = 0.0261), with seedlings growing beneath an intact midstory (UN) (84 ± 13 percent) having greater survival than seedlings whose hardwood midstory was removed after 1 year (R1) (76 ± 17 percent) (p = 0.0280) (fig. 2). The interaction of midstory hardwoods and overstory groupings did not significantly impact seedling survival.

Seedling Growth

Seedling biomass was best explained by a model containing the fixed effect of overstory groupings, and the random effect of block. Seedling biomass in overstory groupings differed significantly (p = 0.0007), with seedlings being significantly larger in the low-density grouping (10.9 ± 1.2 g) compared to both prime density (10.3 ± 1.0 g) and high density (10.0 ± 0.7 g) (fig. 3). Seedling biomass did not vary among midstory treatments (fig. 4). Midstory treatments and their interaction with overstory groupings did not significantly impact seedling biomass, and were therefore not included in the model.

DISCUSSION

Tree regeneration on xeric sites is a long-term process. Thus, the results of our 2-year study should be viewed only as a preliminary indicator of longleaf pine seedling performance under a variety of competitive positions. Future analyses featuring longer term data and more

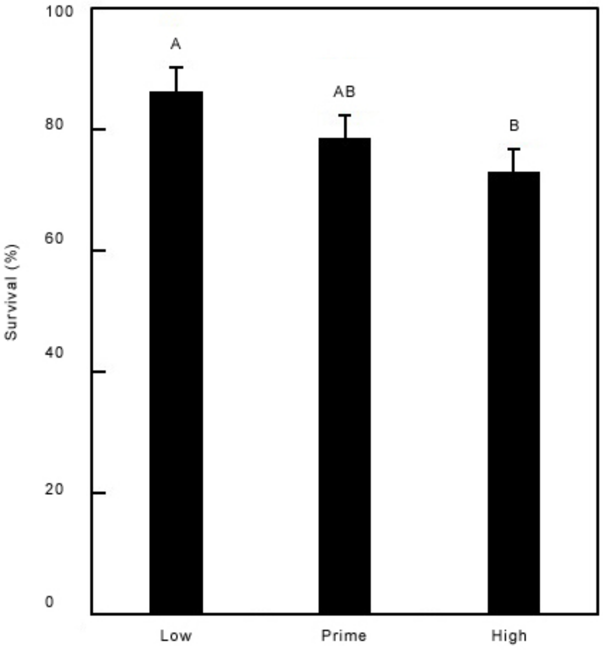

Figure 1—Average 2-year survival (percent) of planted longleaf pine seedlings among overstory groupings (less than 12 m^2/ha (low), 12 to 18 m^2/ha (prime), greater than 18 m^2/ha (high)). Error bars represent one standard error. Bars with differing letters denote a significant difference at the 0.05 level from Tukey-Kramer multiple comparison tests.

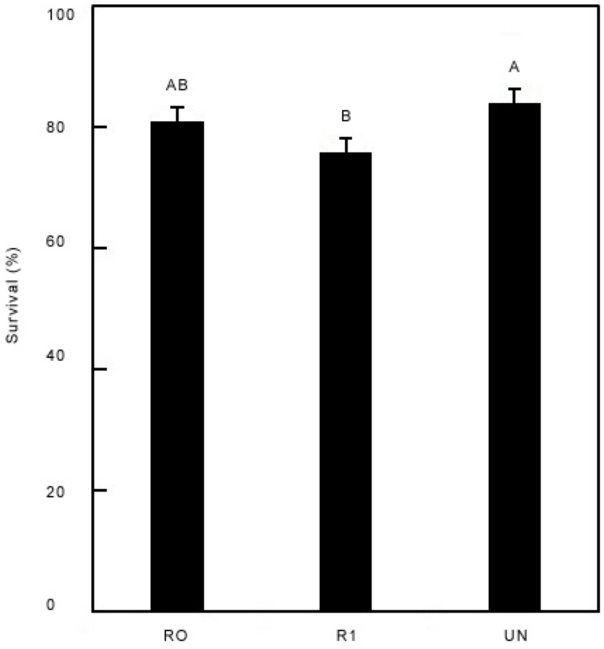

Figure 2—Average 2-year survival (%) of planted longleaf pine seedlings among midstory treatments (treatment prior to planting (R0), treatment after 1 year (R1), or left untreated (UN)). Error bars represent one standard error. Bars with differing letters denote a significant difference at the 0.05 level from Tukey-Kramer multiple comparison tests.

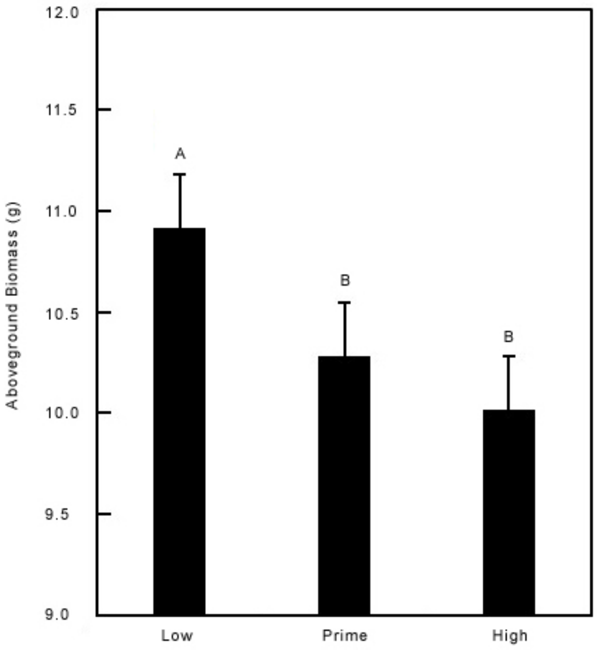

Figure 3—Average 2-year aboveground biomass (g) of longleaf pine seedlings among overstory groupings (less than 12 m^2/ha (low), 12 to 18 m^2/ha (prime), greater than 18 m^2/ha (high)). Error bars represent one standard error. Bars with differing letters denote a significant difference at the 0.05 level from Tukey-Kramer multiple comparison tests.

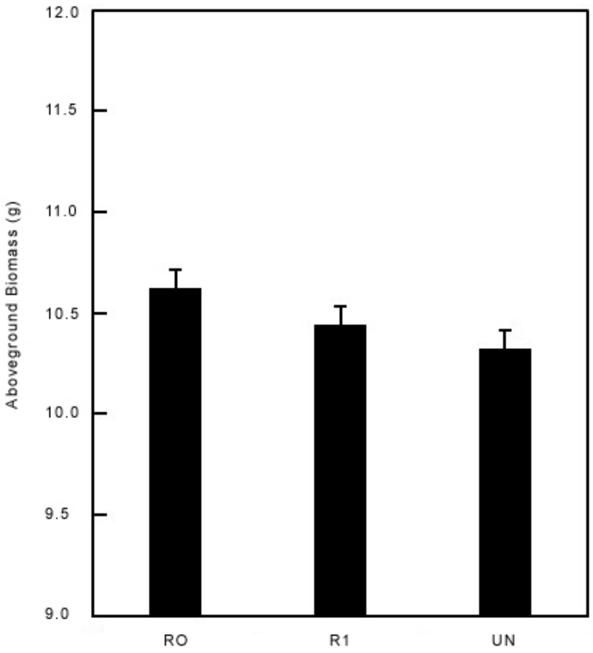

Figure 4—Average 2-year aboveground biomass (g) of longleaf pine seedlings among midstory treatments (treatment prior to planting (R0), treatment after 1 year (R1), or left untreated (UN)). Error bars represent one standard error. There were no significant differences among treatments at the 0.05 level from Tukey-Kramer multiple comparison tests.

detailed physiological evidence will provide better indicators of the complex relationships introduced here.

Overstory Density

Longleaf pine seedling survival exhibited an inverse relationship with overstory density, where survival decreased as overstory density increased. Interestingly, differences in survival were only detected between the low- and high-density groupings, indicating that managing overstory density within the prime RCW range did not have a strong negative influence on longleaf pine seedling survival after 2 years. This apparent competitive effect of high overstory density may have been caused by belowground competition (Brockway and others 1998), as even at the high overstory densities light availability averaged 1045 μmol/m^2/s, exceeding the favorable light threshold of 800-900 μmol/m^2/s (Jose and others 2003). Consistent with our findings, Grace and Platt (1995) demonstrated a similar negative relationship between overstory density and seedling survival. In contrast to our findings, a similar study conducted in southwestern Georgia, under xeric conditions, did not find a significant relationship between survival and overstory density after one growing season (Palik and others 1997). However, given the short measurement interval, it remains difficult to discern whether this finding reflected overstory facilitation or the short measurement duration.

Aboveground seedling biomass exhibited the same relationship as survival, where growth decreased as overstory density increased. These results support the findings of other studies (Grace and Platt 1995, Palik and others 1997, Pecot and others 2007) reporting a negative relationship between overstory density and longleaf pine seedling growth. However, in contrast to our findings on seedling survival, managing overstory density within the prime RCW range significantly reduced seedling growth. Assessing the effect of the overstory on growth is likely a more sensitive early indicator of overstory influence, as longleaf pine seedlings have been shown to persist in the grass stage in low-resource environments for up to 15 years (Boyer 1990).

Midstory Treatments

Understanding the role of midstory hardwoods on xeric sites is critical for future restoration efforts, as the current practice of burning or otherwise controlling hardwood midstory may be inadvertently contributing to longleaf regeneration failures. Our findings demonstrate that seedling survival was highest in the untreated plots. Moreover, seedling growth was not significantly impacted by the presence of a midstory. Collectively, these findings provide early evidence supporting the existence of midstory facilitation on xeric sites (Maestre and others 2009) and the findings of Wahlenberg (1946) and Loudermilk and others (2016). From a management perspective, this suggests prescribed burning to reduce competition on longleaf seedlings is not having the intended positive effect. It should also be noted that removing the midstory after one growing season did negatively impact longleaf pine seedling survival, which may have resulted in micro-environment change following midstory hardwood removal.

CONCLUSIONS

Plant competition has long been considered an influential factor influencing longleaf pine regeneration. Our preliminary findings suggest that maintaining overstory density within the prime RCW range is negatively influencing longleaf pine seedling growth, but not survival. In contrast, reducing midstory hardwood competition is benefiting neither seedling survival nor growth. After 2 years, we detected no interactions between overstory density and the presence of midstory hardwoods. Future analyses will provide further clarification on whether mature trees or the midstory are inhibiting or facilitating longleaf pine regeneration.

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RESTORATION OF LONGLEAF PINE IN THE SOUTHERN REGION OF THE U.S. FOREST SERVICE: AN OVERVIEW OF THE MILLION-ACRE CHALLENGE

Jeff M. Matthews, Janet Hinchee, and James M. Guldin

Abstract—The forested landscapes of the Southern United States have been dramatically altered by land management practices over the last 150 years, which have in turn greatly reduced the extent of several unique ecosystems and the native flora and fauna to which they are adapted. A case in point is the current status of fire-adapted longleaf pine (*Pinus palustris*) ecosystems, which have declined by 97 percent since European colonization. Although resource managers across the South began efforts to restore longleaf pine on public and private lands more than 70 years ago, efforts are now underway on National Forest System lands in the Southern Region to increase the pace and scale of the restoration of longleaf pine. We focus on efforts to restore longleaf pine under the auspices of America's Longleaf Restoration Initiative, which was authorized by Congress in 2009. In October 2017, the Forest Service, U.S. Department of Agriculture, launched the Million-Acre Challenge, whose goal is to put an additional 1 million acres of longleaf pine-dominated ecosystems back in our national forests. This restoration effort will bring longleaf pine back to sites where it had been eliminated or reduced in scale and scope, and on sites to which it is ecologically adapted, in an effort to increase resilient landscapes that are adaptable to future climate changes. As one of the largest public land management agencies in the longleaf range, the Forest Service embraces the opportunity to lead this restoration effort and to provide successful results that can support and encourage other public agencies and private landowners to follow suit.

INTRODUCTION

There are many compelling reasons to restore longleaf pine (*Pinus palustris*). The species is renowned for high-quality lumber, has excellent resistance to insects and diseases, and is tolerant of drought. Importantly, it is highly adapted to survive and thrive with frequent surface fires, and a host of wildlife and plant species are uniquely adapted to these ecosystems (Kirkman and Jack 2017). Moreover, more than any other southern forest type, longleaf pine ecosystems have an extraordinary historical and cultural legacy (Finch and others 2012).

To restore more acres of longleaf pine, managers need to have an understanding of the historical and current extent of longleaf pine ecosystems and the opportunities to increase the prominence of the species in the future—specifically, where restoration is ecologically appropriate, operationally efficient, and can achieve important ecological outcomes with flora and fauna that depend upon bringing fire-adapted ecosystems back to the landscape. The historical perspective is depressingly easy to establish. Forests in which longleaf pine was dominant or prominent once covered 92 million acres from Virginia to Texas (Frost 1993) but had declined to just over 3 million acres by the 1990s (ALRI 2009).

A large-scale effort to restore this keystone species across its range will certainly have opportunities and challenges. First, the critical importance of prescribed fire in these fire-adapted longleaf pine ecosystems means that priorities might be given to ownerships where controlled burning can be more easily done, such as public lands or large private ownerships, rather than family forests smaller than 100 acres for example. Longleaf pine stands also reach their best habitat value for fire-adapted flora and fauna at ages 40-50 years and older, which again can probably be more easily attained on public lands or conservation-based private ownerships rather than private lands managed for timber value. Third, private lands such as family forests tend to change owners over time, and changes in ownership often are tied to changes in management plans; lands in the public domain or private lands under conservation easement offer a long-term land tenure suited to management of older stands of this iconic species. Finally, efforts to restore habitat for the endangered red-

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cockaded woodpecker (*Leuconotopicus borealis*) are a key driving force to restore longleaf pine on public lands.

RESTORATION OF LONGLEAF PINE: EFFORTS IN THE PAST DECADE

The America's Longleaf Restoration Initiative (ALRI), authorized by Congress in 2009, is a collaborative effort across agencies, organizations, and partners who collectively address the concern over loss of longleaf forests and work together to reverse the downward trend. The first action under the ALRI was the preparation of a Range-wide Conservation Plan (ALRI 2009), developed through the collaboration of 22 State agencies and private organizations, along with support from several Federal agencies. Over the last 10 years, this plan has been the guiding document of restoration efforts to reach the ALRI goal of 8 million acres of longleaf pine either restored or on the path to restoration by 2025.

Under the ALRI, the U.S. Departments of Agriculture, Defense, and Interior entered into a Memorandum of Understanding in 2010. Agency representatives from each department have met regularly each quarter to share successes and offer support to the grander longleaf restoration efforts, and senior executives from each of the three organizations guide the strategic effort as the Federal Coordinating Committee (FCC). The Longleaf Partnership Council (LPC) was formed in 2011 as a 33-member body that coordinates efforts and advocates for increased restoration efforts. This is a diverse group of land managers, conservation experts, scientists, and landowners representing State, Federal, private, and industrial interests who come together for the greater good. The leadership of the LPC meets regularly with the FCC to coordinate the strategic aspects of restoration. However, the work on the ground is coordinated by the LPC, primarily within 17 Significant Geographic Areas (SGA). Each SGA is managed by a Local Implementation Team (LIT) (fig. 1) comprising resource managers, conservation experts, and other partners interested in working with longleaf pine. Most of the national forests with significant longleaf pine acreages are tied to a LIT.

Of course, the key to making this work successful is funding. The primary source of funding for ALRI's restoration program is the National Fish and Wildlife Foundation (NFWF) Longleaf Stewardship Fund, which pools funds from public and private sources, and

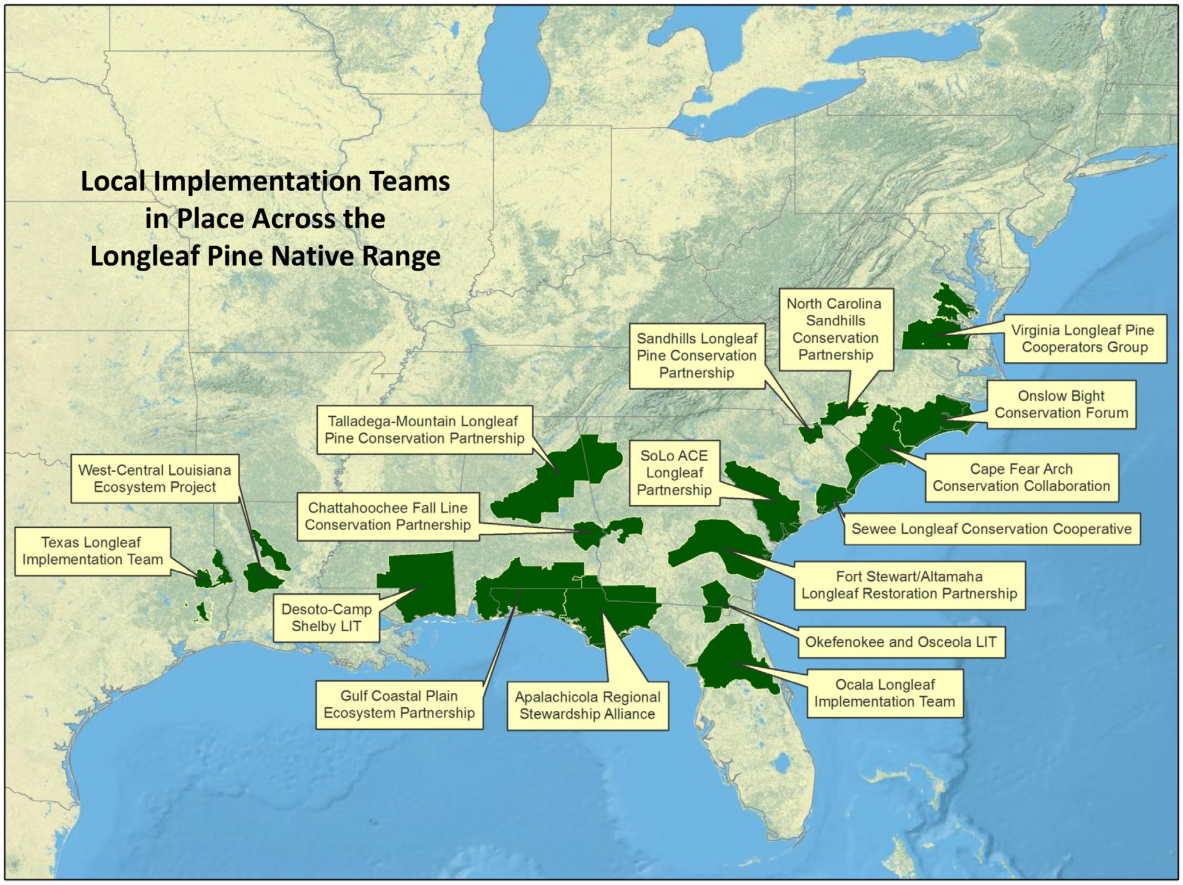

Figure 1—Local Implementation Teams across the range of native longleaf pine.

distributes those funds to the LITs through competitive grants. The NFWF Longleaf Stewardship Fund has been the single largest financial contributor to longleaf pine restoration. This fund has been able to increase the pace and scale of restoration and promote shared stewardship and collaboration. The Longleaf Stewardship Fund is supported by private entities such as the Southern Company, International Paper, Altria Group, Moore Charitable Foundation, and the American Forest Foundation, as well as Federal agencies. Since 2012, the fund has awarded $30.6 million for projects to restore 92,500 acres and to enhance 1,400,000 acres of existing longleaf pine (ALRI 2018). In 2018 alone, over $6.5 million were awarded for longleaf pine projects. In 2018, rangewide accomplishments included over 2 million acres of habitat improvements, a number that includes documented acres of prescribed burning and midstory/understory work in addition to roughly 130,000 acres of planted longleaf pine stands that were established. Seventy percent of the accomplishments occurred on public lands, and 68 percent of the accomplishments occurred within the SGAs.

However, to achieve the ALRI goal of 8 million acres by 2025, an additional 3.3 million acres of longleaf pine must be established (ALRI 2017). With the current progress of 150,000 acres per year of new planted stands, and assuming no losses, longleaf-dominant acres should equal 6,050,000 acres in 2025. In March 2016, the LPC discussed the rate of change in longleaf pine area based on Forest Inventory and Analysis (FIA) data and they concluded that restoration efforts were lagging behind the rate needed to attain the 8-million-acre goal by 2025 (McIntyre and others 2018). Even though FIA data have yet to capture the acres that are moving towards dominance by longleaf pine (Guldin and others 2016), more needed to be done—and it would have to happen on Federal lands. Indeed, the LPC identified increasing longleaf pine restoration efforts on Federal lands as one of the "game changers" (in other words, the "specific, action-oriented strategies that will significantly accelerate the pace of restoration") in stemming the decline of longleaf pine (ALRI 2017: 15).

THE MILLION-ACRE CHALLENGE ON NATIONAL FOREST SYSTEM LANDS

In response to LPC leadership's April 2016 report on this lag to the FCC, the Forest Service Southern Regional Forester, Tony Tooke asked the Regional Office staff a simple question in July of 2016: "Where are we at in the region with longleaf restoration and how can we do better?" This was key—as the manager of the largest number of acres in the longleaf range, the Forest Service has been and will continue to be a key partner for the ALRI, and is viewed by the ALRI as a leader in longleaf pine restoration for public and private land managers across the region. These questions led to the formation of the Regional Longleaf Restoration Team (RLRT), comprising Regional Office staff, Forest and District line officers and staff, and Southern Research Station scientists. The RLRT spent about 5 months taking an assessment of the opportunities and barriers associated with increasing the pace and scale of restoration, an initial effort that led to the building of many relationships and an increased enthusiasm for longleaf restoration.

By January 2017, a draft regional longleaf strategy had been approved by the directors in the Regional Office; the Regional Forester also approved but emphasized that the plan needed "good numbers and good maps." In response, a subgroup of resource specialists in data interpretation, ecosystem modeling, and Geographic Information Systems (GIS) worked together for about 3 months to develop draft estimates of the current area in longleaf pine, as well as the area that had biological potential to be restored to longleaf pine. The RLRT sent these estimates to the national forests in the summer of 2017 for validation. Feedback from that validation was used to develop a comparison between the desired longleaf acres from each national forest's Land and Resource Management Plan (forest plan), the biological potential for longleaf pine based on ecosystem models or LANDFIRE vegetation and fuels data products, and estimates of both the current acres in longleaf pine and the acreage goals that could be attained by 2025 for each national forest.

As all of these estimates and revisions were being made, especially acknowledging the validation of data by the respective national forests, it became apparent that there was an opportunity to make a landmark announcement not just to the Southern Region of the Forest Service, but also to the FCC, the LPC, and to public and private land managers across the South. As a result, on October 23, 2017, the new acting Regional Forester, Ken Arney, issued the "Million-Acre Challenge"—stating that the national forests of the Southern Region were committed to establishing an additional 1,000,000 acres on the path towards restoration of longleaf pine.

In February 2018, Forest Supervisors and their key Staff Officers met with Regional Office leadership to discuss increasing longleaf restoration efforts and how the Regional Office could best support the field units. In March 2018, Forest Supervisors were asked to develop the specific strategies they would pursue to achieve their acreage goals, including annual milestones for attaining these goals. Each national forest was then asked over the summer of 2018 to spatially assess acres currently on the path towards restoration and specific plans for acres to be put on the path in fiscal years 2019 and 2020. As a result, each national forest has a challenge acreage goal to reach by 2025, and a spatial representation of planned progress that will further aid future planning and coordination across ownerships within the greater longleaf range. In addition, over the course of fiscal year 2018, Regional Office staff conducted a series of field visits to meet with Forest Leadership Teams and discuss concerns with achieving acreage goals.

How can this Challenge be met under the limited options available? Currently, the two silvicultural approaches to widespread restoration of longleaf pine are to replant it in areas to which it is adapted (and where it is absent) and to encourage (increase) the dominance of longleaf pine in stands where it is currently a minor component. Given the limitations on the former, the latter may prove more promising. Recent research (Guldin 2018, Guldin and others 2016) suggests the possibility of managing stands with a minor component of longleaf pine through free thinning that harvests the non-longleaf component, retains longleaf, and thereby increases the dominance of longleaf after thinning (fig. 2). If that management approach is successful, estimates of the area of longleaf pine that can be restored based on the RLRT's calculation method may increase substantially. This idea was vetted with LPC leadership and then included in regionwide recommendations for longleaf pine restoration (ALRI 2017).

After all, the current estimate of 4.7 million acres of longleaf pine rangewide does not include all of the acres being actively managed for longleaf restoration that have yet to achieve longleaf dominance. Hence, to further develop the Million-Acre Challenge, the RLRT defined the concept of a stand "on the path towards restoration" by identifying the first concrete step that managers have taken to implement a restoration treatment (table 1). In an effort to better account for all the good work being done on the ground, the RLRT worked with the LPC leadership in the fall of 2016 to develop a "three-step trigger system" for counting National Forest System acres on the path towards longleaf pine restoration (fig. 3). The idea started with a conversation around Forest Inventory and Analysis data in comparison with data available in the FSVeg (U.S. Forest Service 2017) stand exam database. Current regional estimates of longleaf pine are based on Forest Inventory and Analysis data; those data are augmented on National Forest

Figure 2—Free thinning (harvesting pines that were not longleaf) in a mixed-pine stand on the Francis Marion National Forest retained the longleaf pine trees in the overstory and in regenerating groups. (Photo by James M. Guldin, U.S. Forest Service)

Table 1—Development of the Million-Acre Challenge to increase the pace and scale of longleaf pine restoration on National Forest System lands

Forest	Historical longleaf range	Current longleaf range	Potential additional range	Longleaf present but not dominant	Desired[a] 2008	Desired[a] 2017	Challenge: New acres on the path by 2025
				acres			
NFs in Alabama	229,397	160,430	68,967	24,477	201,400	201,400	40,970
Chattahoochee-Oconee NFs	1,006	526	480	20	1,100	30,150	29,624
NFs in Florida	552,264	219,031	333,233	37,691	220,548	441,811	222,780
Francis Marion and Sumter NFs	140,396	50,432	89,964	12,496	53,501	112,317	61,885
Kisatchie NF	339,920	128,569	211,351	59,068	263,000	271,936	143,367
NFs in Mississippi	580,345	247,477	332,868	2,787	580,345	580,345	332,868
NFs in North Carolina	41,453	15,917	25,536	1,529	34,300	34,300	18,383
NFs in Texas	231,373	30,891	200,482	7,044	138,180	185,098	154,207
Savannah River Site[b]	—	47,133	—	—	—	—	—
Regionwide	2,116,154	853,273	1,262,881	145,112	1,492,374	1,857,357	1,004,084

NF: National Forest.

[a] Forest plan data were compiled in 2008 for the America's Longleaf Restoration Initiative conservation plan published in 2009. Since then, some national forests have increased the biological potential for longleaf pine based on ecosystem modeling/LANDFIRE analysis.

[b] The Savannah River Site is managed by the U.S. Forest Service but is administered by the U.S. Department of Energy, so the accomplishments and goals were not represented nor included in the totals for accomplishments on national forests or the Million-Acre Challenge.

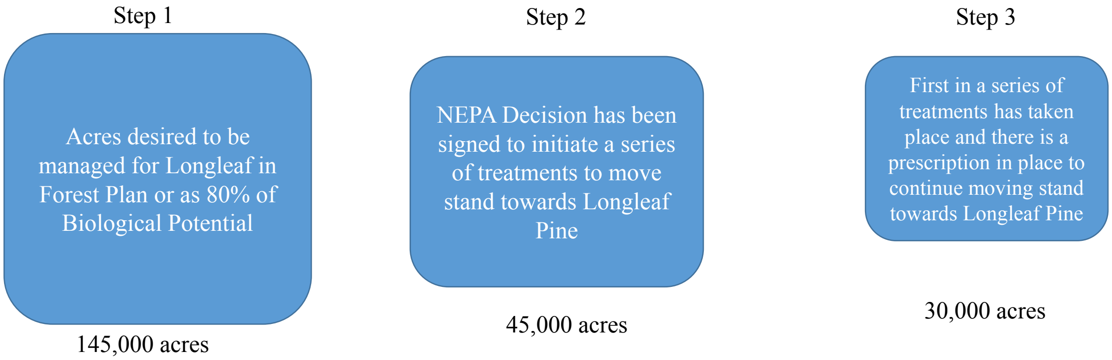

Figure 3—An example of the three-step trigger system to count acres on the path towards longleaf pine restoration on a national forest. NEPA = National Environmental Policy Act.

System lands using FSVeg stand exam data, which is based on forest type. As a result, stands that are being transitioned from a different forest type into longleaf pine over time are missed under the current reporting method. The RLRT also recognizes that the process of restoration does not occur overnight and in fact may go on for 30 to 40 years or more. Moreover, the ALRI does use forest type as its metric for restoration, so the three-step trigger system will improve the consistency of quantifying the pace of restoration on National Forest System lands.

Figure 3 provides an example of a national forest that may have some stands currently on the path towards restoration (step 1), where there is a signed National Environmental Policy Act (NEPA) decision (step 2), and a prescription to move a stand to a desired condition of longleaf and a restoration process that has begun (step 3). Counting acres on the path towards restoration at step 1 or step 2 would be premature as no treatments have taken place on the ground yet. At step 3, the three-step trigger system ensures that acres are not counted until restoration efforts have actually begun on the ground and there is a plan in place to see the process through. Acres "on the path" is a category of acres that to date has not been counted, but it is important to include these in our regional assessments (table 2). This inclusion is valuable for two reasons: 1) it is important to capture and be aware of the great work that resource managers are doing to restore longleaf; and 2) when the year 2025 arrives and if the restoration has not met the 8-million-acre ALRI goal, it will be important to objectively specify how much area is currently in longleaf pine-dominant stands and how much area is actively on the path to restoration.

Using the National Forests in Alabama as an example, the historical range of longleaf pine was established at 229,397 acres. Currently, there are 160,430 acres of longleaf pine-dominant stands (Forest Type 21) within the range. This difference represents the potential additional acres (the opportunity) of 68,967 acres. According to stand exam data summarized in FSVeg (U.S. Forest Service 2017), there are also 24,477 acres with a minor component of longleaf pine. This is based on the 20 percent of stands that have stand exam plot data across the region, where the stand is not typed as a pure or mixed longleaf pine stand types, but there are some longleaf trees recorded in the plot data. In the forest plan, there were 201,400 acres shown as desired for longleaf pine (National Forests in Alabama 2004). The 2017 desired column in table 1 is based on the greater of either the area cited in the forest plan or 80 percent of the biological potential in the ecosystem modeling/LANDFIRE analysis. That "80 percent of biological potential" calculation was used as a conservative estimate to allow for errors in the data, and for operability issues or other ecological or managerial constraints on the ground. So, the final column in table 1 is the challenge for the National Forests in Alabama, which is to put an additional 40,970 acres on the path towards restoration by 2025. This number may seem daunting, but it does not mean that the plan would be to clearcut and plant that many acres. It also does not mean that land managers are going to advocate planting longleaf everywhere; as with all decisions being made in the agency, the goal is to re-establish longleaf pine where it is biologically appropriate.

Based on the responses from the eight national forests and the Savannah River Site, there are 370,653 acres currently on the path towards restoration, which account for 37 percent of the goal of 1 million acres (table 2). That is exciting, because for the first time the RLRT has an accounting of the acres that are on the path to restoration, which helps tell more of the story of the restoration efforts on the ground. This does not mean that there are an additional 370,653 acres in longleaf-dominant stands today; rather, this represents the future stands that will be present if treatments continue to keep these stands on the path towards restoration. With the planned addition of 254,546 acres on the path in FY2019 and FY2020, the national forests could reach 62 percent of the million-acre goal by the end of 2020 (table 2).

Table 2—Area of National Forest System lands currently on the path towards restoration based on the three-step trigger system

Forest	Challenge: New acres on the path by 2025	Currently on the path	Additional planned on the path in 2019	Additional planned on the path in 2020
	acres			
NFs in Alabama	40,970	24,477	1,194	2,062
Chattahoochee-Oconee NF	29,624	11,953	12,000	12,000
NFs in Florida	222,780	0	51,487	69,687
Francis Marion and Sumter NFs	61,885	9,189	990	6,868
Kisatchie NF	143,367	88,130	11,349	11,349
NFs in Mississippi	332,868	203,543	7,744	6,148
NFs in North Carolina	18,383	684	1,700	1,900
NFs in Texas	154,207	32,677	29,485	28,583
Savannah River Site[a]	24,549	10,174	—	—
Regionwide	1,004,084	370,653	115,949	138,597

NF: National Forest.

[a] The Savannah River Site is managed by the U.S. Forest Service but is administered by the U.S. Department of Energy, so the accomplishments and goals were not represented or included in the totals for accomplishments on national forests or the Million-Acre Challenge.

THE VALUE OF PARTNERSHIPS IN LONGLEAF PINE RESTORATION

The ALRI goal of 8 million acres by 2025 is ambitious. If each of the public and private landowners in the region went about restoring longleaf pine on their own, no doubt some progress toward the goal would be made. But it is certain that even more can be achieved if land managers work collaboratively, strategically, and across boundaries of ownership in a shared stewardship approach. Just because ownership boundaries exist does not mean the potential vegetation types should change. Tools and mechanisms already exist for jointly conducting burns and other land management activities. Patience will also be required. After all, it takes time to shift and make longleaf pine a higher priority in NEPA analysis and hence it is to be expected that planned 2019 accomplishments are lower than those planned for 2020. If national forests have maps of work planned in 2019 and 2020, then this information will be available for conversations with partners and adjacent landowners to collaborate on projects.

Partnerships are among the most valuable assets available and will prove critically important: the Forest Service will not be fully successful with the Million-Acre Challenge and the restoration of longleaf pine without the support of and collaboration with partners. It is not just restoration on National Forest System ground that is important, but also working with partners and neighboring landowners to link up blocks of habitat. Many avenues exist that can coordinate and provide that support. Partners can provide additional funding and resources. For example, on a good burning day, weather might permit several prescribed fires on a given national forest ranger district, but the district may not have the staff or assets to properly implement multiple prescribed burns. However, when partners bring their staff and assets to the table, the mission can be more easily accomplished. Partners are also able to advocate for Forest Service restoration efforts, both with the public and with lawmakers at the State and Federal level. Sometimes people do not believe what the Forest Service line officer or resource specialist suggests about a given management practice; however, those same publics will listen to a valued partner.

An example of a partnership that is working well is the North Carolina Sandhills Conservation Partnership. This group formed nearly 20 years ago and consists of many Federal, State and private partners across a large landscape with a focus on common goals of restoring longleaf pine (fig. 4). The shared resources of the partnership enable managers to achieve more than if each individual entity focused on their own piece of land. Moreover, this partnership has developed its own goals in terms of priority areas to focus on for habitat connectivity and to maximize the effectiveness of the treatments. Collectively, proposals are developed to seek out grant funding to conduct treatments across many land ownerships and that all contribute towards advancing the goals of the broader group. Resource managers with the North Carolina Sandhills Conservation Partnership have worked with the Uwharrie National Forest to improve landscape management, including input on where to focus restoration efforts, providing opportunities to engage with landowners, leveraging funding, and maintaining a focus on restoration when the forest is distracted by other events such as hurricanes.

SUMMARY

The Southern Region of the Forest Service has worked hard to map existing longleaf pine stands and to identify areas that have the potential for longleaf pine. In doing so, the ambitious "Million-Acre Challenge" will go a long way toward achieving the equally ambitious ALRI goal of 8 million acres of longleaf pine restored, or on the path to restoration, by 2025. In one sense, the work being done on national forests is a model for other public and private landowners to refocus their efforts in longleaf pine restoration across the South. But equally importantly, the Southern Region recognizes and embraces the value of working with partners across ownerships in a shared stewardship context, to achieve not only the National Forest System challenge but the ALRI challenge as well. These are goals that will continue through the year 2025 and for the duration of the 21st century. All the while, it is important to remember that the goal of restoration is not just to bring back longleaf pine as a dominant tree species; it is to restore the fire-adapted mature pine ecosystems that are so dramatically underrepresented on the landscape and to provide for the many species of flora and fauna that depend upon these ecosystems. After all, while the number of acres of longleaf-dominant forests is an important *measure* of success, the response in wildlife and species diversity associated with fire-adapted longleaf pine ecosystems is the equally if not more important *outcome*.

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Figure 4—A maintenance-class longleaf pine stand on State game lands in the Carolina Sandhills, Moore County, North Carolina. (Photo by James M. Guldin, U.S. Forest Service)

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IS PLANTING STOCKTYPE CRITICAL TO LONG-TERM FIELD PERFORMANCE OF LONGLEAF PINE?

Shi-Jean S. Sung, Mary Anne S. Sayer, Daniel J. Leduc, and James D. Haywood

Abstract—Longleaf pine (*Pinus palustris* Mill.) seedlings of five stocktypes, namely, bareroot (BR) and 108- or 164-ml closed-walled cavities of Superblock® or Copperblock® Styroblock containers, were planted at the Palustris and Escambia Experimental Forests. The 120-ml Jiffy® Forestry Pellets (JP) seedlings were also planted at the Palustris site. Among all stocktypes at planting, the BR and JP seedlings had the greatest and smallest root collar diameter, stem length, and fascicle density, respectively. Copper treatment did not affect seedling growth variables at planting. Nine months after planting, seedling survival was the lowest for BR and the highest for seedlings of closed-walled cavities. After 8 years, the Escambia saplings did not differ in growth among all stocktypes whereas the JP saplings were shorter than the rest of the Palustris saplings. Occurrence of drought during the first two field seasons was associated with high mortality and low plot-level stem volume for the BR saplings after 8 years.

INTRODUCTION

The disappearance of about 97 percent of the 37 million ha of pre-European settlement longleaf pine (*Pinus palustris* Mill.) ecosystems in the Southeastern United States was caused by unsustainable harvest for timber and naval stores products, land-use changes that included conversion to agricultural crops or faster-growing loblolly pine (*P. taeda* L.) and slash pine (*P. elliottii* Englem.) forests, urbanization, and exclusion of natural fire regimes from the landscape (Frost 2006, Landers and others 1995). Over the last 3 decades, many public, industrial, and private land managers have planted either bareroot (BR) or container seedlings to artificially regenerate longleaf pine forests in the Southeastern United States (Landers and others 1995, Van Lear and others 2005). Compared to BR seedlings, container longleaf pine seedlings generally have a wider planting window and greater first-year field survival (South and others 2005). For the 2005–2006 planting season, 70 percent of all longleaf pine seedlings produced in the Southeastern United States were of the container stocktype (McNabb and Enebak 2008). This trend of preference for container longleaf pine seedlings continues to date. However, between the ages of 5 and 10 years, juvenile stem instability (such as leaning, toppling, and windthrow) occurs most commonly among container longleaf saplings during or after high sustained winds (Haywood and others 2012, South and others 2001, Sung and Dumroese 2014). Widespread toppling in container lodgepole pine (*P. contorta* Dougl.) plantations in British Columbia was attributed to spiraled lateral roots in the root plug (Balisky and others 1995, Burdett and others 1986).

A few modifications in container cavity designs have been attempted to improve the morphology of container seedling lateral roots. One of the improvements is to coat the interior wall of the cavities with a copper (Cu) compound (such as copper oxychloride). Cu stops seedling primary lateral roots from elongating once they reach the cavity wall (Burdett 1978, Ruehle 1985). Longleaf pine seedlings cultured in Cu-coated cavities produced more new higher order roots than those cultured in non-Cu cavities during root growth potential tests (South and others 2005; Sword Sayer and others 2009, 2011). The Cu root pruning treatment also favored root biomass allocation to the taproot and secondary lateral roots of longleaf pine seedlings (Dumroese and others 2013; Sword Sayer and others 2009, 2011). The benefit of chemical root pruning to stem vertical stability was observed by Krasowski (2003) who found that lodgepole pine grown in Cu cavities had fewer leaning seedlings than those grown in non-Cu cavities 3 years after planting. Another cavity improvement is the presence of slits or vents along the cavity wall. Once lateral roots reach these openings, they are air pruned.

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Planted Scots pine (*P. sylvestris* L.) seedlings cultured in slit cavities showed improved root system structure and stem straightness compared to seedlings grown in closed-walled cavities (Rune 2003). Longleaf pine seedlings cultured in vented cavities had fewer deformed lateral roots and a larger taproot than seedlings grown in the closed-walled cavities (Sung and Haywood 2016).

In most longleaf pine plantation establishment studies, the early field performance of planted longleaf pine seedlings is based on survival, groundline diameter, and seedling emergence from the grass stage. A few studies have established the relationship between planting stock quality and the early field performance of container longleaf pine seedlings. For example, in a field trial of longleaf pine seedlings cultured in three container cavity sizes with or without Cu coating, planting stock size and subsequent first-year field growth were closely related (Sword Sayer and others 2009). Seedlings from 164-ml cavities had greater root collar diameter (RCD) and biomass during nursery culture and 1 year after planting compared to seedlings from 60-ml cavities (Sword Sayer and others 2009). Although Cu root pruning did not affect longleaf pine seedling RCD at lifting, the Cu seedlings were larger in stature compared to those cultured without Cu root pruning 5 years after planting (Haywood and others 2012). Here, we compared seedling growth characteristics at planting for longleaf pine seedlings cultured in soft, meshed-walled Jiffy® Forestry Pellets (air lateral root pruning), closed-walled cavities of Superblock® containers, closed-walled cavities with Cu coating of Copperblock® (chemical lateral root pruning) containers, and nursery beds (BR). Seedling survival through 9 months after planting and sapling survival and growth 8 years after planting are also reported.

MATERIALS AND METHODS

Seedling Production

A south Alabama seed source, Seed Lot 01-2-121-1-06-01 (U.S. Department of Agriculture, Forest Service, Ashe Seed Bank, Brooklyn, MS), was used to grow all stocktypes. This seed lot was processed in 2006 and had 96-percent germination after a 14-day stratification.[1] For the BR treatment, seeds were sown in late April 2009 at the Georgia Forestry Commission's Flint River Nursery in Byromville, GA (32°17'N, 83°97'W) at a density of 86 m^{-2}. We grew all container seedlings in a facility of the Forest Service Southern Research Station in Pineville, LA (31°19'N, 92°26'W). Seeds were sown at one seed per cavity on May 19, 2009 inside a greenhouse. Seedlings were brought outdoors in late June and cultured until being planted in early December 2009. Container types included Superblock® (Beaver Plastics, Edmonton, Alta, Canada) (SB); Copperblock® (Beaver Plastics, Edmonton, Alta, Canada) (CuB) which had a coating of copper oxychloride on the interior cavity wall, except the ridges; and Jiffy® Forestry Pellets (Jiffy Products of America, Inc., Norwalk, OH) (JP) which consisted of packed peat inside a soft meshed-wall that was fully soaked in tap water prior to seed sowing. Specifications for each container type are shown in table 1.

The nursery protocol for container seedlings generally followed that of Sword Sayer and others (2009). Fertilization was accomplished by the addition of Osmocote® 19-6-12 slow-release fertilizer (Scotts Company, Marysville, OH) to the growing medium at the time of sowing and application of Peters® Professional 20-20-20 water-soluble liquid fertilizer (J.R. Peters, Inc., Allentown, PA) during seedling culture. Twice as much liquid fertilizer was given to the JP seedlings because Jiffy® Forestry Pellets do not contain slow-release Osmocote® fertilizer in their densely packed peat plugs. Seedling fascicles were not clipped during nursery culture.

Field Experiment

The study was established at two field sites on experimental forests in Louisiana and Alabama. The Palustris Experimental Forest is within the Kisatchie National Forest in Rapides Parish, LA (31°04'N, 92°37'W). The soil is a complex of Malbis fine sandy loam (fine-loamy, siliceous, subactive, thermic Plinthic

Table 1—Container cavity specifications for both the Superblock® (SB) and Copperblock® (CuB) containers and the fully soaked, expanded Jiffy® Forestry Pellets (JP)

Container	Volume	Top diameter	Length	Density
	ml	*cm*	*cm*	*number* m^{-2}
112/105 (medium) (SB, CuB)	108	3.5	14.9	531
77/170 (large) (SB, CuB)	164	4.2	15.2	366
36100 Super (JP)	120	3.8	10.2	592

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[1] Personal communication. 2019. B. Crane. Regional Geneticist, U.S. Department of Agriculture, Forest Service, Region 8, Atlanta, GA 30309.

Paleudults), Ruston fine sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Paleudults), and Smithdale sandy loam (fine-loamy, siliceous, subactive, thermic Typic Hapludults). The Escambia Experimental Forest is in Escambia County, AL (31°00'N, 87°04'W). The soil is a complex of Troup fine sand (loamy, kaolinitic, thermic Grossarenic Kandiudults) and Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults).

In fall 2009, four blocks with seven plots each were established at the Palustris site and four blocks with six plots each were established at the Escambia site. Blocks were established by topography. Treatment plots contained 14 rows of 14 trees planted at a 2- by 2-m spacing for 196 planting spots per treatment plot of 0.0784 ha. The center 10 rows of 10 trees were the measurement plot. Treatments at the Palustris site were (1) BR, (2) 108-ml Superblock® (SB-M), (3) 108-ml Copperblock® (CuB-M), (4) 164-ml Superblock® (SB-L), (5) 164-ml Copperblock® (CuB-L), (6) direct seeding (DS) of the same seed lot as the seedlings, and (7) JP. All treatments except for JP were also installed at the Escambia site. The JP seedlings were only planted at the Palustris site because low seed germination and poor seedling survival reduced the number of JP seedlings available for planting at the end of the cultural period. The DS treatment was used to produce a natural root system for comparison purposes. In early December 2009, four seeds coated with capsaicin (to deter rodents) were placed at each of the 196 planting spots in each DS plot and covered with a thin layer of soil. In early December 2009, the BR seedlings were planted within 2 days of lifting from the nursery beds. Container seedlings were watered the day before being extracted from the containers, stored in plastic bags in a cold room, and planted within 3 days of being extracted.

Laboratory and Field Assessments

Before planting, 20 seedlings of each stocktype were randomly selected for growth characteristics assessments including root collar diameter (RCD), stem length, bud diameter and length, fascicle number, and longest fascicle length. Root collar diameter was measured by digital calipers at the root collar. Stem length was measured by a ruler between the root collar and the base of a terminal bud. Terminal bud diameter was measured with digital calipers at the widest part of the bud. The bud length was measured from the base to the tip. Fascicle density (number of fascicles per cm of stem) was calculated. Seedling root-bound index (RBI) was calculated as the ratio between RCD and cavity top diameter expressed in percentage. Seedling survival was assessed 3, 6, and 9 months after planting except that 3-month survival was not assessed for the Escambia seedlings. Eight years after planting, survival, total height, and diameter at breast height (d.b.h.) were measured with a height pole and calipers, respectively. Individual sapling volume was approximated as a cone:

$$V = \frac{1}{3}\pi\left(\frac{d.b.h.}{2}\right)^2 (total\ height) \qquad (1)$$

Plot-level stem volume was calculated as the sum of stem volume for all surviving saplings within a plot.

Statistical Analysis

At each site, the study was established in a randomized complete block design with each of the four blocks containing seven (the Palustris site) or six (the Escambia site) planting stocktypes. The DS treatment only produced three seedlings on the Escambia site and was dropped from the analyses. A one-way analysis of variance (ANOVA) was used to examine the effects of planting stocktypes on seedling growth characteristics at planting [RCD (mm), terminal bud diameter (mm) and length (cm), stem length (cm), number of fascicles, fascicle density (per cm of stem), length of the longest fascicle (cm), and RBI (percent)]. Field performance of stocktypes was compared at each site separately because JP seedlings were not planted at the Escambia site. A one-way ANOVA with blocks was used to examine seedling survival (percent) 3 to 9 months after planting and sapling field performance after 8 years [survival (percent), total height (cm), d.b.h. (mm), and plot-level stem volume (dm^3)] using SAS® PROC GLM (SAS 2004). If stocktypes differed, a separation of treatment means was done using Duncan's multiple range test. Data from all but JP saplings were combined by site, and a multi-location two-way ANOVA (site and stocktype) with blocks nested within sites was used to test for significant differences between sites in the growth variables. The F-tests and mean separation tests were considered significant at $\alpha < 0.05$.

RESULTS AND DISCUSSION

Nursery Phase

Seed germination in the greenhouse in Pineville, LA, began six days after sowing. Sixteen days after sowing, germination was 81, 79, 82, 75, and 53 percent for the SB-M, CuB-M, SB-L, CuB-L, and JP treatments, respectively. Final percentages of germination assessed 28 days after sowing were 89, 79, 85, 79, and 60 percent, respectively, for the SB-M, CuB-M, SB-L, CuB-L, and JP stocktypes. Many seeds sown to the JP plugs germinated. However, the protruding radicals <0.5 cm in length failed to penetrate the densely packed peat and eventually dried up and caused germinant mortality. An improvement in the JP design is needed to help longleaf pine germinants anchor into the peat plug. Percentages of harvestable seedlings in mid-September were 86, 75, 81, 75, and 55 percent of sown seeds for the SB-M, CuB-M, SB-L, CuB-L, and JP stocktypes, respectively.

Among all stocktypes at planting, the BR were the largest and the JP were the smallest in RCD, stem length, and fascicle number and density (table 2). Compared to container longleaf pine seedlings grown at the same facility as the current study, seedling RCD at planting in the current study was generally within the reported range of 4.2 to 7.3 mm (Jackson and others 2012, South and others 2005, Sword Sayer and others 2011). However, South and others (2005) reported a much larger RCD for BR (13.6 mm) and JP (7.0 mm) seedlings than the BR (9.0 mm) and JP (4.8 mm) seedlings in the current study. The JP seedlings also grew the shortest fascicles among all stocktypes (table 2). It is possible that the small size of the JP seedlings was, in part, due to the amount of liquid fertilizer given not meeting their needs.

At the end of the nursery culture, the Cu root pruning treatment did not affect any of the seedling growth characteristics (table 2). The effects of Cu root pruning treatment on longleaf pine seedling growth at planting or the early field performance have not been consistent among studies. Seedling RCD at planting and 1 or 2 years after planting was not affected by Cu treatment (South and others 2005, Sword Sayer and others 2011). However, Dumroese and others (2013) reported that the Cu treatment significantly affected seedling RCD at planting. Except for RBI, the SB-L seedlings were larger than the SB-M seedlings in all growth characteristics assessed (table 2). Compared to the CuB-M seedlings, the CuB-L seedlings had greater bud diameter and length but were similar in RCD, stem length, number of fascicles, fascicle density, and length of the longest fascicle (table 2). In the study of Sword Sayer and others (2011), RCD of longleaf pine seedlings grown in 164-ml cavities were greater than those in 108-ml cavities for both CuB and SB cavities.

The range of RBI for individual container seedlings in this study was between 7.9 and 26.0 with a mean of 16.2. South and others (2005) indicated that early field mortality increased greatly for seedlings with an RBI greater than 27.0. However, several studies showed that longleaf pine seedlings cultured for regular duration of 27 to 35 weeks did not have an RBI that approached the 27.0 threshold of mortality (Dumroese and others 2013, Jackson and others 2012, Sword Sayer and others 2011). In other words, seedling field mortality was not associated with inadequate rooting volume (RBI >27.0) in the current study or those studies by Dumroese and others (2013), Jackson and others (2012), or Sword Sayer and others (2011).

Seedling Field Performance

On both sites, predation completely removed seeds from all DS spots within 1 week of sowing. The DS plots were re-seeded in early January 2010, but this effort also succumbed to predation. A 2-year drought began in March 2010 (3 months after planting) on the Palustris site and in June 2010 (6 months after planting) on the Escambia site (fig. 1). The percentage of seedling survival decreased greatly from March 2010 to June 2010 for the BR and JP plots on the Palustris site (table 3). Although more BR seedlings survived on the Escambia site than on the Palustris site, we attribute early mortality among the BR seedlings at both sites and among the JP seedlings at the Palustris site to drought. The 3-month delay in drought occurrence and the sandy soils on the Escambia site may be responsible for higher survival for the Escambia BR seedlings than

Table 2—Growth characteristics of six stocktypes of longleaf pine seedlings assessed before planting (*n* = 20 seedlings per container type)

Type	RCD	RBI	Bud length	Bud diameter	Stem length	Fascicle	Fascicle density	Longest fascicle
	mm	*percent*	*cm*	*mm*	*cm*	*number*	*number cm*$^{-1}$	*cm*
BR	9.0 a	--	1.1 a	7.3 a	3.7 a	42 a	11.1 a	35.4 a
SB-M	5.7 d	16.3 a	0.4 cd	4.0 cd	2.0 c	12 c	6.2 c	31.1 b
CuB-M	6.2 cd	17.8 a	0.5 c	4.8 c	2.2 bc	14 bc	6.5 c	33.5 ab
SB-L	7.4 b	17.7 a	0.8 b	6.0 b	2.3 b	21 b	8.9 b	35.8 a
CuB-L	7.0 bc	16.8 a	0.8 b	5.8 b	2.4 b	18 bc	7.8 bc	35.7 a
JP	4.8 e	12.6 b	0.3 d	3.4 d	1.4 d	5 d	3.9 d	19.6 c
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

RCD: root collar diameter; RBI: root-bound index. BR: bareroot; SB-M: 108-ml Superblock®; CuB-M: 108-ml Copperblock®; SB-L: 164-ml Superblock®; CuB-L: 164-ml Copperblock®; JP: 120-ml Jiffy® Forestry Pellets.

Means in each column followed by the same letter were not significantly different at α <0.05 based on Duncan's multiple range test.

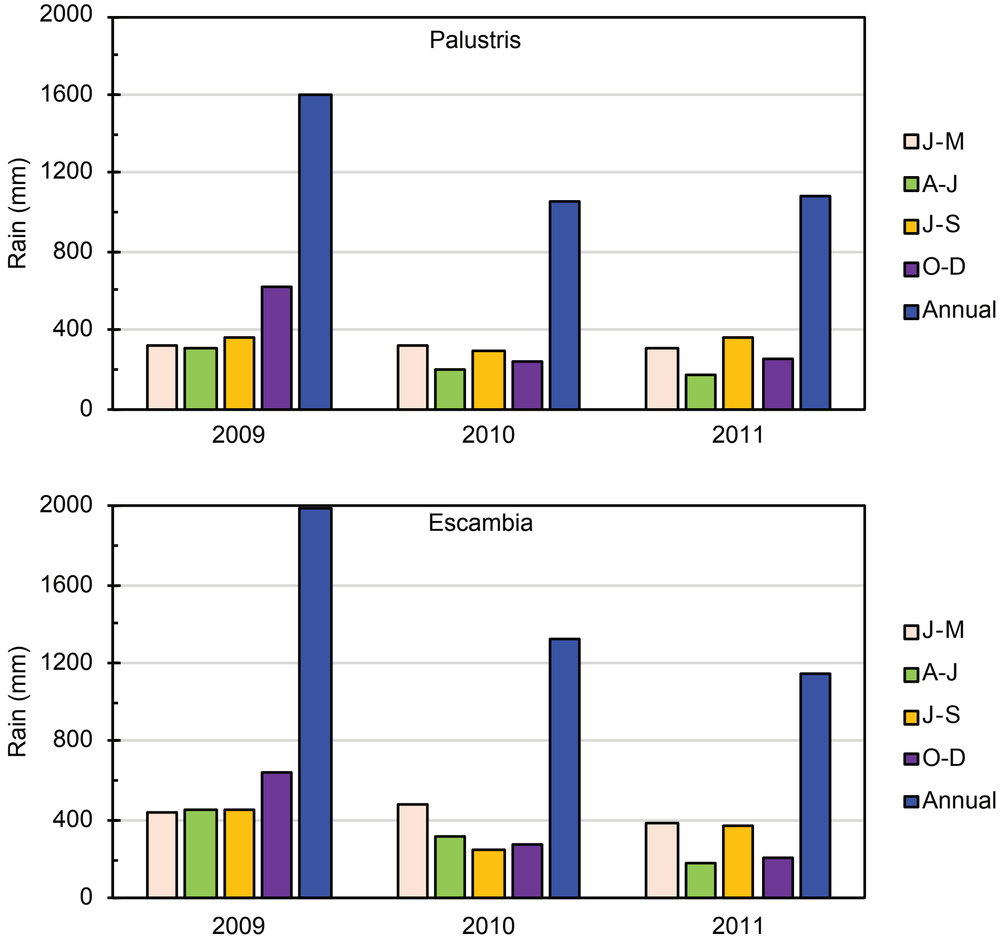

Figure 1—Quarterly and annual rainfall for the Palustris and Escambia Experimental Forests from 2009 to 2011.

for the Palustris BR seedlings. In a study by South and others (2005), BR seedlings had between 67 and 94 percent second year survival on all four planting sites with between 43 and 88 percent survival for container seedlings of various stocktypes. No drought was cited in that study. Similar to the results at the Palustris site (table 3), survival of the JP seedlings (50 to 82 percent) was the lowest among container stocktypes on each planting site in the study of South and others (2005). However, unlike the current study, seedling RCD at planting was not different between JP and the rest of container stocktypes in the study of South and others (2005), suggesting that container seedling mortality may be caused by factors in addition to seedling size.

By the end of the eighth year, only 9 and 31 percent of BR seedlings were alive on the Palustris and Escambia sites, respectively (table 3). At planting, the BR seedlings had similar longest fascicle length to those of CuB-M, SB-L, and CuB-L seedlings, and the BR seedlings had the greatest fascicle density among all stocktypes (table 2). South (1998) suggested that the improved survival of BR longleaf pine seedlings with clipped fascicles was related to reducing transpiration stress. However, the JP seedlings had the shortest and fewest fascicles among all stocktypes (table 2) and also had low survival 9 months after planting (table 3). Therefore, numbers of fascicles and their lengths at planting alone do not explain the high mortality of JP seedlings in our study. South and others (2005 and references cited therein) concluded that low survival of BR seedlings under drought conditions is one of the main reasons container stock is the preferred stocktype for establishing longleaf pine plantations. Our results suggest that the JP seedlings are not a good alternative to other container stocktypes due to a low percentage of harvestable seedlings at lifting, smaller growth parameters at planting, and low early field survival. On the Palustris site, fewer CuB-M seedlings than SB-M seedlings were alive at 6 and 9 months after planting (table 3). Eight years after planting, neither Cu treatment nor cavity size affected sapling survival on the Palustris site. On the Escambia site, the CuB-L saplings had greater survival than the SB-L saplings after 8 years. Survival among all saplings grown in the closed-walled containers ranged between 56 and 72 percent after 8 years. A 2-year drought during the first and second field seasons in this study showed the merit of longleaf pine reforestation using container-grown seedlings instead of the BR seedlings.

Table 3—Survival (percent) between 3 months and 8 years after planting for various stocktypes of longleaf pine seedlings at the Palustris and Escambia Experimental Forests

Type	Mar 2010 (3 mo)	Jun 2010 (6 mo)	Sep 2010 (9 mo)	Dec 2017 (8 yr)
Palustris Experimental Forest				
BR	92 b	24 d	18 d	9 c
SB-M	99 a	97 a	93 a	66 a
CuB-M	97 a	88 b	83 b	62 a
SB-L	98 a	91 ab	87 ab	56 a
CuB-L	98 a	90 ab	88 ab	58 a
JP	94 b	74 c	67 c	37 b
p value	0.0002	<0.0001	<0.0001	<0.0001
Escambia Experimental Forest				
BR	-	55 b	48 b	31 c
SB-M	-	83 a	81 a	61 ab
CuB-M	-	90 a	89 a	70 ab
SB-L	-	90 a	89 a	61 b
CuB-L	-	90 a	89 a	72 a
p value	-	<0.0001	<0.0001	<0.0001

BR: bareroot; SB-M: 108-ml Superblock®; CuB-M: 108-ml Copperblock®; SB-L: 170-ml Superblock®; CuB-L: 170-ml Copperblock®; JP: 120-ml Jiffy® Forestry Pellets.

Means in each column followed by the same letter were not significantly different at α <0.05 based on Duncan's multiple range test.

The long-term impact of seedling quality at planting was evident with the JP stocktype. The JP seedlings grew the least in total height among all stocktypes after 8 years on the Palustris site (table 4). Among the Superblock® and Copperblock® stocktypes, Cu treatment and cavity size did not impact total height, d.b.h., or plot-level stem volume of longleaf pine saplings on either site 8 years after planting (table 4). In a study established with longleaf pine seedlings grown in Superblock® or Copperblock® cavities of three sizes (including the 108-ml and 164-ml cavities used in the current study), the Copperblock® saplings were greater in total height and d.b.h. than the Superblock® saplings after the fifth growing season (Haywood and others 2012). Similar to the current study, saplings from the 164-ml cavities were not different in total height or d.b.h. than saplings of the 108-ml cavities after 5 years (Haywood and others 2012). Although BR saplings on the Palustris site were similar in stature as the SB or CuB saplings, their plot-level stem volume was much lower due to low survival (table 4).

Eight years after planting, total height, d.b.h., and plot-level stem volume were significantly different between the two sites (table 5). There was a significant interaction between treatment and site in regard to survival at age 8. The SB-M saplings ranked highest in the eighth

Table 4—Total height, diameter at breast height, and plot-level stem volume for various stocktypes of longleaf pine seedlings 8 years after planting on the Palustris and Escambia Experimental Forests

Type	Total height	d.b.h.	Plot-level stem volume
	cm	*mm*	dm^3
Palustris Experimental Forest			
BR	505 a	72.0	73.4 b
SB-M	525 a	70.2	515.1 a
CuB-M	560 a	70.7	495.0 a
SB-L	539 a	69.0	412.3 a
CuB-L	540 a	66.5	411.0 a
JP	432 b	59.8	185.2 b
p-value	0.0040	0.0506	<0.0001
Escambia Experimental Forest			
BR	598	69.0	304.4
SB-M	577	64.2	487.7
CuB-M	567	63.2	566.4
SB-L	559	61.3	440.1
CuB-L	608	66.9	629.2
p-value	0.4402	0.2798	0.0561

d.b.h.: diameter at breast height; plot-level stem volume: sum of stem volume among all surviving saplings within a plot.

BR: bareroot; SB-M: 108-ml Superoblock®; CuB-M: 108-ml Copperblock®; SB-L: 164-ml Superblock®; CuB-L: 164-ml Copperblock®; JP: 120-ml Jiffy® Forestry Pellets.

Means in each column followed by the same letter or no letters were not significantly different at α < 0.05 based on Duncan's multiple range test.

Table 5—Comparisons of field performance by five stocktypes of longleaf pine seedlings on the Palustris and Escambia Experimental Forests 8 years after planting

Site	Survival	Total height	d.b.h.	Plot-level stem volume
	percent	*cm*	*mm*	dm^3
Palustris	50	534	69.7	381.3
Escambia	59	582	64.9	485.6
p-value		0.0005	0.0069	0.0077

d.b.h. = diameter at breast height.

Jiffy® seedlings were not planted on the Escambia site and were not included in this comparison.

There was a significant interaction between treatment and site in survival ($p < 0.05$).

year survival on the Palustris site whereas the CuB-L saplings ranked highest in survival on the Escambia site (table 3). Saplings of the Escambia site had greater total height and smaller d.b.h. than those of the Palustris site (table 5). Therefore, the greater plot-level stem volume on the Escambia site was associated with greater survival of the Escambia plantings compared to the Palsutris site. Between the ages of 5 and 10 years, the physical stability of container longleaf pine saplings may be compromised during or after high sustained winds (Haywood and others 2012, South and others 2001, Sung and Dumroese 2014). In this and other studies, only a few saplings had stem displacement which might be the result of once-leaned or toppled saplings that later grew upward by stem overcorrection (Sung and others 2012). Unlike the improved stem stability for lodgepole pine seedlings grown in Cu containers (Krasowski 2003), the positive effects of lateral root pruning treatment (by Cu or air) on the physical stability of longleaf pine saplings are yet to be realized in this study.

CONCLUSIONS

This study extended the traditional short-term (1 to 2 years) evaluation of the field performance of planted longleaf pine seedlings to a long-term (8 years) evaluation. Seedlings grown in 164-ml Superblock® cavities were larger in all growth characteristics than those in 108-ml Superblock® cavities at planting. These cavity size-associated differences in seedling total height or diameter no longer existed 8 years after planting. The copper root pruning treatment did not affect seedling growth at planting or 8 years after planting. Jiffy® Forestry Pellets seedlings survived less and grew less compared to seedlings grown in closed-walled cavities. The surviving bareroot saplings had similar total height and d.b.h. compared to those cultured in closed-walled cavities. The 2-year drought after planting, however, caused low early field survival and low plot-level volume for the bareroot saplings compared to those from the closed-walled cavities. The timing of drought and soil texture may be associated with differences in bareroot seedling performance on the two sites. The absence of growth differences among saplings from the four types of closed-walled cavities 8 years after planting suggests that the choice of closed-walled containers for establishing longleaf pine plantations makes little difference.

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LONGLEAF PINE HYBRIDIZATION: IS THERE A GROWING PROBLEM?

James P. Barnett, Rabiu Olatinwo, D. Paul Jackson, and Stacy Blomquist

Abstract—Longleaf pine (*Pinus palustris*) seedlings grown from seeds collected from two seed orchards in 2014 showed evidence of hybridization with loblolly pine—as much as 80 percent had some stem elongation in the container nursery. This stem elongation, however, was not to the extent that has typically characterized bareroot seedlings of Sonderegger pine (*P.* x *sondereggeri*), the recognized hybrid of longleaf and loblolly (*P. taeda*) pine. Seedlings from these collections were quantified and outplanted. These outplanted seedlings were tracked to determine if they were Sonderegger pine and analyzed by DNA techniques to confirm their taxonomic status. The results indicate that hybridization has not occurred. Seedling development following outplanting and DNA analyses indicate these seedlings are not markedly different from those of typical longleaf pine. The reason for the unusual stem elongation in the nursery has not been determined.

INTRODUCTION

In the summer of 2015, the manager of a container nursery in southern Georgia reported that up to 80 percent of longleaf pine (*Pinus palustris*) seedlings from two seed orchards being grown under contract were showing significant stem elongation. This is the traditional and accepted method for determining if longleaf seedlings have been hybridized with loblolly pine (*P. taeda*). Such hybrids, named Sonderegger pines (*P.* x *sondereggeri*) (Chapman 1922), are typically culled at the nursery due to the poor form and quality they show when outplanted (Wakeley 1954). Based on this reputation, many landowners decline to plant Sonderegger seedlings. However, the elongation observed in the container nursery had not developed to the extent (12 to 15 cm) noted in bareroot nurseries where other seedlings have previously been classified as Sonderegger pines (fig. 1).

The two orchards are major sources of seeds for the longleaf pine reforestation program in the Southern Region of the Forest Service, U.S. Department of Agriculture. The Craig Seed Orchard, located in south Mississippi, is owned by the Mississippi Forestry Commission but provides longleaf seeds to the Southern Region. The Stuart Seed Orchard, located at Stuart Nursery on the Kisatchie National Forest in central Louisiana, provides seed for West Gulf reforestation in Louisiana and Texas. When stem elongation was observed on longleaf seedlings from these orchards, the immediate questions were: if these seedlings are Sonderegger pines, is the genetic base for longleaf pine being compromised, and should these seedlings be outplanted? Also, is this a 1-year phenomenon or an indication of possible longer term effects of climate change?

Because of the serious implications, scientists from the Forest Service, Southern Research Station's (SRS) Research Work Units (RWUs) 4552, 4159, and 4158 at Pineville, LA, joined a Longleaf Pine Hybridization Team[1] to (1) conduct DNA analyses of the seed sources in question to determine whether hybridization occurred; (2) monitor the morphological development of the seedlings before and after outplanting; (3) determine if weather conditions at time of pollination may have increased the opportunity for cross-pollination; and (4) provide scientific data for managers to make decisions on the use of the seedlings. Through a multi-pronged approach, we hoped to learn if hybridization between longleaf and loblolly pines in the two orchards had occurred and if DNA analysis of seeds can be used to determine the status of hybridization in stored seeds. To do this, SRS scientists in Pineville coordinated the development of DNA markers for the determination of

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[1] Longleaf Pine Hybridization Team members were James Barnett, Emeritus Scientist, SRS RWU-4159; Brian Strom, Research Entomologist, and Rabiu Olatinwo, Research Plant Pathologist, SRS RWU-4552; D. Paul Jackson, Associate Professor, Louisiana Tech University, School of Agricultural Sciences and Forestry; Stacy Blomquist, Public Affairs Officer, Kisatchie National Forest; Alex Mangini, Entomologist, Forest Health Protection; Susana Sung, Research Plant Physiologist, SRS RWU-4158; and Jessica McKenney, Research Associate, Louisiana State University AgCenter.

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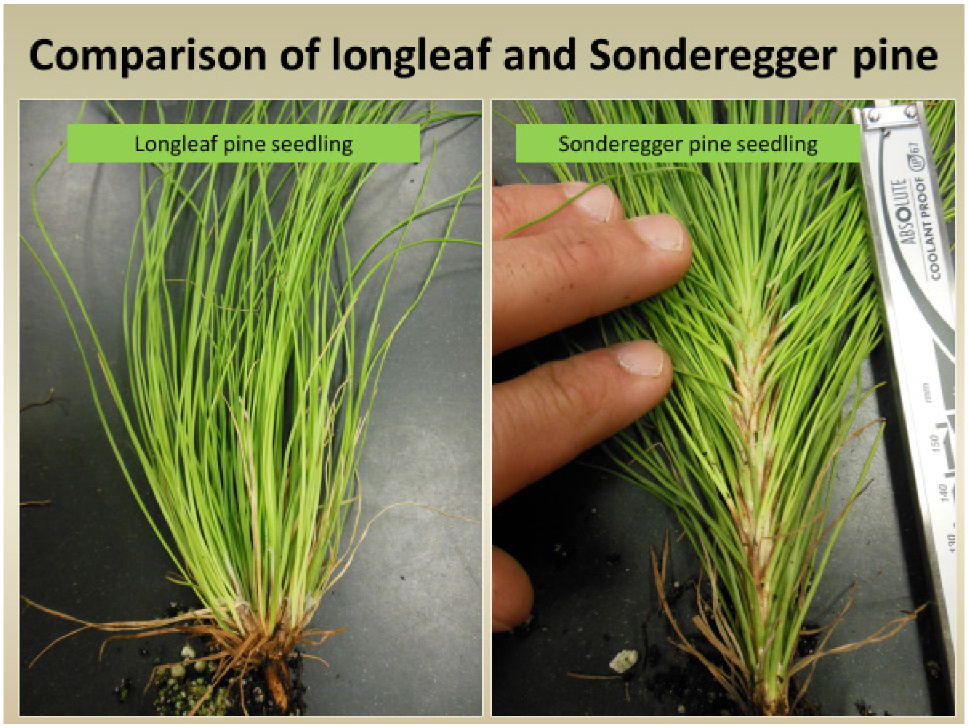

Figure 1—Standard visual differences between container longleaf and Sonderegger pine seedlings.

hybridization with geneticists from the SRS Southern Institute of Forest Genetics (RWU-4160) at Saucier, MS, and the Southern Region in Atlanta, GA. Collaboration with Louisiana Tech University's School of Agricultural Sciences and Forestry facilitated the study of seedling morphological development. Staff at the Pineville offices of Southern Region, Forest Health Protection and the Kisatchie National Forest provided expertise, resources, and a planting site at the Stuart Seed Orchard.

METHODS

Seedlot Acquisition

Since the status of about 12,000 container longleaf pine seedlings was in question, an immediate objective was to determine if hybridization of seed from cones collected in 2014 from the Craig and Stuart seed orchards had occurred (fig. 2). Several hundred container seedlings from these seedlots were selected randomly, taken from the nursery, and shipped to Louisiana Tech University in late July 2015. Another collection of cones from the Craig Seed Orchard was made in the fall of 2015. Mike Lee of the Mississippi Forestry Commission coordinated the cone collection, and the Forest Service's cone and seed processing facility at Brooklyn, MS, processed the seeds. Seedlings were also grown from stored seeds from the Craig Seed Orchard's 2013 and 2014 crops and from the Stuart Seed Orchard's 2014 crops for another evaluation of seedlings from the seedlots. Seeds from these sources were grown at the International Forest Company nursery at Evans, LA. These seedlings were subjected to the same detailed measurements as those from the earlier evaluations.

In addition to growing seedlings again from both 2014 collections from the Craig and Stuart seed orchards, seeds from Craig Seed Orchard's 2013 and 2015 collections were sown to be evaluated. This was done to determine if the possible hybridization was just a 1-year occurrence or a developing trend. Because no published information on the growth and development of container-grown Sonderegger seedlings is available, plants from Stuart Seed Orchard that met the traditional criteria for hybridization and would have been historically culled were instead outplanted to provide a comparison for evaluating the development of those grown from the 2014 sources in question.

Seedling Morphology in the Nursery

Sonderegger seedlings in the past were noted in beds of bareroot longleaf pines by their prominent stem elongation of 12 to 15 cm —clearly, they stood up above the surrounding longleaf plants that remained in the grass stage. This is the only current means to quantify Sonderegger pine seedlings in the nursery. Through the summer and fall, monthly measurements of needle length and stem elongation were made for individual seedlings to document their growth and development. Subsets of these seedlings were outplanted in the fall of 2015 so that growth patterns could be determined and related to results of DNA analyses.

Figure 2—The location of the two seed sources in question are near the same latitude. The Louisiana site is the Stuart Seed Orchard of the Kisatchie National Forest, and the Mississippi site is the Craig Seed Orchard of the Mississippi Forestry Commission.

Craig Seed Orchard 2014 seedlot—In August 2015, four trays with 198 container longleaf pine seedlings each from the Craig Seed Orchard were taken to Louisiana Tech University for the evaluation of seedling morphology. Seedling morphological measurements included root collar diameter, height (stem between cotyledons and the tip of the terminal shoot bud), longest needle length, and fascicle and primary needle presence. The seedlings were measured on August 10, September 21, and November 9, 2015. Stem elongation was recorded to the nearest half centimeter.

Stuart Seed Orchard 2014 seedlot—In October 2015, two trays with 198 container longleaf pine seedlings each from the Stuart Seed Orchard were taken to Louisiana Tech University for the evaluation of seedling morphology. The same measurements described above were performed on October 5 and November 20, 2015.

Craig Seed Orchard 2013 seedlot—In October 2015, one tray with 198 container longleaf pine seedlings from the Craig Seed Orchard was brought to Louisiana Tech University for the evaluation of seedling morphology. The same measurements were performed on these seedlings on October 5 and November 20, 2015.

Seedling Development After Outplanting

The first outplanting of seedlings in the fall of 2015 was lost due to feral animals that pulled most of the seedlings from the ground. Seedlings from the same sources were grown at a Louisiana container nursery in following years from stored seed and the planting site moved to the Stuart Seed Orchard where they were more easily protected and monitored.

Seedlings were randomly outplanted to monitor their individual development. Further randomization was achieved by sorting seedlings by their stem elongation measurements (least to most) and then numbering them sequentially. A random sequence of numbers was generated from 1 to the maximum number (343 for the Craig Seed Orchard 2014 seedlot, 185 for the Stuart Seed Orchard 2014 seedlot). Seedlings were arranged in trays by their sequence number, brought to the field, and outplanted in that sequence (Jackson and others 2020). To provide a comparison with known Sonderegger seedlings, seedlings culled because of hybridization from a Stuart Seed Orchard 2016 seedlot were outplanted to compare their performance with the study seedlings from the Craig Seed Orchard 2014 seedlot. Heights of these seedlings were measured after the first growing season.

DNA Evaluation

Samples of needle tissue were taken from seedlings of known size and needle development for DNA analysis. Barbara Crane, Regional Geneticist of the Southern Region, also authorized analysis of 48 tissue samples from this crop to be done by the National Forest Genetics Laboratory (NFGEL) at Placerville, CA. This lab has the expertise and tools needed to separate southern pine species using chloroplast technology.

Early discussions with geneticists from SRS RWU-4160 and the Southern Region about their assistance in conducting the needed DNA analyses of the samples indicated limitations due to both the status of marker development for the species and the timely availability of unit resources to conduct the analyses. With the recent hire of Rabiu Olatinwo as a Research Plant Pathologist at SRS RWU-4552 in Pineville, an effort began to develop DNA techniques for separating longleaf from known loblolly and Sonderegger pines on site. Through his efforts, procedures for establishing appropriate DNA markers for longleaf and loblolly pine were developed. This study provided an evaluation of his approach with the somewhat different techniques developed by SRS RWU-4160 and Southern Region personnel.

To determine if the seedlings with some limited stem elongation were indeed hybridized, seedlings were analyzed and had their DNA compared by using two chloroplast DNA markers with a set of specific primers for each (one for longleaf pine and one for loblolly pine) (Olatinwo and others 2020). Olatinwo and others (2020) extracted DNA from each seed using the Qiagen DNeasy® Plant Mini Kit (Qiagen Inc., Valencia, CA) according to the manufacturer's protocol. The DNA from known longleaf pine and loblolly pine were included in the polymerase chain reaction (PCR) amplification to serve as positive controls in evaluating the seed samples. Amplification of DNA was performed in 10 µl PCR reaction in an Eppendorf Mastercycler® Pro PCR machine (Eppendorf AG, Hamburg, Germany). Gel electrophoresis was performed to examine amplified products by loading 5 µl PCR products on 1-percent agarose gels. The agarose was stained with ethidium bromide after 20 minutes of electrophoresis, and the resulting bands were visualized under ultraviolet (UV) illumination to confirm positive or negative amplifications. A band indicates positive amplification, while no band indicates negative. A positive with the longleaf marker identifies a sample as a longleaf pine, while a negative with longleaf marker indicates the sample is not a longleaf pine. Similarly, a positive with the loblolly marker identifies a sample as a loblolly or a Sonderegger pine, while a negative with the loblolly marker indicates the sample is not a loblolly or a Sonderegger pine. Therefore, if a sample is longleaf-marker positive, it is not a Sonderegger hybrid.

Weather Patterns During Pollination

Weather patterns at or near the orchards, especially temperatures, during the 2013 pollination period for longleaf and loblolly pine were evaluated. Data comparison to weather measurements from this and earlier years were made to try to understand if hybridization of these seed sources may have occurred. Boyer (1973, 1978) established that heat accumulation can be used to accurately predict peak pollen shed. Degree-day heat sums can be derived from local temperature data. The procedure can provide early warning of unusually early or late flowering. Degree-day heat sums for longleaf and loblolly pine accumulate from base temperatures of 50 and 55 °F, respectively. Peak pollen shed is predicted when 1,208 degree days for longleaf and 636 degree days for loblolly accumulate. This procedure was used to determine peak pollen shed times in the spring of 2013 that led to the development of the two sets of cones in 2014. Because actual data documenting pollination times for longleaf and loblolly pine are not available, Boyer's heat-sum models were used to predict pollination periods for these species and the overlap using historical weather data from nearby weather stations. These analyses provide some understanding of climatic changes that may have resulted in changes of pollination time overlap between longleaf and loblolly. Importantly, evaluations were made to evaluate whether the year 2013 (the pollination year for the questionable seed from the two orchards) was likely to have pollen/receptivity overlap between the two species.

RESULTS

Seedling Morphology in the Nursery

At the time of the last measurement, 79 percent of a sample of 343 seedlings from the 2014 Craig Seed Orchard seedlot had initiated some level of stem elongation with a range from 1.5 cm to 13.0 cm (table 1). A stem measurement of 1.0 cm was characterized as being normal for longleaf pine due to the hardening of the area for normal bud set. At the time of the last measurement for the 2014 Stuart Seed Orchard

Table 1—Seedlings grown in 2015 from 2014 Craig and Stuart Seed Orchard seedlots with stem elongation in the nursery

	Craig Seed Orchard seedlot	Stuart Seed Orchard seedlot
Elongation (*cm*)	Number (*percent*)	Number (*percent*)
≤1.0	71 (21)	22 (12)
1.1–2.5	105 (31)	73 (39)
2.6–5.0	143 (42)	74 (40)
5.1–7.5	21 (6)	16 (9)
≥7.6	3 (<1)	0 (0)
Total	343	185

Seedlings were measured in November 2015 before outplanting.

seedlot, 88 percent of a sample of 185 seedlings had initiated some level of stem elongation with a range from 1.1 cm to 7.0 cm (table 1). Finally, at the time of the last measurement of the 2013 Craig Seed Orchard seedlot, only two seedlings (1.9 percent) of a sample of 102 seedlings had initiated stem elongation exceeding 1.0 cm, and they measured only 2.5 cm and 3.0 cm. These results are typical for a normal longleaf pine seed source.

Seedling Development After Outplanting

Outplanted seedlings from the Craig Seed Orchard 2014 crop performed like longleaf in the field trial—the only seedling with appreciable elongation was a known hybrid in the seedlot. The Sonderegger seedlings had stem elongation when planted and continued to grow after planting with most growing to about 24 cm after 1 year (table 2).

DNA Evaluation

The results of gel electrophoresis of PCR products from the longleaf-marker primers used in evaluating DNA samples from 64 pine seedlings (29 from the Stuart Seed Orchard 2014 seedlot, 17 from the Craig Seed Orchard 2014 seedlot, and 18 from Craig Seed Orchard 2013) showed no indication of hybridization (fig. 3). Natural hybridization between longleaf and loblolly was not detected in the sample of seedlings evaluated from the three seedlots included in this study; however, the genetic markers and the corresponding specific primers developed for detection of a "pure" longleaf from a Sonderegger hybrid or loblolly will facilitate routine evaluation of suspect pine seedings in the future. The methodology will also allow evaluation of hybridization in the seeds themselves.

Weather Patterns During Pollination

The application of the heat-sum data to the Craig and Stuart seed orchards provide the following information. In years 2002, 2005, 2006, 2009, 2012, and 2013, longleaf pine reached peak flowering before loblolly. Conversely, in years 2001, 2003, 2004, 2007, 2008, 2010, 2011, 2014, 2015, and 2016, loblolly pine reached peak flowering before or at the same time as longleaf pine.

The graphic data are reflected in these flowering times that are provided in figure 4. These data confirm Boyer and Woods' (1973) conclusion that pollination times for longleaf and loblolly frequently overlap, and which species reaches peak pollen shed first varies from year to year. Our data do not provide any clarity on whether pollination time had any influence on the 2014 seed crop seedling developmental issue.

DISCUSSION

The report in 2015 that a large portion of seedlings from two longleaf pine seed sources collected in 2014 may have been hybridized naturally with loblolly pine raised concern among forest geneticists and silviculturists. The results of our DNA analyses and the field outplanting studies indicate that hybridization was not responsible for the stem elongation phenomenon. DNA analyses conducted locally and by both the SRS RWU-4160 scientists and the National Forest Genetics Laboratory specialists indicate that hybridization did not occur. The outplanted seedlings have remained in the grass stage and are performing as typical longleaf pine seedlings. The seedlings grown from the 2014 Craig and Stuart seed orchard seedlots do not meet the Sonderegger characterization. Some limited stem elongation occurred

Table 2—Development of seedlings after one growing season from the Craig Seed Orchard 2014 seedlots compared to culled Sonderegger seedlings from the Stuart Seed Orchard 2016 seed source

Craig Seed Orchard 2014 seedlot			Stuart Seed Orchard 2016 Sonderegger seedlings[a]		
Stem elongation (*cm*)	Number of seedlings	*Percent*	Height (*cm*)	Number of seedlings	*Percent*
≤2.0	162	72	≤10	1	<1
2.1–3.0	37	16	11–20	29	22
3.1–4.0	21	9	21–30	78	60
4.1–5.0	4	2	31–40	22	17
5.1–6.0	0	0	41–50	1	<1
≥6.1	1[b]	<1	≥51	0	0
Total	225	100	Total	131	100

[a] The Sonderegger seedlings had stem elongation when planted and continued to grow after planting.

[b] The only Craig Seed Orchard seedling with appreciable elongation was a known hybrid in the seedlot.

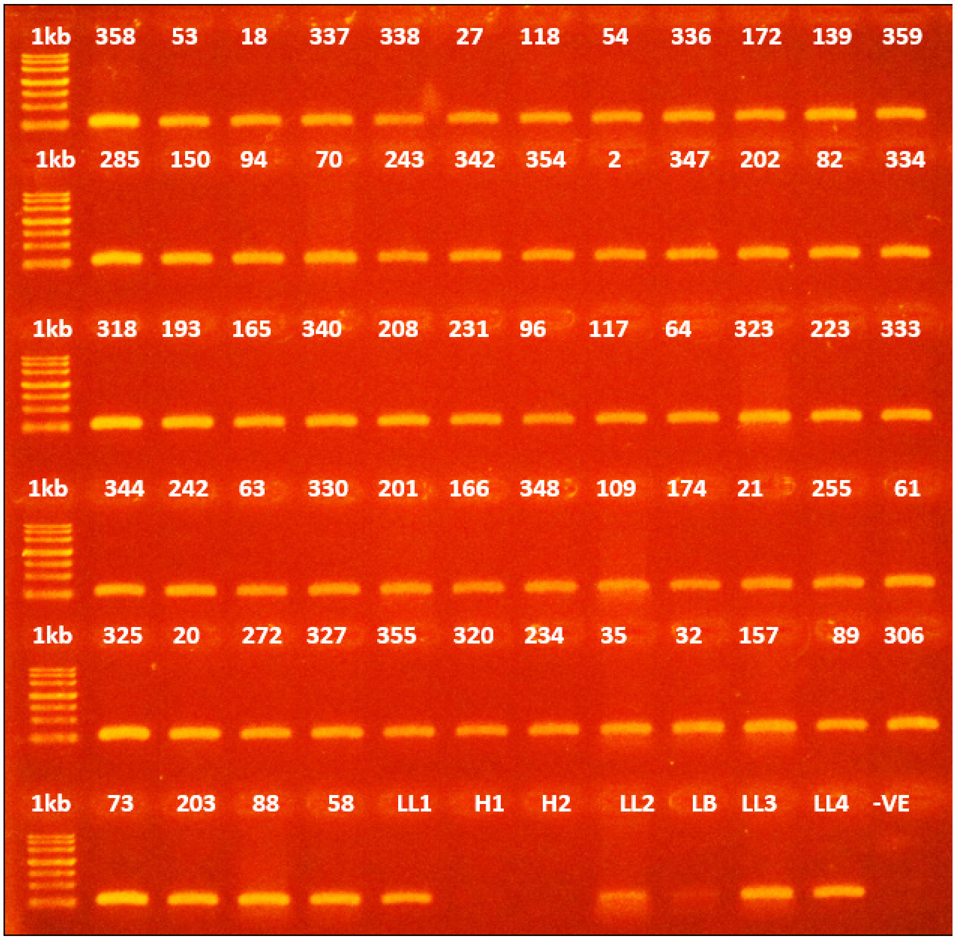

Figure 3—DNA samples LL1–LL4 are known to be longleaf positive, H1 and H2 are from a known Sonderegger hybrid, LB is from a loblolly seedling, and -VE was included as a control.

in the container nursery in 2015, but what caused this phenomenon? One premise is that this development may have occurred as the result of some nursery application. The nursery manager indicated, however, that this development was limited to these two seedlots among several seed sources being grown. Another thought is that it resulted from a shift in pollination times between longleaf and loblolly pine that might have favored hybridization.

Unfortunately, we have no answer to the question of what caused this stem elongation phenomenon in the nursery. Most likely it was triggered by some nursery-related application, but we have no direct evidence. There could be other possible mechanisms. For example, could increasing temperatures resulting from climate change be affecting the pollination sequences of the two species? Little information has been published about the growth and development of Sonderegger pine seedlings, particularly for container-grown plants.

Given that natural hybridization between the two species is known to occur, but the Sonderegger pine hybrid is considered to have lower quality than either parent, should these seedlings be planted?

A series of evaluations has begun to determine if these seedlings will continue to elongate and develop more traditional Sonderegger characteristics or remain in the grass stage typical of longleaf pine. It became obvious that it would take time to outplant and evaluate the seedlings and to develop the genetic markers needed for the DNA analyses. Because of this uncertainty, the land managers involved decided not to plant the seedlings, and all remaining seedlings not used for this study—nearly 12,000—were destroyed. We believe our outplanted studies, including plantings of known Sonderegger seedlings, will provide needed information on the growth and development of Sonderegger seedlings and the quality of these trees in established stands.

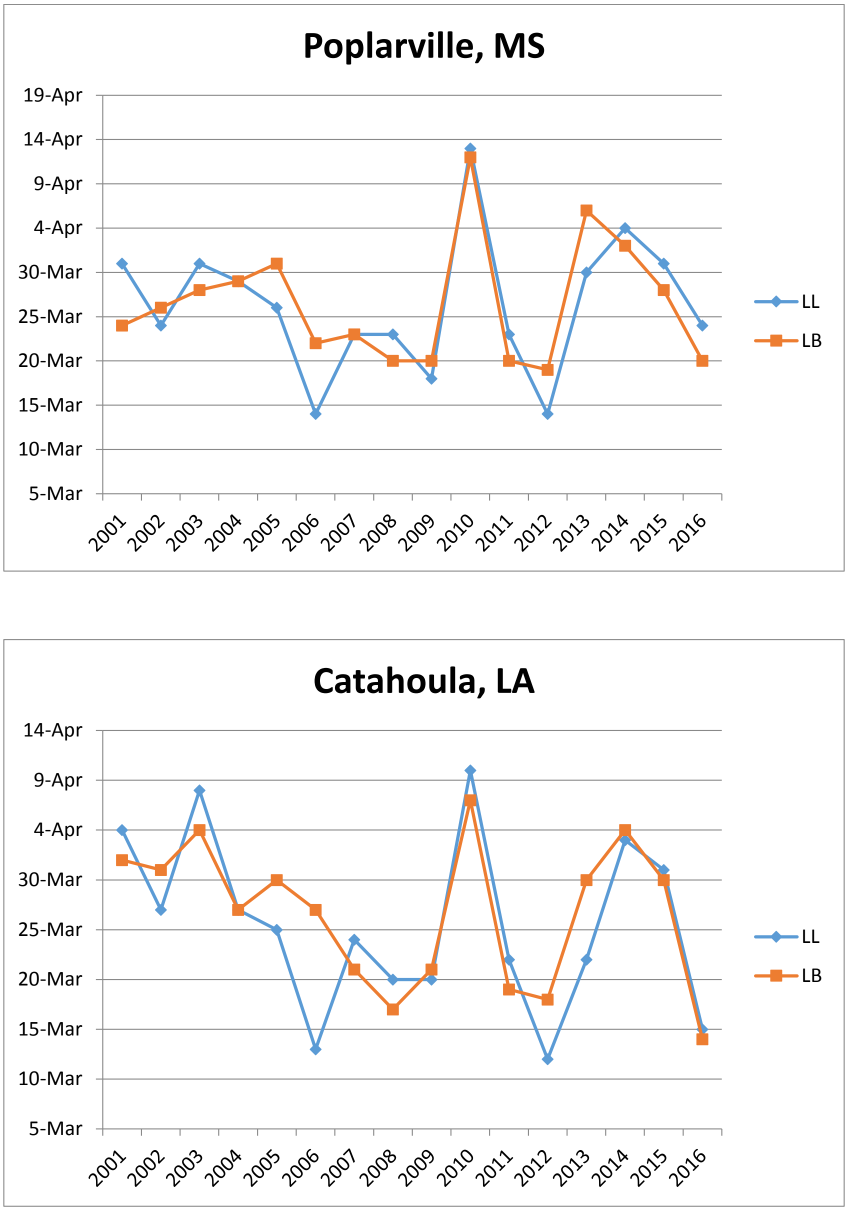

Figure 4—A comparison of projected peak pollination dates (based on historical weather data from nearby weather stations in Poplarville, MS, and Catahoula, LA) for longleaf and loblolly pines in the Craig and Stuart Seed Orchards under evaluation. Overlap in pollination times occurs frequently and seems to have little consistent effect on the quantity of Sonderegger seedlings produced.

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SITE PREPARATION FOR LONGLEAF PINE RESTORATION ON HYDRIC SITES: TREE- AND STAND-LEVEL RESPONSES 15 YEARS AFTER PLANTING

Connor D. Crouch, Benjamin O. Knapp, Michael C. Stambaugh, Susan A. Cohen, Joan L. Walker, and G. Geoff Wang

Extended abstract—Longleaf pine (*Pinus palustris* Mill.) restoration is an important land management goal throughout the Southeast. On hydric sites within the Atlantic Coastal Plain, restoration may involve site preparation prior to planting in order to overcome challenges to seedling establishment, such as abundant competition and poor soil drainage (Brockway and others 2006). An earlier study of longleaf pine plantations on hydric flatwoods sites in Onslow County, NC, indicated that site preparation improved seedling growth but not survival through 2 years after planting (Knapp and others 2006). Although investment in site preparation assumes that treatments will result in long-term benefits to stand establishment, lasting impacts of site preparation on longleaf pine are not well understood. Therefore, we sampled the same study 15 years after planting to determine impacts of site preparation on stand development. Eight treatments were applied prior to planting the seedlings. These treatments included an untreated control (flat-planting), six combinations of two initial vegetation control treatments (chopping or herbicide) with three planting site treatments (flat-planting [no treatment], mounding, or bedding), and an herbicide-chopping-bedding treatment. Study treatment codes used throughout this abstract indicate the type of site preparation used: C = chop, H = herbicide, F = flat, M = mound, B = bed.

Our findings indicate that site preparation significantly improved long-term establishment of longleaf pine on hydric flatwoods sites. One-way analysis of variance (ANOVA) indicated that basal area significantly differed among the eight study treatments ($p < 0.001$). Mean basal area for CHB and HB, which approached 3.5 m^2/ha, was significantly greater than that of CM, CF, and F, which were near or below 1 m^2/ha (fig. 1). Two-way factorial ANOVA, excluding the F and CHB treatments, indicated that planting site treatments ($p = 0.009$) and vegetation control treatments ($p = 0.001$) affected basal area, while there was no significant interaction between the treatment types ($p = 0.848$). Bedding resulted in significantly greater basal area than flat-planting, and herbicide application resulted in significantly greater basal area than chopping 15 years after planting.

We also conducted stem analysis to determine if these stand-level differences among treatments were the result of earlier emergence from the grass stage or increased growth after emergence. One-way ANOVA indicated that there were significant differences in age of emergence from the grass stage among the eight study treatments ($p < 0.001$). CF, which had a mean emergence age of 9.25 years after planting, emerged significantly later than the other seven study treatments (table 1). The other treatments had mean emergence ages ranging from 3.72 to 5.46 years and did not significantly differ from each other. One-way ANOVA also found significant differences in mean annual height growth after grass stage emergence among the eight study treatments ($p < 0.001$). HM and HB, with mean height growth exceeding 0.5 m/year, grew significantly faster than F and CF, which had mean growth rates of 0.33 m/year and 0.23 m/year, respectively (table 1). CF had significantly lower annual height growth than all treatments except for F and CM. These findings indicate that increased height growth after grass stage emergence seemed to contribute more directly to long-term stand establishment outcomes than did the timing of grass stage emergence.

Restoration may encompass a range of objectives, and if improved long-term growth or survival of planted seedlings is an important aspect of a restoration effort, then herbicide application and/or soil manipulation may be necessary on hydric flatwoods sites. However, maximizing tree growth and stand density may not be necessary for reaching restoration objectives. For example, longleaf pine savannas are characterized by

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scattered trees and occur within site types similar to our study location. Our findings indicated that high levels of longleaf pine seedling mortality occurred without site preparation, but the control stands resulted in upwards of 100 trees/ha that were out of the grass stage by 15 years after planting. Longleaf pine ecosystem restoration typically seeks to not only establish an overstory of longleaf pine but also maintain or improve the ground layer plant community (Walker and Silletti 2006). Therefore, a balance must be struck between site preparation that promotes longleaf pine establishment and minimizing detrimental impacts of those treatments on native flora (Johnson and Gjerstad 2006). Our future work seeks to address this tradeoff by examining the long-term effects of site preparation on the understory plant community in longleaf pine plantations.

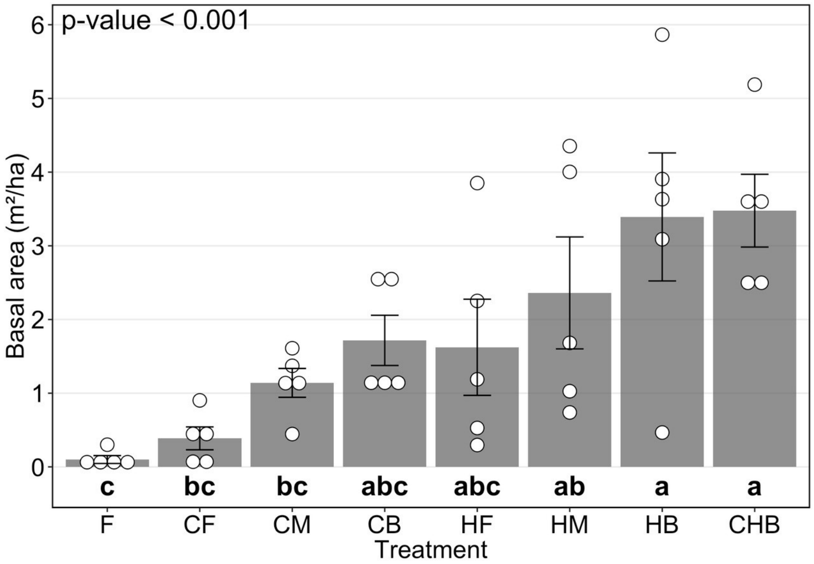

Figure 1—Mean longleaf pine basal area for each site preparation study treatment 15 years after planting. Bars show treatment means and standard errors; points show means of each experimental unit. Same letters indicate no significant difference α = 0.05) among treatments based upon Tukey-adjusted pairwise comparisons; *p*-value is from one-way ANOVA. C = chop; H = herbicide; F = flat; M = mound; B = bed.

Table 1—Mean tree-level responses to site preparation study treatments 15 years after planting

Treatment	Age of grass stage emergence	Mean annual height growth after emergence (*m/year*)
F (control)	5.07 b	0.33 bc
CF	9.25 a	0.23 c
CM	4.93 b	0.40 abc
CB	5.29 b	0.45 ab
HF	5.46 b	0.44 ab
HM	3.77 b	0.52 a
HB	3.72 b	0.53 a
CHB	4.82 b	0.45 ab
p-value	<0.001	<0.001

Same letters indicate no significant difference (α = 0.05) within a response variable based upon Tukey-adjusted pairwise comparisons; p-values are from one-way ANOVA tests.

C = chop, H = herbicide, F = flat, M = mound, B = bed.

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FIELD OBSERVATIONS OF LONGLEAF PINE SEEDLINGS TO EXAMINE POSSIBLE HYBRIDIZATION

D. Paul Jackson, Rabiu Olatinwo, James P. Barnett,
Brian Strom, and Shi-Jean Susana Sung

Abstract—Stem elongation in the nursery is the traditional and accepted indicator that hybridization between longleaf pine (*Pinus palustris*) and loblolly pine (*P. taeda*) has occurred. These hybrids, known as Sonderegger pines (*P.* x *sondereggeri*), are reported to have distorted limb structure and low-quality wood. As a result, landowners avoid using them. Recently, a large number of longleaf pine seedlings grown in a nursery from particular seedlots displayed unusual stem elongation and were assumed to be Sonderegger pines. It was determined that long-term observations of their development were necessary. Seedlings that displayed true longleaf pine morphology, stem elongation but with atypical longleaf or Sonderegger pine morphology (suspected hybrids), and true Sonderegger pine morphology were outplanted in arranged plots. After assessing the current measurement data, there is no indication that the suspected hybrids are Sonderegger pines. The trees will continue to be monitored for many years to see if their development corresponds to what is known about true longleaf pine or true Sonderegger pine morphology.

INTRODUCTION

Land managers plant longleaf pine (*Pinus palustris*) for many reasons, including high-value forest products and to help restore its diverse ecosystem (Jose and others 2006). Hence, longleaf pine seedling quality is important. During lifting and processing of longleaf pine seedlings in the nursery, seedlings are sometimes detected that have characteristics associated with Sonderegger pine (*P.* x *sondereggeri*), an undesirable hybrid produced from the cross-pollination of longleaf and loblolly pine (*P. taeda*) (Chapman 1922). Wakeley (1954) described mature Sonderegger pines as having bole and limb distortion and non-merchantable-quality timber. The hybrid may develop heavier branches connected at weaker limb unions (more forked) leading to increased breakage in adverse weather conditions (Dorman 1976). From a management perspective, prescribed fires used to control herbaceous and woody competition in the first few years following longleaf pine plantings can cause mortality to Sonderegger pines, as this hybrid has terminal buds at heights vulnerable to flames. There is also concern that, if planted, genes from Sonderegger pine will backcross into the longleaf pine population influencing future seed crops.

It is important to understand the developmental differences between longleaf pine and Sonderegger pine in order to understand why the latter species has been traditionally undesirable. True longleaf pine seedlings form buds that remain near the soil line surrounded by fascicle needles, and they do not extend or bolt until they begin growing out of this “grass stage” (Wahlenberg 1946). It is during the grass stage when prescribed fire is used to eliminate competitive vegetation near longleaf pine seedlings to allow them to begin height growth (Jose and others 2006). Longleaf pine is considered out of the grass stage when either height growth reaches about 12 cm or ground-line diameters reach 25 mm (Wahlenberg 1946). Sonderegger pine hybrids exhibit stem elongation and have heightened terminal buds that stand above true longleaf pine seedlings in the nursery. Once observed, these putative Sonderegger pines are culled before being packaged and shipped for outplanting. This culling limits the chance of planting a seedling that is not a true longleaf pine, and it ensures the purity of future stands.

In 2015, there were reports from a Georgia tree seedling nursery that longleaf pine seeds from a Louisiana (LA) source and a Mississippi (MS) source produced

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seedlings that exhibited significant stem elongation (Barnett and others 2020). Because land managers avoid planting Sonderegger pine, the nursery disposed of millions of the suspect seedlings. In response, a team of researchers interested in evaluating seedling development established observational plots comprised true longleaf pine, true Sonderegger pine, and samples of these suspected Sonderegger pine from the Louisiana and Mississippi sources, over a 3-year span (Barnett and others 2020).

These "suspect" seedlings were evaluated morphologically and molecularly to determine if they were Sonderegger pines or if they had possibly developed abnormally for another reason (Barnett and others 2020). Plans are to monitor growth and development of the trees for many years. The plots containing known Sonderegger pine may also shed light on whether the hybrid develops as described in the past (Wakeley 1954) or if it develops into a tree that could be a timber resource.

FIELD ESTABLISHMENT

Field plots were established on the Catahoula Ranger District of the Kisatchie National Forest near Pollock, LA, in an open field site. Grass and forb species made up the major component of seedling competition. All plots consisted of 50 seedlings on 2.4- by 2.4-m spacing. Plots were arranged 4.8 m apart, and each plot represented a particular seedlot. Within each plot, randomization of seedlings for seedlots that produced suspected hybrids was done by sorting seedlings by their stem elongation measurements (recorded at Louisiana Tech University) and then numbering them sequentially. A random sequence of numbers was generated from 1 to the maximum number. Seedlings were then arranged in trays by their sequence number, brought to the field, and outplanted in that sequence. Treatments were not employed on the seedlings prior to outplanting as their growth and morphology will be monitored for development to compare among seedlots.

The MS-2014 and LA-2014 seedlots represented suspect seedlings that showed a high percentage of stem elongation in the nursery (Barnett and others 2020). Seedlings from the MS-2015 seedlot did not exhibit stem elongation in the nursery and had morphology consistent with longleaf pine, and they served as a comparison to the suspect seedlings grown from the MS-2014 and LA-2014 seedlots. Sonderegger pine seedlings being evaluated were culls from the International Forest Company (IFCO) nursery in Evans, LA. In total, 1,250 seedlings were planted in 25 plots. Seedlings were outplanted in December 2016 and March 2018.

Outplanting: December 16, 2016—Nine plots were planted with a total of 450 seedlings. Four plots (200 seedlings) were planted with seedlings from the MS-2014 seedlot and five plots (250 seedlings) were planted with seedlings from the MS-2015 seedlot. One-year height measurements were conducted on January 25, 2018, and 2-year height measurements were conducted on March 1, 2019. Only seedlings with height measurements of ≥5 cm were recorded. The plots were prescribed burned on May 14, 2018, and survival data were recorded.

Outplanting: March 27, 2018—Eight plots were planted with a total of 400 seedlings. Four plots (200 seedlings) were planted with seedlings from the MS-2014 seedlot, and four plots (200 seedlings) were planted with seedlings from the LA-2014 seedlot. The seedlings evaluated in these plots were grown from seed per operational practices at the IFCO nursery in Evans, LA, during the 2017 growing season. One-year height measurements were conducted on March 1, 2019. Only seedlings with height measurements of ≥5 cm were recorded.

Adjacent to these plots were another 8 plots planted with a total of 400 Sonderegger pine seedlings. These hybrid seedlings were culled at the IFCO nursery in Evans, LA, and saved for field evaluations. One-year height measurements of these seedlings were also conducted on March 1, 2019.

RESULTS AND DISCUSSION

Outplanting: December 16, 2016—After one growing season, the average height of seedlings per plot was similar between both seedlots (table 1). Overall, of those measured, the MS-2014 suspected hybrid seedlings and the MS-2015 true longleaf pine seedlings averaged 5.50 cm and 5.27 cm in height, respectively, after one growing

Table 1—Mean seedling heights after one (Year 1) and two growing seasons (Year 2) for each plot of the Mississippi 2014 (MS-2014) seedlot (suspected hybrids) compared to each plot of the Mississippi 2015 (MS-2015) seedlot (true longleaf pine)

	MS-2014 Suspected hybrid		MS-2015 True longleaf pine	
Plot	Year 1	Year 2	Year 1	Year 2
	--------------------------*cm*--------------------------			
1	5.62	9.20	5.16	9.53
2	5.31	8.94	5.10	9.89
3	5.45	8.25	5.10	8.60
4	5.64	9.47	6.00	8.59
5	-	-	5.00	7.03

season. About 14 percent of the MS-2015 longleaf seedlings and 42 percent of the MS-2014 suspected hybrid seedlings had reached measurable height after 1 year (table 2). The MS-2014 seedlings displayed some level of stem elongation at planting which may have contributed to that seedlot having more measurable seedlings compared to the MS-2015 true longleaf pine seedlings after 1 year.

During the first year of growth, longleaf pine seedlings typically remain in the grass stage and allocate energy into building a more robust root system (Wahlenberg 1946). After a longleaf pine seedling's second growing season, grass stage emergence is possible (Jackson and others 2012). After two growing seasons, the MS-2015 longleaf pine seedlings and MS-2014 suspected hybrid seedlings remained similar in height, averaging 8.96 cm for the MS-2014 seedlings and 8.72 cm for the MS-2015 seedlings (table 1). In addition, the number of measurable MS-2015 longleaf pine seedlings increased 59 percentage points to 73 percent, while the number of measurable MS-2014 suspected hybrids increased 23 percentage points to 65 percent (table 3). The average heights of all seedlings per plot did not reach the 12-cm threshold for grass stage emergence published by Wahlenberg (1946). Also, the MS-2014 suspected hybrid seedlings lacked terminal growth that is typically associated with Sonderegger pine seedlings. These observations indicate that the suspected hybrids are responding more like true longleaf pine seedlings.

Seedling survival was 97 percent for all plots combined after one growing season with the loss of four MS-2014 seedlings and seven MS-2015 seedlings (table 2). The prescribed fire occurred during the second growing season, and overall survival was reduced to 92 percent

Table 2—The number of seedlings that measured above or below the 5-cm threshold and survival for each plot after one growing season for the Mississippi 2014 (MS-2014) seedlot (suspected hybrids) compared to the Mississippi 2015 (MS-2015) seedlot (true longleaf pine)

	MS-2014 Suspected hybrid			MS-2015 True longleaf pine		
Plot	<5 cm	≥5 cm	Dead	< 5 cm	≥ 5 cm	Dead
	-------------------------*number of seedlings*--------------------------					
1	28	20	2	37	12	1
2	28	22	0	36	14	0
3	28	20	2	38	5	5
4	27	23	0	47	2	1
5	-	-	-	48	2	0

Two true Sonderegger pines planted in MS-2015 plot 3 were not included in the reported data.

Table 3—The number of seedlings that measured above or below the 5-cm threshold and survival for each plot after two growing seasons for the Mississippi 2014 (MS-2014) seedlot (suspected hybrids) compared to the Mississippi 2015 (MS-2015) seedlot (true longleaf pine)

	MS-2014 Suspected hybrid			MS-2015 True longleaf pine		
Plot	<5 cm	≥5 cm	Dead	< 5 cm	≥ 5 cm	Dead
	-------------------------*number of seedlings*--------------------------					
1	15	27	8	7	43	0
2	12	34	4	6	44	0
3	13	29	8	12	29	7
4	6	41	3	11	36	3
5	-	-	-	16	32	2

Two true Sonderegger pines planted in MS-2015 plot 3 were not included in the reported data.

with a total of 23 MS-2014 seedlings and 12 MS-2015 seedlings lost (table 3). The elongated stems of the MS-2014 suspected hybrids may have contributed to their mortality by being at heights vulnerable to flames from a prescribed burn. Also, the herbaceous and sparse woody vegetation on the site may have contributed to some of the mortality.

Outplanting: March 27, 2018—The seedlings being evaluated in these plots included two seedlots (LA-2014 and MS-2014) that were suspected as being hybrid Sonderegger pine based on their abnormal morphology displayed in the nursery. After 1 year of growth in the field, 46 percent of the LA-2014 seedlings and 36 percent of the MS-2014 seedlings had reached the 5-cm threshold for height measurements (table 4), and neither seedlot produced stem elongation similar to what is typically expressed by Sonderegger pines. For those measured, the overall average height of the LA-2014 and MS-2014 seedlings was 6.05 cm and 5.98 cm, respectively (table 4). The seedling growth in these plots was similar to the 1-year seedling growth recorded in adjacent plots for the MS-2014 suspected hybrid seedlings and MS-2015 true longleaf pine seedlings planted in December 2016. Seedling survival was 96 percent for the LA-2014 seedlings and 99 percent for the MS-2014 seedlings (table 4).

The purpose behind planting Sonderegger pine seedlings in plots was to evaluate their morphology over time. Will the Sonderegger pine seedlings develop into unusable gnarly, weak trees (Dorman 1976, Wakeley 1954), or could they be useful as a timber resource? Schoenike and others (1975) reported that when Sonderegger pines were removed from a longleaf pine nursery and planted on a Piedmont site in South Carolina, they had similar limb and bole formation to that of loblolly pine after 9 years. To our knowledge, there has not been a comparative study to document the developmental differences between longleaf and Sonderegger pine when planted in plots side by side as seedlings from known sources on the same managed site. To make a true comparison of bole and scaffold limb formation with longleaf pine, it will take several more years of Sonderegger pine growth and development. After 1 year in the field, Sonderegger pine seedlings in each of the eight plots averaged about 25 cm in height with the shortest Sonderegger seedling measured being 10 cm and the tallest one measured being 55 cm. The MS-2014 and LA-2014 seedlings were only measured at the threshold of 5 cm. The tallest MS-2014 and LA-2014 seedlings measured were 24 and 20 cm, respectively, and those were most likely true Sonderegger pines that happened to be mixed in the seedlot. The heights of all other seedlings in both seedlots measured below 10 cm.

CONCLUSIONS

The suspected hybrids did not grow to heights displayed by the true Sonderegger pine. That information along with the suspected hybrids growing morphologically similarly to longleaf pine may indicate the MS-2014 and LA-2014 seedlots are, in fact, true longleaf pine. Furthermore, analyzing the deoxyribonucleic acid (DNA) from tissues of seedlings from each seedlot indicated there was no evidence of hybridization (Barnett and others 2020). At this time, the reason behind the abnormal stem elongation for the MS-2014 and LA-2014 seedlots cannot be explained. These observational plots will continue to be monitored for tree growth and development to gain a better understanding of their morphology.

Table 4—Mean seedling height, number of seedlings that measured above or below the 5-cm threshold, and survival for each plot after one growing season for the suspected hybrid seedlings from the Mississippi 2014 (MS-2014) seedlot compared to the suspected hybrid seedlings from the Louisiana 2014 (LA-2014) seedlot

	LA-2014				MS-2014			
		Abundance				Abundance		
Plot	Height	<5 cm	≥5 cm	Dead	Height	<5 cm	≥5 cm	Dead
	cm	------------*number*------------			*cm*	--------------*number*--------------		
1	7.03	35	13	2	7.20	35	15	0
2	5.83	10	37	3	5.73	35	15	0
3	5.58	24	24	2	5.48	21	27	2
4	5.78	30	19	1	5.53	34	16	0

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OPTIMUM PRESCRIBED FIRE CONDITIONS FOR FOLIAGE REGROWTH AMONG LONGLEAF PINE SEEDLINGS

Mary Anne S. Sayer, Michael C. Tyree, and Brian M. Rudd

Abstract—We synthesized experimental observations in central Louisiana to estimate the season and precipitation conditions for optimal post-scorch foliage regrowth among longleaf pine (*Pinus palustris* Mill.) seedlings. After severe crown scorch, starch reserves support foliage regrowth and are at their maximum concentration in March through May. When sustained longleaf pine seedling vigor is desired, prescribed fire in March through May is optimal if seedlings have not experienced prolonged drought. We observed that 2 sequential years of severe drought reduced peak starch for 2 years after drought ended. Therefore, when high seedling vigor is desired and prolonged drought has occurred, a prescribed fire delay or other means of vegetation control may be needed until foliage mass and peak starch levels are restored. Furthermore, when seedling development has advanced beyond the grass stage, prescribed fire should be applied during the period of peak starch concentration, but before or after there is a high risk of terminal bud mortality.

INTRODUCTION

By the mid-20th century, longleaf pine (*Pinus palustris* Mill.) shifted from being a major to a minor *Pinus* species in the Southeastern United States (Frost 2006). Research has since resolved many of the problems that contributed to the loss of this fire-climax species (Barnett 2002, Boyer 1993, Brockway and Lewis 1997, Croker and Boyer 1975, Kush and others 1996, Palik and others 1997). At present, restoration of longleaf pine ecosystems is an ongoing emphasis among Federal, State, and private agencies that manage forested land in the Southeastern United States (America's Longleaf 2009).

Longleaf pine requires full sunlight to survive and become dominant in a forest stand (Brockway and others 2006). Once longleaf pine is established, repeated fire not only sustains longleaf pine ecosystem structure, but also reduces competition for light between longleaf pine seedlings and competing vegetation (Haywood 2015, Haywood and others 2001, Mitchell and others 2009). Where aggressive competition for light is anticipated between seedlings of longleaf and other southern pines, the early introduction of prescribed fire may be warranted. Since the average duration of the longleaf pine "grass" stage is 2 to 5 years (Brockway and others 2006, Haywood 2007), it may be necessary to prescribe burn longleaf pine seedlings while they are in this stage of development (Longleaf Alliance 2009). However, it is anticipated that longleaf pine seedlings in the grass or "hardy growing" stages of development (Wahlenberg 1946) will experience complete crown scorch during prescribed fire.

Will this loss of crown prove to be a problem? Southern pine production is closely related to canopy leaf area by the direct relationship between leaf area and photosynthesis in tree crowns (Jokela and others 2004, Vose and Allen 1988). Longleaf pine sustainability also relies on crown health and function regardless of developmental stage (Gonzalez-Benecke and others 2014, Mitchell and others 2009). For mature longleaf pines, a lag in foliage re-establishment after crown scorch was implicated as the cause of low current annual stem increment in the year of prescribed fire (Ford and others 2010). Past research has also shown correlation between stemwood growth loss and poor foliage regrowth after defoliation among other southern pine species (Boyer 2000, Haywood 2009, Johansen and Wade 1987, Weise and others 1987). Among grass stage longleaf pine seedlings, root collar diameter growth was reduced after fire, and it was suggested this was due to prioritization of carbohydrate allocation to needle production (Knapp and others 2018).

The regrowth of scorched longleaf pine foliage is possible by the end of the growing season after prescribed fire (Sayer and others 2018, Sword Sayer and Haywood 2006). Two mechanisms of this response are current photosynthate produced by non-scorched

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foliage and starch stored in parenchyma cells (Chung and Barnes 1980, Klein and Hoch 2015). Complete crown scorch eliminates current photosynthate as a mechanism of foliage regrowth, and new foliage growth depends on stored starch. Similar to other southern pines (Adams and others 1986, Gholz and Cropper 1991, Ludovici and others 2002), longleaf pine starch reserves are characterized by a distinct seasonal pattern of availability (Sayer and others 2018, Sword Sayer and Haywood 2006). Our objective is to synthesize this published information with corresponding patterns of annual precipitation to describe the seasonal window and precipitation conditions when post-scorch foliage regrowth is optimum among longleaf pine seedlings.

MATERIALS AND METHODS

Mature Tree Woody Root Starch

Seasonal woody root starch concentrations of mature longleaf pines were quantified in two experiments in central Louisiana on the Calcasieu Ranger District of the U.S. Department of Agriculture, Forest Service, Kisatchie National Forest, Rapides Parish, LA. In study 1, 65-year-old longleaf pines were severely crown scorched or were not crown scorched during a September 1996 prescribed fire. Starch concentrations of woody roots, 2 to 5 mm in diameter, were evaluated at a 1- to 2-month interval between May 1997 and May 1998 (Sword and Haywood 1999). In this study, small woody root starch concentration was reduced for 17 months after severe crown scorch. In study 2, small woody root starch concentrations were measured among 45- to 50-year-old longleaf pines at a monthly interval between March 1998 and April 2001 (Sword Sayer and Haywood 2006). Treatments were 24 biennial or triennial prescribed fires in March, May, or July (Haywood and others 2001). Prescribed fires in 1998 did not scorch tree crowns, and leaf area indices were similar among the three prescribed fire treatments. In studies 1 and 2, small woody roots were frozen, freeze-dried, and ground to pass a 1-mm^2 mesh sieve. Starch concentrations of dried and ground root samples were quantified by a modification of the procedure of Jones and others (1977).

For the present evaluation, average starch concentrations of small woody roots in two replications that were not scorched in study 1 were calculated by sampling interval and year. Similarly, average starch concentrations of small woody roots in two replications that were prescribed burned but not crown scorched in March, May, or July in study 2 were calculated by month and year. Coefficients of variation were calculated by monthly interval.

Sapling Taproot Starch

Seasonal taproot starch concentrations of sapling longleaf pines were measured in central Louisiana on the Winn Ranger District of the U.S. Department of Agriculture, Forest Service, Kisatchie National Forest, Rapides Parish, LA. This study assessed the physiological and growth responses of longleaf pine saplings to (1) no prescribed fire or (2) application of prescribed fire in May 2011 or October 2012 (Sayer and others 2018). Taproot starch concentration was reduced by prescribed fire in May or October. The May response was correlated with foliage regrowth after crown scorch; whereas, the October response represented a void of normal starch accumulation that was likely due to allocation of fixed carbon to foliage regrowth after crown scorch. In this study, taproots of 6- to 8-year-old saplings that were or were not prescribed burned were sampled in February, March, May, June, July, September, and October of 2011, 2012, and 2013. Taproot tissues were frozen, freeze-dried, ground to pass a 1-mm^2 mesh sieve, and analyzed for starch concentration by Dairyland Laboratories, Inc. (Arcadia, WI) using the acid hydrolysis method (Vidal and others 2009).

For the present evaluation, taproot starch concentration was averaged among three saplings by non-burned treatment plot and sampling interval. Subsequently, mean taproot starch concentrations among three replications were averaged by sampling interval.

Precipitation Estimates

Monthly precipitation near mature longleaf pine studies 1 and 2 in 1997 through 2001 was estimated by two sources. In 1997 and 2001, precipitation was monitored by an electronic weather station in an open field approximately 20 and 16 km from studies 1 and 2, respectively. Similarly, in 1998, 1999, and 2000, precipitation was monitored approximately 10 and 6 km from studies 1 and 2, respectively. Mean monthly precipitation over the 30-year period between 1971 and 2000 was estimated by long-term data from two locations near Alexandria, LA (NOAA 2019).

At the sapling longleaf pine study, a centrally located electronic weather station recorded precipitation in 2011 through 2013. Mean monthly precipitation in 2010 and over the 25-year period between 1988 and 2013 was estimated by long-term data from two locations near Winnfield, LA (NOAA 2019).

RESULTS AND DISCUSSION

Seasonal Starch Availability

Under most circumstances, bud scales and a dense accumulation of fascicles around the buds of longleaf pine seedlings insulate buds from heat damage by fire (Brockway and others 2006, Komarek 1974). While terminal buds are insulated from fire, the stature of longleaf pine seedlings predisposes foliage to crown scorch by prescribed fire. This loss of mature foliage interrupts photosynthesis and allocation of recently fixed carbon to regrow scorched foliage. The regrowth of scorched foliage among longleaf pine seedlings, therefore, depends on stored carbohydrate until new foliage matures and exports current photosynthate.

Starch reserves are important to foliage regrowth after defoliation (Bond and Midgley 2001, Climent and others 2004, Galiano and others 2011, Wigley and others 2009). Furthermore, starch is the primary source of stored carbohydrate in *Pinus* (Gower and others 1995). Across three studies, we observed that mature trees and saplings of longleaf pine exhibited similar seasonal patterns of starch accumulation and mobilization (Sayer and others 2018, Sword and Haywood 1999, Sword Sayer and Haywood 2006). Among mature trees, starch accumulation occurred between November and March with maximum starch concentrations in March through May and starch mobilization in May through July (fig. 1A). Sapling starch exhibited a similar annual pattern (fig. 1B). Monthly coefficients of variation associated with the starch concentration of mature longleaf pine small woody roots indicated that starch variation was greater during June through January compared to February through May (table 1). These observations suggest that the availability of starch to regrow scorched longleaf pine foliage among seedlings is at its maximum in March through May. While starch may be available after May for post-scorch foliage regrowth, factors that affect seedling carbon physiology during the growing season influence starch availability on a year-to-year basis.

Drought Effects on Available Starch

Environmental conditions that reduce carbon fixation in November through March have the potential to reduce maximum starch concentrations attained in March through May. Similarly, factors that accelerate starch mobilization in May through July reduce the duration of starch availability for post-scorch foliage regrowth after May. For mature trees and saplings, year-to-year differences were apparent in starch concentration during its peak in March through May and as it was mobilized

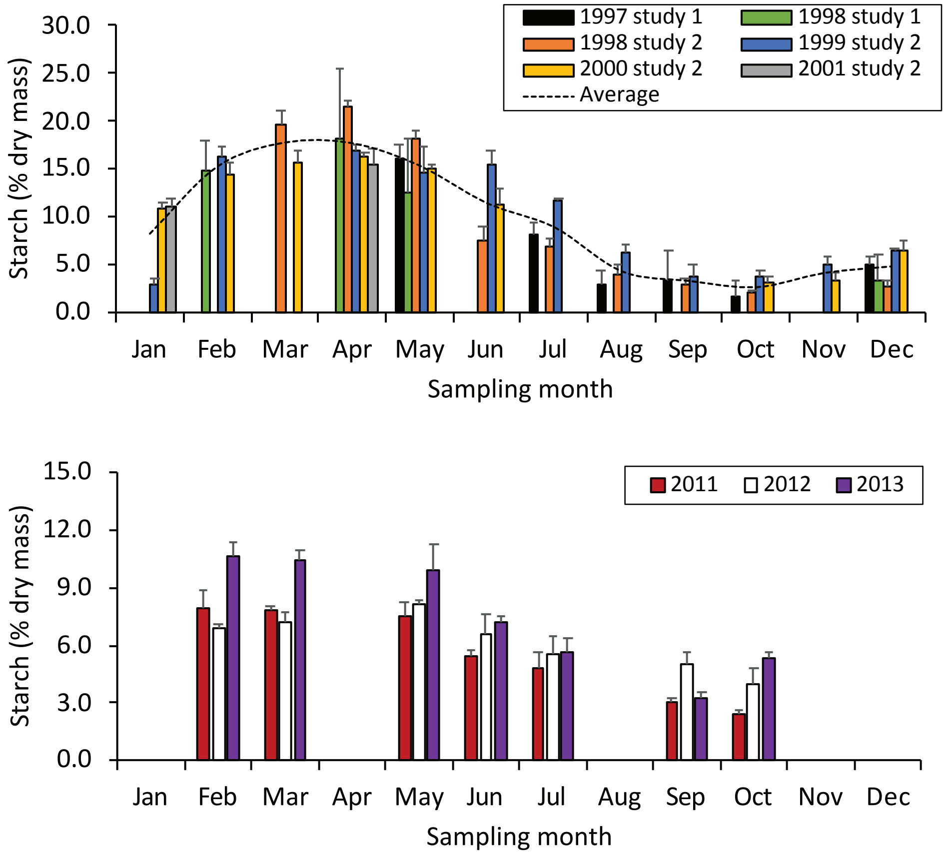

Figure 1—Small woody root starch concentrations of mature longleaf pines (A) or taproot starch concentrations of longleaf pine saplings (B) by sampling month in central Louisiana. Mature tree values are the mean of two replications in study 1 that were not prescribed burned in 1996 (Sword and Haywood 1999) or the mean of two replications that did not exhibit crown scorch after plots were prescribed burned in 1998 (Sword Sayer and Haywood 2006). Sapling values are the mean of three replications that were not prescribed burned in 2011 or 2012 (Sayer and others 2018). Sampling months are January (Jan), February (Feb), March (Mar), April (Apr), May, June (Jun), July (Jul), August (Aug), September (Sep), October (Oct), November (Nov), and December (Dec). Starch concentrations are expressed as a percentage of root dry mass, and bars represent one standard error of the mean. The magnitude of y-axes differs between figures.

in May through July (fig. 1A and 1B). In study 2, a reduced level of peak starch concentration in mature longleaf pine woody roots was associated with periodic drought in 1998, 1999, and 2000 (Sword Sayer and Haywood 2006).

During our sapling study, annual precipitation in 2010 and 2011 was 44 and 54 percent less, respectively, than the 30-year average between 1988 and 2013 (fig. 2A). Quarterly precipitation in January–March and April–June of 2010 and 2011 and in July–September and October–December of 2011 was more than 40 percent less than normal (fig. 2B). In contrast, annual precipitation in 2012 and 2013 was 19 and 22 greater, respectively, than the 30-year average between 1988 and 2013. A comparison of mean peak starch levels of saplings between 2011 and 2013 (8.5 mg g^{-1}), mature trees in studies 1 and 2 (17.7 mg g^{-1}), and 5-year-old longleaf pine saplings in

Table 1—Coefficients of variation for monthly values of small woody root starch concentration as determined by two or more annual means across two studies of mature longleaf pine between 1997 and 2001

	Month											
Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
n	3	3	2	5	5	3	3	3	3	3	2	5
CV	56.1	6.4	15.5	13.3	13.1	34.1	27.3	39.4	11.9	34.7	25.8	35.2

Jan = January; Feb = February; Mar = March; Apr = April; Jun = June; Jul = July; Aug = August; Sep = September; Oct = October; Nov = November; Dec = December.

n = number of annual means used to calculate coefficients of variation.

CV = coefficient of variation.

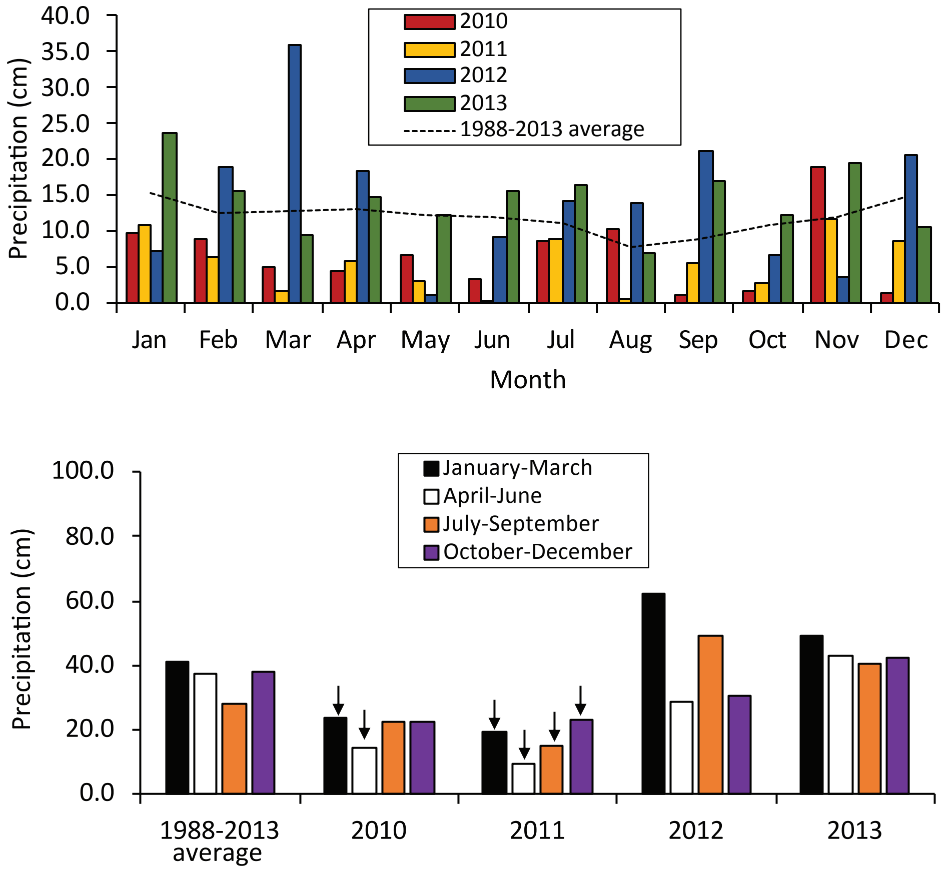

Figure 2—Monthly (A) and quarterly (B) precipitation among experimental longleaf pine saplings in 2011, 2012, and 2013 and estimates of monthly and quarterly precipitation near Winnfield, LA, in 2010 and averaged for 30 years between 1988 and 2013 (dashed line). Arrows indicate annual quarters in which precipitation was at least 40 percent less than the 30-year average.

the absence of prolonged drought (25 mg g^{-1}) (Kuehler and others 2006) suggests that water deficit over 2 years negatively affected sapling starch accumulation in 2011 through 2013. We do not attribute the range in magnitude of these observations to differences in woody root type because starch levels are comparable between the taproot and woody lateral root tissues of longleaf pine (Aubrey and Teskey 2018). Furthermore, it is unlikely that variation in starch analyses was responsible for differences in peak starch concentration because similar minimum values of starch were observed in August through November regardless of methodology.

Prolonged drought has the potential to affect longleaf pine carbon allocation to starch in at least two ways. First, the net photosynthesis of longleaf pine is sensitive to water deficit (Addington and others 2006, Jose and others 2003). Second, under prolonged drought, premature fascicle senescence and carbon limitations to *Pinus* foliage growth reduce total foliage mass (Pallardy and others 1995, Schoettle and Fahey 1994). In association with drought relief in 2012 and 2013, peak starch concentration among saplings in 2013 was 40 percent greater than in 2011 and 2012 but was more than 40 percent less than values reported for mature longleaf pines (Sword Sayer and Haywood 2006) and 5-year-old longleaf pines (Kuehler and others 2006). We propose these losses of starch storage between 2011 and 2013 were due, in part, to the negative effect of drought on gas exchange during starch accumulation in January through March 2011 and the overlapping negative effect of prolonged drought in 2010 and 2011 on total sapling foliage mass in 2011 through 2013. Fascicle-level gas exchange rates may have responded positively to drought relief in 2012 and 2013 leading to a relative increase in peak starch by early 2013. However, we did not observe recovery of normal peak starch levels during 2012 and 2013 after the prolonged drought in 2010 through 2011 ended in 2012.

SUMMARY

Starch is the primary source of carbohydrate to regrow the scorched foliage of longleaf pine seedlings and young saplings. Starch availability is greatest in March through May and may also be adequate to regrow scorched foliage for a limited period after May. At this point, however, starch availability is subject to annual variation. Severe drought for 2 years not only reduced but delayed the recovery of peak starch levels in longleaf pine saplings. When sustained longleaf pine seedling vigor is desired but drought has reduced foliage mass, a delay in prescribed fire application or other means of vegetation control should be considered until foliage mass and peak starch levels are restored. These guidelines apply to seedlings in the grass stage of development and, with one exception, to individuals that have initiated height growth. Longleaf pine terminal bud expansion generally begins in late February and continues through mid-April (Sung and others 2013). During this window of time, elongating terminal buds are vulnerable to heat damage. However, with continued development, they escape mortality by a combination of favorable fire intensity, distance from lethal temperatures, and insulation due to newly emerged fascicles. Therefore, when there is a risk of fire damage to expanding terminal buds, prescribed fire should be applied during the period of peak starch concentration but before or after the risk of terminal bud mortality.

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ESTABLISHING FIRE INTENSITY AND DURATION ON SMALL RESEARCH PLOTS USING A THERMAL IMAGING CAMERA

Edward C. Yost, Martin R. Schubert, Tyler Gifford, and Wayne K. Clatterbuck

Extended abstract—To study the effects of fire on red maple (*Acer rubrum*) seedlings, an experimental plantation was established. Fuels were needed to create fires of low and high intensity to reproduce conditions of wildfires in upland hardwood forests with a high red maple component. Because the amount of natural fuel needed to produce fires of low and high intensities was unknown, the purpose of this research was to study the type and amount of fuel that resulted in low and high intensity fires and fires of differing duration. This research was a pilot study and the experiment was not replicated at this time. This research was conducted at the University of Tennessee, Forest Resources AgResearch and Education Center, Cumberland Forest Unit (N 36º 3.045’, W 84º 28.905’) in Oliver Springs, TN.

The experiment was conducted in part in an open field where there was ample space. A total of four plots were established, each with a different fuel type and arrangement. Three plots with simulated fuels were located on a mown grass surface. One natural plot located in a forest was utilized as a control to provide a comparison. The natural plot (Natural) was located on a southeast aspect of minimal slope with a red maple overstory. The three field plots were situated on the ground with no duff or leaf litter layers and were directly exposed to sunlight. To simulate hardwood forest fuels, red maple leaves and loblolly pine (*Pinus taeda*) needles (1-hour fuels) and 1 inch by 1 inch by 12 foot white pine (*Pinus strobus*) furring strips (10-hour fuels) were used. Leaves and pine straw were gathered several months in advance and air dried on tarps in a pole barn. Fuel amounts were measured using a 1 cubic foot cardboard box which was pre-weighed. To ensure uniformity, leaves and pine straw were measured separately by hand-filling and weighing the boxes. The average dry weights of 1 cubic foot of leaves (11.0 ± 1.7 (standard deviation) ounces) and pine straw (10.7 ± 2.5 ounces) were similar. Three 14 foot by 14 foot square plots were loaded with fuels. Fuels were loosely spread across the area with no trampling. The three fuel loads that were used included leaves only (LO), leaves and pine straw (LP), and leaves, pine straw, and wood (LPW). To create a low fire intensity, Plot LO was loaded with 24 cubic feet of leaves spread throughout the plot with 6 cubic feet on the 1-foot-edge buffer and 18 cubic feet spread evenly within the inner 12-foot by 12-foot area. To create a medium intensity fire burn, Plot LP was loaded with 24 cubic feet of fuel; 12 cubic feet of pine straw was spread as a bottom layer and 12 cubic feet of red maple leaves on top of the pine straw. To create a high fire intensity, the final plot LPW was loaded with leaves, pine straw, and the 1 inch by 1 inch by 12 foot wood strips. Plot LPW was loaded with three layers: 12 cubic feet of pine straw spread as the base layer, 24 cubic feet of red maple leaves in the middle, and 24 12-foot-long wood strips added as the top layer. To simulate a 2 x 2 plant spacing grid, each set of two strips were placed one foot apart in each row in a double cross hatch pattern. The strips were elevated on 2-inch blocks above the fine fuels to prevent compaction and another 12 strips were layered perpendicularly across the first layer in the same fashion.

Ignition of the plot fires was conducted using a 1.25-gallon drip torch. The torch fuel consisted of three parts of diesel and one part gasoline. Plot fires were set by running a single line of fire along the plot perimeter. Plots were burned on March 14, 2018. Plot LO was the first plot burned at 13:43 followed by Plot LP, Plot LPW, and Plot Natural at 14:18, 15:37, and 17:16, respectively. Fire weather was recorded and winds during burning were from variable directions but remained light ranging from 4.9 to 6.0 mph. Temperatures were cool on the day of the burn, reading 38 °F during the first burn and reaching 41 °F during the final burn. Relative humidity values remained consistent throughout the burning of all plots, ranging from 25.9 to 33.0 percent. The temperatures of the fires were recorded using a Micro-Epsilon thermoIMAGER ® Infra-red TIM 400 camera. The Micro-Epsilon thermoIMAGER and associated TIMCONNECT software provided a platform for the accurate measurement and digital documentation of fire temperatures that is compatible with mainstream software programs. According to the manufacturer, a thermoIMAGER detects emissivity and converts it into temperatures using special sensor technology (Micro-Epsilon 2018). The camera used non-contact technology and recorded in real time at 80 Hz. The camera was outfitted with a 30° lens to increase the field of view. The camera resolution was 382 x 288 pixels with a sensitivity of 32.1 °F, accuracy of ±2%, and a temperature range from –4 °F to 2732 °F. The camera

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recorded temperatures in the 7.5 and 13 µm wavelengths and was calibrated to 0.95 emissivity (Micro-Epsilon, 2018). The camera was placed on a tripod 3.5 feet high, and 10 feet from plot edge to allow for a full view of the plot. Recording was stopped when temperatures had cooled to 392 °F.

The highest maximum temperature recorded was 1628 °F in plot Natural, consistent with forest fire temperatures measured by others that ranged between 1616 °F and 2238 °F (Dupuy and others 2003, Van Wagner and Methven 1978). When compared to Natural, the LO and LPW plots displayed lower maximum temperatures and longer duration of increased temperatures. Plot LO had a maximum temperature of 1234 °F, and remained above 392 °F for 17 minutes, 8 seconds. Plot LO also exhibited a rapid rate of heating and a rapid rate of cooling (fig. 1). Plot LP had a maximum temperature of 1450 °F. The amount of time greater than 200 C (392 °F) for Plot LP was slightly less than that of Plot LO, measuring 15 minutes, 19 seconds. The time-temperature relationship of Plot LP was similar to Plot LO. The time-temperature diagram shows a short, rapid heating phase and a short, rapid cooling phase on either side of a sustained phase of high temperatures (fig. 1). Plot LPW sustained a maximum temperature of 1284 °F. This value was higher than that of Plot LO but was lower than that of Plot LP. Plot LPW had the most time greater than 392 °F. for a total of 49 minutes, 29 seconds. Plot LPW exhibited a rapid heating phase and maintained high temperatures with a slow, gradual cooling (fig. 1). Plot Natural sustained the highest maximum temperature of all plots (1628 °F) and the least amount of time greater than 392 °F. The temperature remained above 392 °F for 5 minutes, 51 seconds. Plot Natural had the fastest heating rate and a very short duration of sustained high temperatures. Additionally, Plot Natural showed the fastest cooling time of all plots (fig. 1).

The different fuel types produced two distinct fire intensities. The short duration and low maximum temperature of Plot LO made it suitable as a low fire intensity fuel load. The long duration of sustained high temperatures of Plot LPW made it suitable for the high fire intensity fuel load. This may emulate more intense forest fires that burn dead tree stumps and root systems, creating increased temperatures within the root zones of adjacent trees. Fires of different intensity can be created using artificially arranged natural fuels outside of the forest environment. Use of red maple leaves only (LO) yielded fire intensity metrics that made it suitable for a low fire intensity fuel. A combination of leaves, pine straw, and wood strips (LPW) created high fire intensity with an extended duration that made it suitable as a high fire intensity fuel. The fire intensities in the artificially arranged fuel beds (LO and LP) were similar to the natural fire in that fire temperatures peaked and declined rapidly as fine fuels were consumed. The addition of 10-hour fuels in LPW increased the duration of higher temperatures.

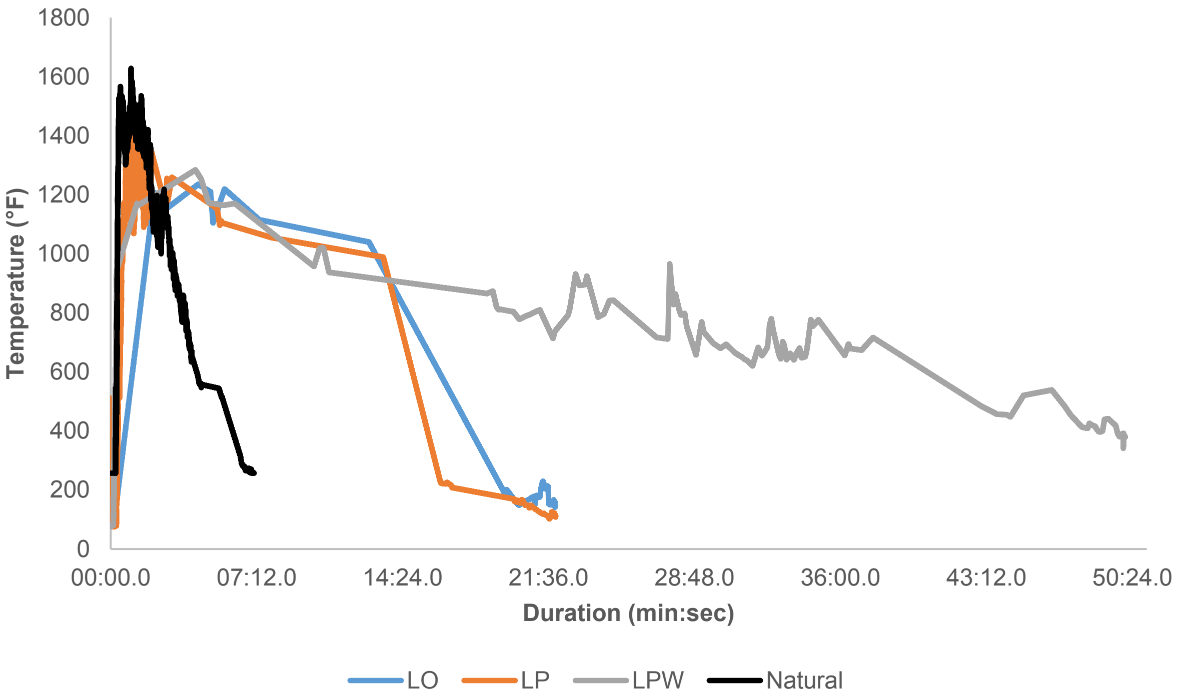

Figure 1—Time-temperature relationship comparison between plots LO (red maple leaves), LP (red maple leaves and pine straw), LPW (red maple leaves, pine straw, and wood strips), and Natural.

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5. Poster Session—
Soils, Disturbance, and Genetics

MANAGEMENT OF LONGLEAF PINE ECOSYSTEMS: CAN SOIL MAP UNITS IMPROVE EVALUATIONS OF SOIL CHANGE?

Jenna Christine Stockton, John Paul Schmidt, Dan Wallace, Mac Callaham, and Daniel Markewitz

Abstract—Adjoining soil map units that vary in slope were evaluated to assess if soil properties differed sufficiently to impact analyses of soil change under longleaf pine (*Pinus palustris*) management. A Piedmont site, an Upper Coastal Plain site, and two Middle Coastal Plain sites in Georgia were sampled. All sites were dominated by an overstory of longleaf pine. A total of 24 profiles were collected to a depth of 200 cm with each site containing two or three map units and two or three profiles within each map unit. Use of visible/near-infrared (VNIR) spectroscopy was also incorporated as a rapid, field-based approach for analyzing soil properties (i.e., clay, carbon [C], and pH_{CaCl2}) that can aid in quantifying soil variability across topographic gradients or dynamic soil properties (DSP) over time. Results indicate that soil map unit phases capturing steepness of slope were not a valuable stratification variable in analyzing DSP under longleaf pine at these sites. Few significant differences were observed with slope steepness at any depth (0–200 cm) for percent clay, percent C, or pH_{CaCl2}. Values ranged broadly across the sites and among depths. Percent clay ranged from <1 to >70 percent, percent C ranged from 0.01 to 3.78 percent, and pH_{CaCl2} ranged from 3.42 to 6.17. Visible/near-infrared calibrations for percent clay demonstrated predictive value (i.e., R^2 = 0.72-0.96) while those for C (i.e., R^2 = 0.55-0.73) and pH_{CaCl2} (i.e., R^2 = 0.20-0.62) indicated some utility for field classification or monitoring of DSP under longleaf pine ecosystems.

INTRODUCTION

Restoration of the longleaf pine (LLP; *Pinus palustris*) ecosystem throughout its historical range has become an important goal for the U.S. Department of Agriculture (USDA), Forest Service and Natural Resources Conservation Service (NRCS). For example, the NRCS participated in the USDA Farm Service Agency's Conservation Reserve Program's Longleaf Pine Initiative (LLPI) that started planting marginal agricultural lands to LLP in 2006. In 2010, the NRCS extended the LLPI to foster regeneration and restoration of LLP on private lands. To do this, the NRCS typically regenerates LLP through planting of seedlings; restoration is most often through the reintroduction of prescribed fire (Platt and others 1988). The NRCS also promotes forest stand improvement through thinning or hardwood removal, restoration and management of rare habitats, and tree/shrub establishment (USDA NRCS 2011).

The NRCS has developed a range of state-and-transition models for the restoration and regeneration of LLP that identify expected shifts in ecological site conditions with a change in management (i.e., agricultural abandonment or introduction of fire). The state-and-transition models are designed for specific physiographic settings and ecological site descriptions that are predominantly defined by plant communities but also by soil properties (Caudle and others 2013). Across the Southeast, soil moisture and percent silt have been identified as critical attributes distinguishing plant community composition and productivity of LLP ecosystems (Peet 2006). For example, in the Middle Coastal Plain of Georgia, both soil moisture and topographic relief class (steeply sloping [>8 percent], undulating [>3–8 percent], or nearly level [1–3 percent]) were found to influence overstory species diversity (Kirkman and others 2004). Similarly, and also in the Middle Coastal Plain of Georgia, landscape position affected soil attributes with greater soil carbon (C) content in bottomlands compared to uplands despite similar LLP management (Silveira and others 2009). These above gradient studies made inferences about LLP ecosystems at the level of soil suborders (e.g., Aquult). In contrast to these broad soil comparisons, studies that have investigated changes in soil properties under LLP with changes in management often limit investigation to a single or a few soil series. A study in southern Georgia, for example, investigated

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changes in soil attributes under LLP after agricultural abandonment and reported working only on two closely related series of Wagram and Norfolk (Markewitz and others 2002). Another study at the Savannah River Site in South Carolina investigating fire frequency and land use history impacts on soil under LLP focused on Blanton and Fuquay series (Bizzari and others 2015).

Within this framework of state transitions for a particular ecological site, there is an interest in understanding how soil characteristics may vary with landscape position (and thus impact LLP communities) and how changing management will change dynamic soil properties (DSP). When studying DSP such as pH or organic C (i.e., properties that are expected to change on human timescales of decades to centuries), it is recommended that studies focus on specific soil map units, specifically the series (Tugel and others 2008). However, this recommendation does not address the fact that a soil series is only one component of a map unit. Differences in slope, historical erosion, or other features indicated by the map unit may be as important as the soil series itself for determining vegetation-soil relationships (USDA NRCS 1993). As such, when studying DSP under LLP one might keep the soil series consistent while sampling across different map unit phases with varying slope, which can impact both LLP communities and soil attributes.

Presently, there is little research concerning how soil map units relating to slope steepness within a soil series might impact inferences about LLP community classification or about DSP under LLP regeneration or restoration. In this study, we analyzed how adjoining map units varying in slope steepness differed in several DSP. We also incorporated the use of visible/near-infrared (VNIR) spectroscopy as a rapid, field-based approach for analyzing soil properties of interest (i.e., clay, C, and $\mathrm{pH}_{\mathrm{CaCl2}}$) that may help evaluate soil variability across slopes or over time. Based on previous research on landscape position, we hypothesized that slope steepness across map units would differ in soil properties affecting soil moisture (i.e., clay) and that $\mathrm{pH}_{\mathrm{CaCl2}}$ and C would be higher in map units with the lowest slopes.

METHODS

Study Sites

This study within Georgia used two sites located within the Piedmont and Upper Coastal Plain and two on the Middle Coastal Plain (fig. 1). The Piedmont site was located on the Hitchiti Experimental Forest (Oconee National Forest) near Juliette in Jones County, while the Upper Coastal Plain site was on private property in Hancock County. The Middle Coastal Plain sites were located within the Ohoopee Dunes Natural Area near Swainsboro (Emanuel County) and the Jones Center at Ichauway near Newton (Baker County). All sites

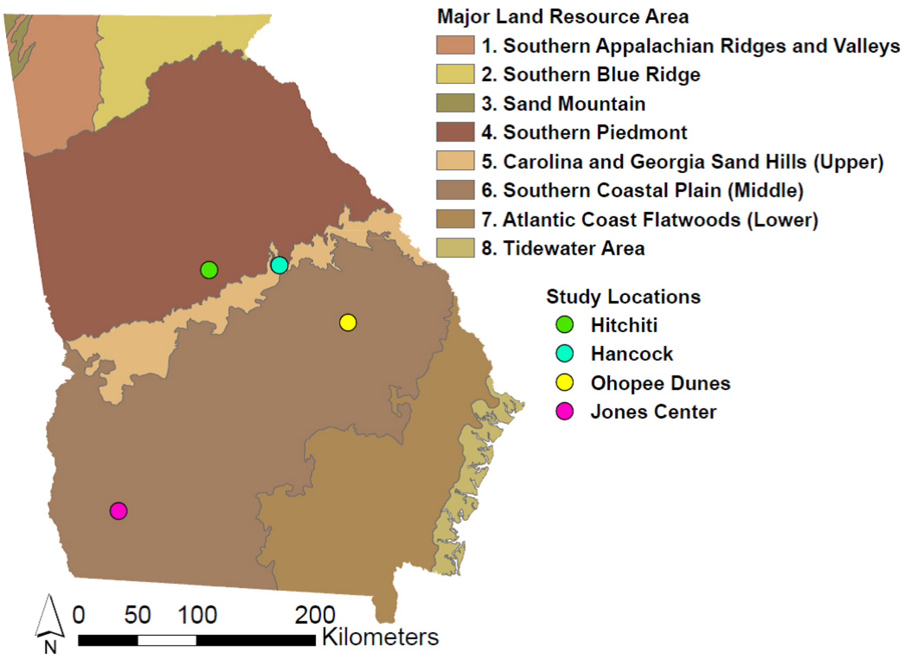

Figure 1—Site locations in the Piedmont (Hitchiti Experimental Forest), Upper Coastal Plain (private property in Hancock County), and Middle Coastal Plain (Ohoopee Dunes Natural Area and Jones Center) in Georgia. Georgia map indicates physiographic regions and sites.

were dominated by an overstory of LLP, although the Piedmont and Upper Coastal Plain sites were planted 8 and 16 years ago while the Middle Coastal Plain sites were more mature (many trees >40 years old), naturally regenerated stands. The Hitchiti and Hancock County sites are both cutover sites converted from loblolly pine stands (*Pinus taeda*) to LLP. The Ohoopee Dunes site is managed by the Georgia Department of Natural Resources as a conservation area with some use of prescribed fire, while the Jones Center site has been minimally harvested and is managed with prescribed fire on a 2-year return interval.

Hitchiti soils consist of the Vance series, which is a fine, mixed, semiactive, thermic Typic Hapludult. The soil map units within this site are VaB2 and VaC2 with a slope of 2–6 or 6–10 percent, respectively, and these units are eroded (fig. 2A). The Hancock County site is dominated by the Bonifay soil series (fig. 2B), which is a loamy, siliceous, subactive, thermic Grossarenic Plinthic Paleudult. The soil map units within this site are BnB and BnD, indicating slopes of 0–6 or 6–12 percent, respectively. The Ohoopee Dunes (fig. 2C) site also consists of the Bonifay soil series but with different soil map unit notation, which can occur between counties. The soil map units of interest are BoB, BoC, and BoD, with slopes of 0–5, 5–8, and 8–12 percent, respectively. Lastly, the Jones Center (fig. 2D) site comprises the Troup soil series, which is a loamy, kaolinitic, thermic Grossarenic Kandiudult. The soil map units of interest are TwB and TwC indicating slopes of 0–5 and 5–8 percent, respectively. These soil series descriptions are based on USDA NRCS Soil Survey Division (https://soilseries.sc.egov.usda.gov).

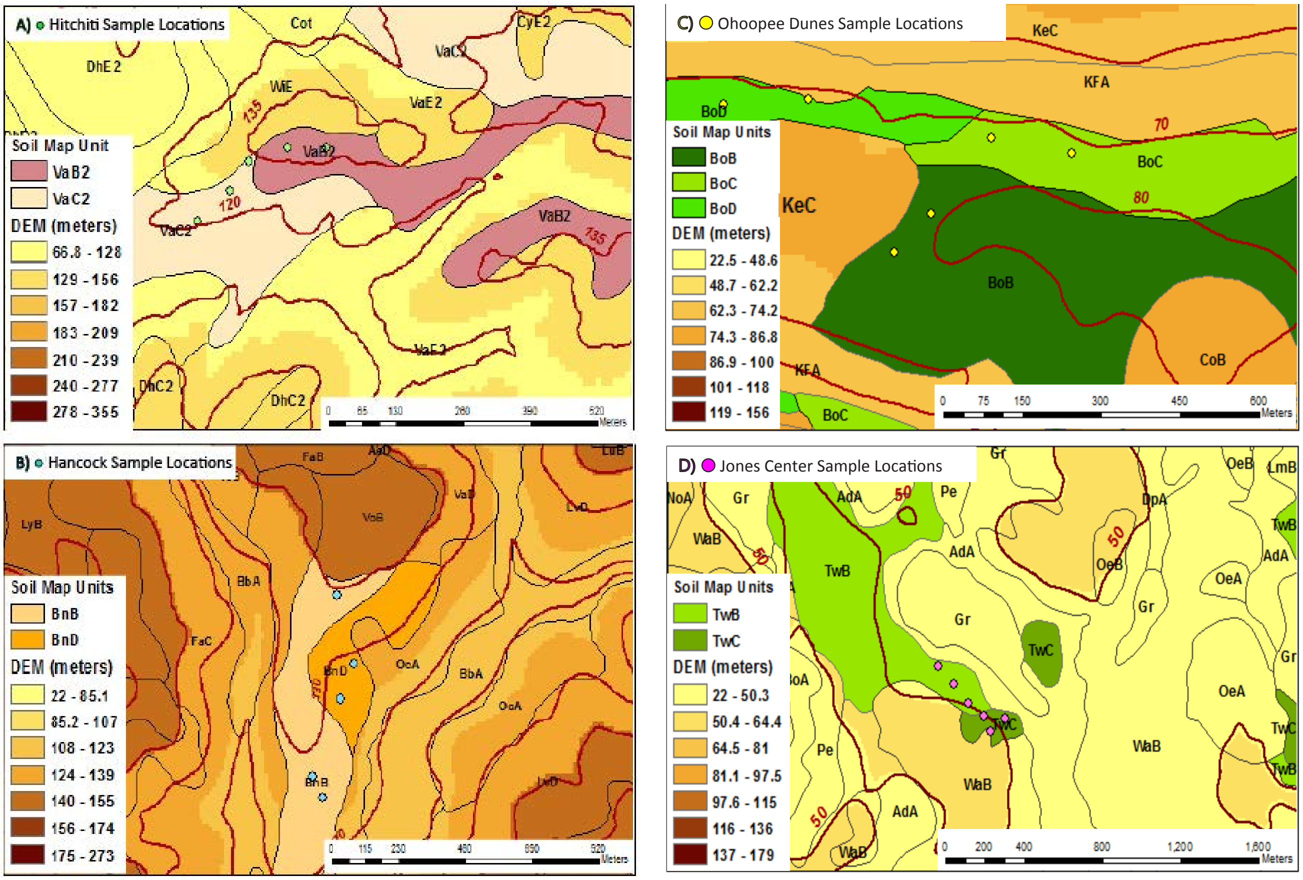

Figure 2—Site maps for A) Hitchiti Experimental Forest, B) private property in Hancock County, C) Ohoopee Dunes Natural Area and D) Jones Center. Maps include soil series, unit phases, sampling locations, and elevation contours (red lines at 10 or 15 (Hitchiti only) m contours) from digital elevation model (DEM). Points in each location indicate the slope gradient across the map units that was sampled for soil and stand attributes.

Soil Sampling and Analyses

In each soil map unit, two or three sampling locations were randomly selected. These random selections in the map units were not always consistent with the slope designation, but the locations were maintained and these few discrepancies are described below. Mineral soils were sampled in two ways. For two upper depths (0–2 and 9–11 cm) used to improve VNIR calibration, a soil punch with 2-cm diameter was used and three to five cores per sampling location were composited. In addition, 20-cm increment samples (i.e., 0–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, 140–160, 160–180, and 180–200 cm) were collected with a 6-cm-diameter soil auger. Sampling location VaC2-3 was an exception with a lithic contact at 120 cm.

A VNIR field spectrometer (Analytical Spectral Devices [ASD], Inc., Boulder, CO) with Indico® Pro software was used to scan soil samples in the field. The VNIR scanned from 350 to 2500 nm in 1-nm increments using a contact probe with a 2-cm-diameter window. The scans were completed by first performing a baseline scan using a Spectralon® white blank (Labsphere, North Sutton, NH). The lens of the contact probe was pressed firmly against the surface of the soil within its sample bag so that no light from the lens was visible. Soil within the sample bag was mixed, and the refreshed surface was scanned again. Each spectrum was averaged from a compilation of 50 readings during each scan. This was performed three times per sample, and the three scans were then averaged. Between each sample, the contact probe was cleaned. A baseline scan was performed after every 10 samples.

Samples were air-dried and passed through a 2-mm sieve. An oven-dry (105 °C) moisture correction factor was determined for each air-dried sample. Soils were analyzed for percent clay using the hydrometer method (Gee and Or 2002), C using a Flash 2000 Series CN soil analyzer (CE Elantech, Inc., Lakewood, NJ), and $\mathrm{pH_{CaCl2}}$ using a 1:1 ratio of soil and 0.01 M $\mathrm{CaCl_2}$ following Thomas (1996).

Stand Attributes

In each plot, all individual trees within a radius of 10 m from the plot center and with a diameter at breast height (d.b.h.) >4 cm were identified and d.b.h. measured to determine basal area. Stem density was calculated within a diameter of 10 m by counting all stems with a height >1 m. Ground cover was determined for a 10-m transect in both the eastward and westward direction from plot center. Ground cover directly below each meter along the transects was classified as green/living, bare soil, or forest floor, and a percentage was calculated for each category. Lastly, three dominant tree heights were measured within the plot. Descriptive data are in table 1.

Statistical Analyses

Soil map units were sorted into flat, medium, and steep categories comprising 0–6, >6–8, and >8–12 percent slope, respectively. Results were analyzed by depth as a randomized block design with some blocks being incomplete (i.e., not all slope categories) and no medium slope in the Piedmont. Soil chemical and physical comparisons were made between region (Piedmont/Upper Coastal Plain and Middle Coastal Plain) and map unit slope (flat, medium, steep) with site (Ohoopee Dunes, Jones Center, Hitchiti Experimental Forest, Hancock County) as the blocking factor that is nested within a region. Data were compared using a mixed effects analysis of variance (ANOVA) across both regions and slope categories, although region x slope interactions only include flat and steep slope categories. Pairwise comparisons were tested for significant difference at $p < 0.05$ using Tukey's Honestly Significant Difference (HSD). If region was not significant, slope data were pooled across region to test among flat, medium, and steep slopes.

Visible/near-infrared raw reflectance spectra were preprocessed using Savitzky-Golay (SG), continuum removal (CR), or wavelets transformations (WT). Spectra and percent clay, percent C, or $\mathrm{pH_{CaCl2}}$ were randomly separated into 20-percent test and 80-percent training datasets. To avoid splitting up soil profiles within these sets, the Kennard-Stone algorithm was used (Kennard and Stone 1969). Partial least square regression (PLSR) after data reduction with principle components analysis or support vector machine (SVM) was used to perform the calibration (Thissen and others 2004). Coefficients of determination (R^2) and the root mean square error (RMSE) were used to compare results. The best calibration was determined for all data, Piedmont/Upper Coastal Plain samples, and Middle Coastal Plain samples. Data were analyzed using R version 3.2.3 using packages Prospctr (Stevens and Ramirez-Lopez 2013) and Soil.spec (Sila and others 2014) and ArcMap version 10.3. For more detail see Stockton (2016).

RESULTS

Soil Profile Attributes

Measured soil attributes across the sites ranged broadly (fig. 3). Percent clay, for example, ranged from <1 percent to >70 percent. Between the regions, clay content was statistically greater in the Piedmont/Upper Coastal Plain versus the Middle Coastal Plain by an absolute amount of ~15 percentage points within 40–60 cm and by ~13 percentage points within 80–100 cm ($p = 0.008$ and 0.03, respectively, fig. 4a). Other depths were not statistically different between the regions. In these depths, after pooling data, among slope steepness, percent clay was ~20 percentage points lower ($p = 0.045$) on an absolute basis when comparing steep slope to flat and medium slopes in 180–200 cm

Table 1—Stand characteristics and soil map unit slope for sites in Georgia, taken at each location in 2015/2016

Region Site	Map unit	Replicate	Map unit slope	Soil series	Basal area	Mean tree height	Stem density	Ground cover		
								FF	GR	BS
					m²/ha	*m*	*stems/ha*	- - - -*percent* - - - -		
Middle Coastal Plain										
Ohoopee Dunes	BoD	1	Steep	Bonifay	2.88	21.20	509	90	0	10
	BoD	2	Steep	Bonifay	20.20	13.13	764	90	10	0
	BoC	1	Medium	Bonifay	16.50	18.97	891	65	35	0
	BoC	2	Medium	Bonifay	8.58	19.34	637	90	10	0
	BoB	1	Flat	Bonifay	18.30	15.03	1,401	85	15	0
	BoB	2	Flat	Bonifay	1.45	11.93	637	90	10	0
Jones Center	TwC	1	Medium	Troup	1.50	11.00	2,165	0	10	90
	TwC	2	Medium	Troup	0.07	2.80	762	0	25	75
	TwC	3	Medium	Troup	0.08	3.40	382	30	10	60
	TwB	1	Flat	Troup	0.23	4.43	3,183	40	10	50
	TwB	2	Flat	Troup	0.00	23.20	509	40	10	50
	TwB	3	Flat	Troup	0.02	2.11	1,655	35	5	60
Piedmont/Upper Coastal Plain										
Hitchiti	VaC2	1	Steep	Vance	0.04	12.30	4,329	20	80	0
	VaC2	2	Steep	Vance	0.03	3.60	5,474	40	60	0
	VaC2	3	Steep	Vance	0.04	3.08	3,310	10	85	5
	VaB2	1	Flat	Vance	0.02	3.67	6,366	40	60	0
	VaB2	2	Flat	Vance	0.08	4.60	2,674	55	45	0
Hancock County	BnB	1	Flat	Bonifay	7.83	10.50	N/A	25	70	5
	BnB	2	Flat	Bonifay	28.70	5.91	N/A	40	30	30
	BnB	3	Flat	Bonifay	26.40	4.57	N/A	20	55	25
	BnD	1	Steep	Bonifay	16.00	25.30	N/A	25	70	5
	BnD	2	Steep	Bonifay	17.20	3.60	N/A	60	30	10

FF = forest floor, GR = green/living vegetation, BS = bare soil, N/A = Not available.

(fig. 4b) and ~13 percentage points lower in 160–180 cm. Other depths were not statistically different for percent clay among steepness.

Within specific sites, map unit profiles did not vary consistently for clay. At the Hitchiti, for example, VaB2 (replicate 1 and 2) had clay concentrations between 40 and 60 percent, and VaC2 (replicate 1 and 2) had 30 to 40 percent clay, which is consistent with a Bt horizon for a Vance soil series. However, VaC2-3 only contained 10 percent clay at the Bt horizon depth (fig. 3). For the Hancock County site, percent clay was generally low (1–5 percent) in the upper 40 cm but increased to a peak of 70 percent clay within the 120–160 cm depth, but variance with slope steepness was inconsistent at this site (fig. 3). Within the Ohoopee Dunes, percent clay generally increased with depth for all map units, with the exception of BoD-1 and BoD-2, which had very little clay present (fig. 3). Within the Jones Center site, percent clay increased relatively consistently with depth and ranged from 0–30 percent (fig. 3).

Percent soil C was significantly different between the regions in 0–2-, 9–11-, and 40–60-cm depths ($p = 0.02$, 0.04, and 0.02, respectively; fig. 4c). Percent soil C within 9–11 cm was 47 percent lower on a relative basis in the Piedmont/Upper Coastal Plain than the Middle Coastal Plain. Differences by slope steepness were only significant in 9–11 cm ($p = 0.0004$). Within the Coastal Plain, medium slope (1.7 percent carbon) was higher than the flat slope (0.65 percent carbon) and the steep slope (0.20 percent carbon; fig. 4d). The flat slopes (0.70 percent) and steep slopes (0.45 percent) in the Piedmont were not significantly different than flat or

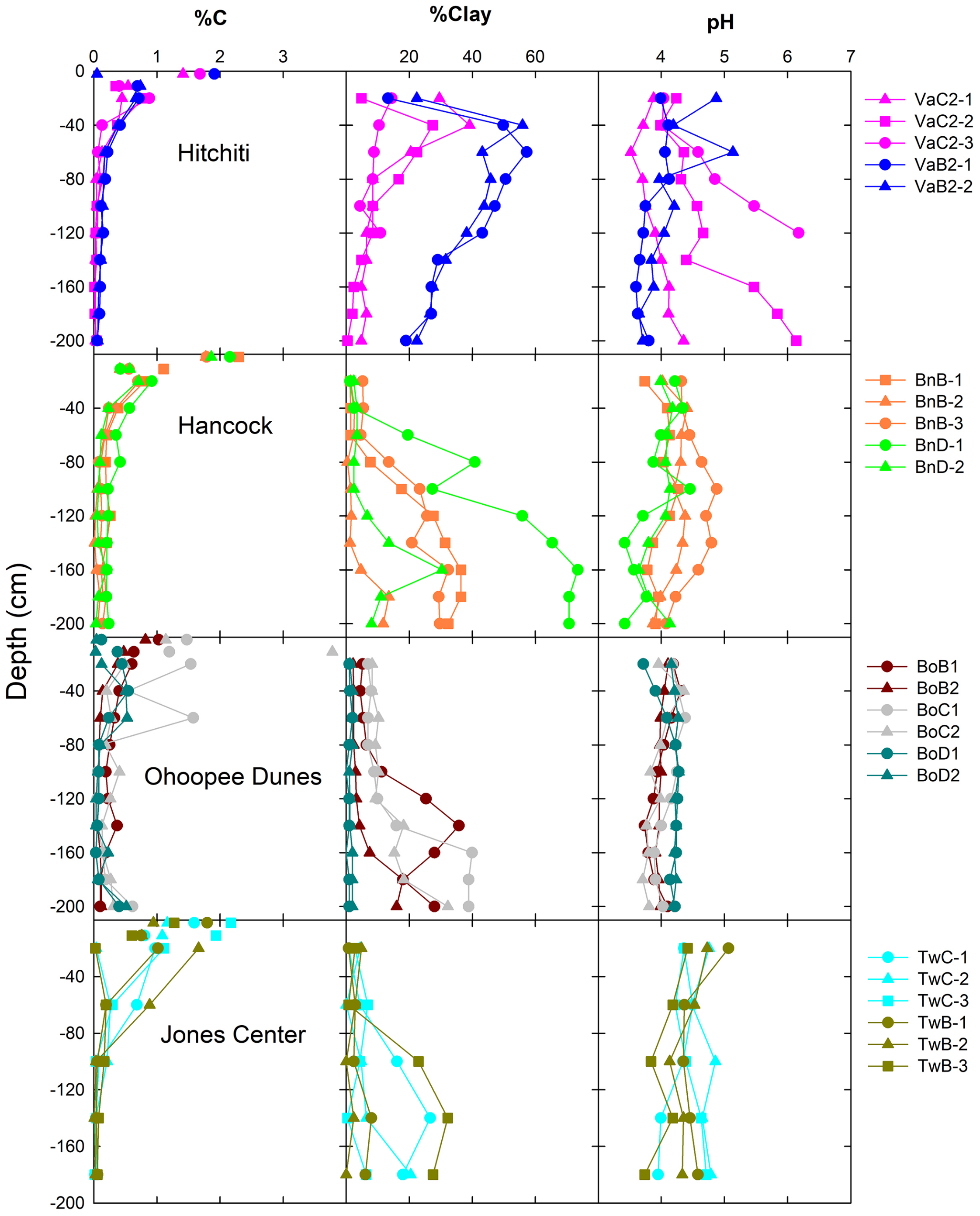

Figure 3—Soil profiles by site and soil series map unit. Within each graph, the same color indicates the same map unit, and different shapes indicate different soil profiles within that map unit category. For soil C, 0–2- and 9–11-cm data are included as well as the 0–20-cm data. Samples were collected 2015/2016.

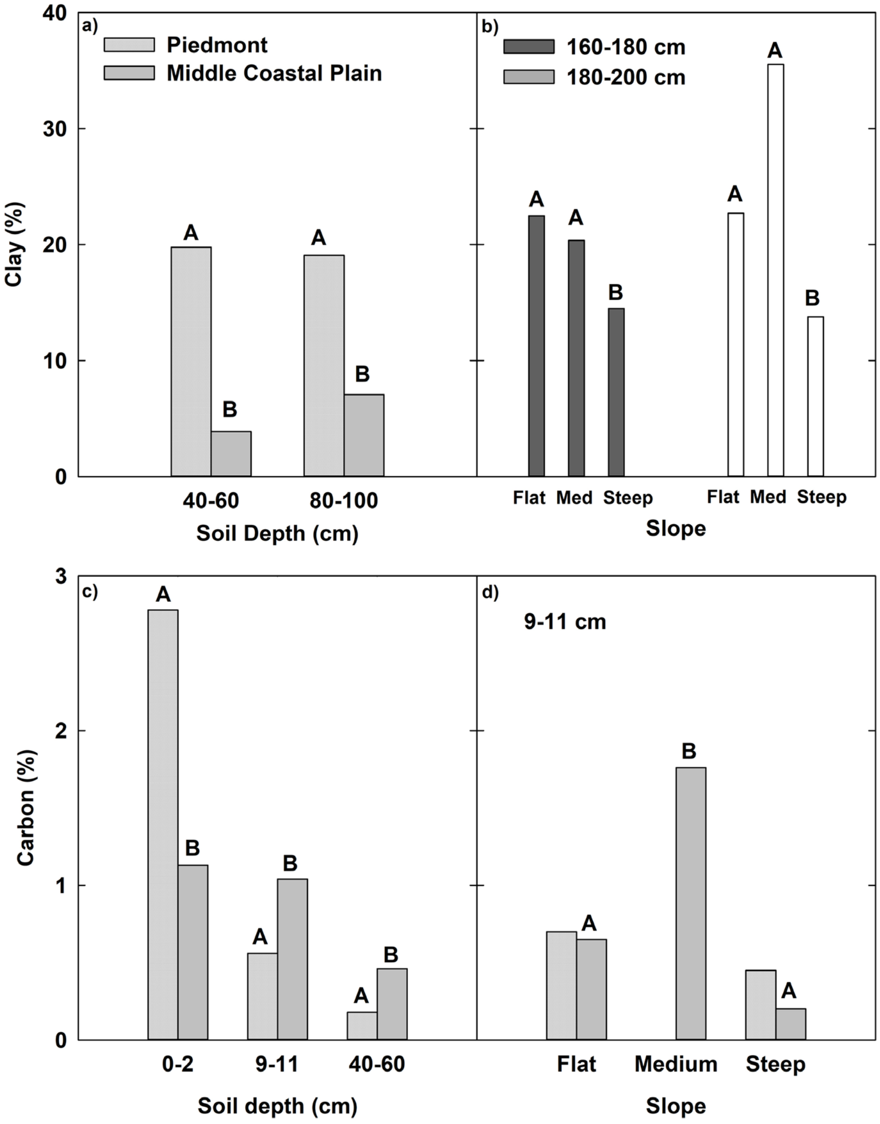

Figure 4—Percent clay averaged by depth and compared by region (a) or slope (b). Percent carbon averaged by depth or depth x region and compared by region (c) or slope within region (c). Capital letters indicate significant differences between regions (a and c) or between slopes (b and d).

steep slopes in the Coastal Plain (fig. 4d). In all the sites, percent C declined steadily with depth for each profile (fig. 3) except for the Ohoopee Dunes where percent C decreased with depth until 180 cm but increased slightly within 180–200 cm (fig. 3).

Finally, pH_{CaCl2} exhibited no significant differences for any depth across region or slope. At the Hitchiti, there was a distinct increase when comparing VaC2 to VaB2, with VaC2 pH increasing with depth, but pH remained fairly consistent with depth for all map units for all other sites (fig. 3).

VNIR Analysis

Field-based VNIR calibrations and validations focused on percent clay, percent soil C, and pH_{CaCl2} for both soil map unit classification and DSP measurement. The analysis investigated calibrations over all the data as well as by region. For all percent clay data, the best model used WT and SVM algorithm for prediction ($R^2 = 0.72$ for predicted versus observed; table 2 and fig. 5). For Piedmont/Upper Coastal Plain or Middle Coastal Plain data separately, PLSR with CR provided the best models ($R^2 = 0.96$ and 0.91, respectively; table 2). The combined data analyses for percent clay also resulted in higher RMSE than either Piedmont/Upper Coastal Plain or the Middle Coastal Plain separately (table 2). For all percent C data, PLSR with WT provide the best predictions ($R^2 = 0.55$). The same PLSR with WT approach was also best for the Piedmont/Upper Coastal Plain ($R^2 = 0.67$) and Middle Coastal Plain ($R^2 = 0.73$). The RMSE, however, did not vary substantially (table 2). Finally, for all pH_{CaCl2} data, PLSR with WT yielded the best model ($R^2 = 0.20$), which was improved for Piedmont/Upper

Table 2—Best prediction models for soil attributes from visible/near-infrared spectra

					Validation		Cross-validation	
Soil attribute	Data	Method	Transformation	N comp.	R^2	RMSE	R^2	RMSE
Clay (%)	All	SVM	WT	8	0.72	0.9719	0.93	1.0281
	P/UCP	PLSR	CR	8	0.96	0.5398	0.96	0.5631
	MCP	PLSR	CR	8	0.91	0.4586	0.94	0.4615
C (%)	All	PLSR	WT	5	0.55	0.8840	0.80	0.9492
	P/UCP	PLSR	WT	11	0.67	0.8906	0.93	0.8985
	MCP	PLSR	WT	3	0.73	0.9996	0.86	1.0217
pH_{CaCl2}	All	PLSR	WT	16	0.20	4.0296	0.82	4.2045
	P/UCP	PLSR	SG	9	0.62	4.1822	0.95	4.1822
	MCP	PLSR	CR	10	0.54	3.3460	0.91	3.3460

All = all data, P/UCP = Piedmont Upper Coastal Plain, MCP = Middle Coastal Plain.

PLSR = partial least square regression, SVM = support vector machine.

CR = continuum removal, SG = Savitzky-Golay, WT = wavelets.

N comp. = number of principle components.

n_{All} = 221, $n_{Piedmont/Upper\ Coastal\ Plain}$ = 116, $n_{CoastalPlain}$= 105.

Coastal Plain using PLSR and SG (R^2 = 0.62) or for Middle Coastal Plain using PLSR and CR (R^2 = 0.54). All pH_{CaCl2} data and Piedmont/Upper Coastal Plain had similar RMSE while Middle Coastal Plain RMSE declined (table 2).

DISCUSSION

When considering sharply delineated polygons of soil map units, it is well recognized that such classifications are not 100 percent pure and will contain inclusions of other soil series or other soil phases (i.e., slopes) (Burrough and others 1997, Odgers and others 2014). Similarly, soil does not usually change abruptly at the polygon boundaries (Greve and Greve 2004). In our study, both issues of inclusions and boundary delineations were evident. At the Hitchiti site, for example, the profiles collected farthest down the hillslope (VaC2-3 and VaC2-2) had an increase in pH_{CaCl2} at depth unlike the other profile in the same map unit (VAC2-1) or the other two profiles in the adjacent map unit phase of the same soil series (VaB2-1 and VaB2-2). This may have been due, in part, to surrounding mafic soils as represented by the Davidson soil series (fine, kaolinitic, thermic Rhodic Kandiudults; DhE2 and DhC2 in fig. 2A). The Rhodic designation indicates a darker color in the Davidson from the mafic rock but may also cause the soil to become more basic with depth compared to the more acidic felsic soils located at the top of the hillslope that have a slightly declining pH with depth (Raulund-Rasmussen and others 1998). These types of inclusions might well impact community composition, as observed by Kirkman and others (2004) at a slightly larger scale but cannot be identified in the absence of finer scale map units (Ogders and others 2014).

Another map unit inconsistency was identified within the Ohoopee Dunes. Despite locating profiles BoD-1 and BoD-2 within the map unit boundary (fig. 2C), the percent clay is well below the other four profiles in the adjacent Bonifay map units (BoC and BoB in fig. 3). In fact, these low clay profiles are not Bonifay as they do not possess an argillic horizon that would be defined by a 4 percent absolute increase in clay with depth (USDA NRCS 1999). Thus, regardless of their location near the middle of the BoD map unit, these profiles display characteristics of the Kershaw soil series (KeC), which is present next to the BoD map unit. This BoD map unit was identified as having 8-12 percent slope, but field observations clearly indicated inclusions of some slopes <8 percent. When using map units for investigations of slope steepness or DSP, it is evident that units must be ground-truthed such that geographical delineations of mapping units are consistent with physiographic realities in the field. This caution is stated in the NRCS Soil Change Guide (Tugel and others 2008) but is often ignored in modeling efforts that may, for example, be interested in estimating soil C sequestration with LLP regeneration across the region.

The two examples above demonstrate some of the potential utility in developing VNIR for field use. In the first example, an ability to measure pH in the field might help identify changes in underlying bedrock, which may alter soil fertility (e.g., phosphorus availability) and thus LLP regeneration or restoration objectives. The VNIR calibrations for pH across all data were poor (R^2 = 0.20), but separating the data into Piedmont/Upper Coastal Plain and Middle Coastal Plain regions yielded improved results (R^2 = 0.62 and 0.54, respectively; table 2). Although these validation results are below what is

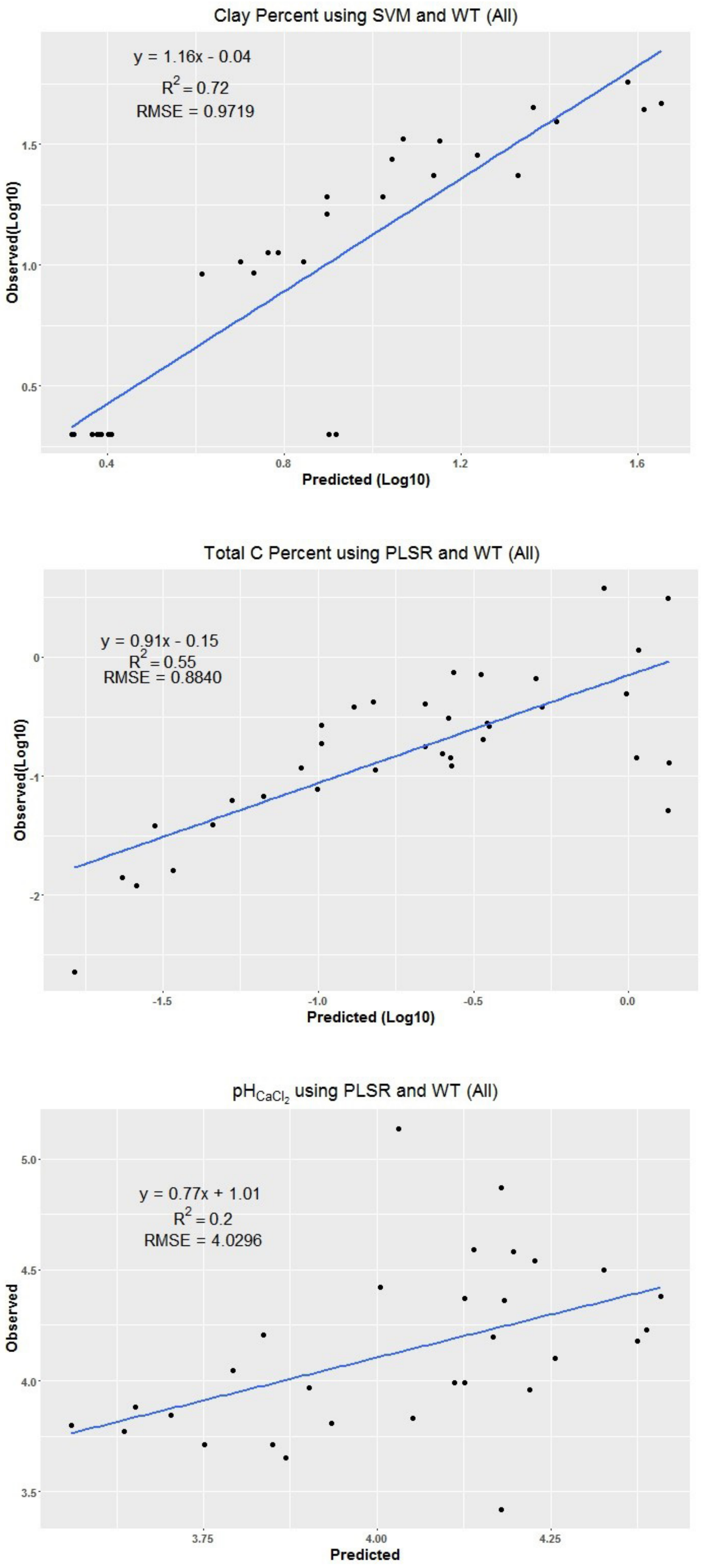

Figure 5—Best validation models across all sites for percent clay, percent C, and pHCaCl2 using support vector machine or partial least square regression (PLSR) after wavelets transformations (WT).

desired for a predictive model (i.e., $R^2 > 0.8$), they still might detect a pH change from 4 to 6 as observed in the Hitchiti site.

We focused on soil variance across soil map unit phases of slope steepness within a soil series as it might relate to understanding changes in DSP during LLP regeneration or restoration. For example, the ability to measure pH as a DSP under LLP regeneration or restoration should prove beneficial. Declines in surface soil (0–10 or 0–15 cm) pH have been observed under LLP regeneration on post-agricultural land compared to reference LLP (Bizzari and others 2015, Markewitz and others 2002), although in both cited cases pH decreases ranged from 4.8 to 4.0 or 4.7 to 4.5. To identify such changes in pH, VNIR prediction models will need to improve.

In the second example above, the ability to measure percent clay in the field might also prove useful. Of the three soil characteristics measured, VNIR predicted percent clay best with validations of $R^2 = 0.72$, 0.96, and 0.91 for all data, Piedmont/Upper Coastal Plain, and Middle Coastal Plain datasets, respectively. Previous VNIR models for clay measurement have also been successful (Waiser and others 2007). The VNIR could be used to classify soils within the field. For example, VNIR may enable a user to determine if and where the argillic horizon starts within a profile, which might help distinguish between an Arenic or Grossarenic designation. Similarly, distinguishing between sandy series such as Kershaw (≤5 percent silt + clay) and Lakeland (>5 percent silt + clay) might be possible in the field. This information could aid with soil mapping and thus regeneration or restoration management decisions.

The final VNIR calibration was for percent C. Prediction models with the PLSR and WT approach performed best with R^2 for validations of 0.55, 0.67, and 0.73 for all data, Piedmont/Upper Coastal Plain, and Middle Coastal Plain, respectively (table 2 and fig. 5). Being able to accurately estimate soil C within the field will help determine how LLP regeneration or restoration may be altering C concentrations or contents, which plays a fundamental role in soil fertility. Also, knowing the amount of C being stored during LLP regeneration or restoration has taken on a particular interest relative to atmospheric carbon dioxide (CO_2) concentration and fire management (Lavoie and others 2014, Butnor and others 2017).

Previous studies within LLP have clearly demonstrated changes in soil C with regeneration, fire, and landscape position. For example, in the Middle Coastal Plain of South Carolina, soil on post-agricultural lands regenerating with LLP had 0–15-cm soil C values of 0.9 percent compared to reference LLP of 1.35 percent (Bizzari and others 2015). In the Middle Coastal Plain of Georgia, similar results were observed for 0–10-cm soil (mean ± 1SE) in regenerating stands (0.6 ± 0.6 percent C) relative to reference stands (2.19 ± 0.19 percent C) (Markewitz and others 2002). In this same Georgia location, LLP in the absence of fire had 2.57 percent C while regularly burned reference stands had 1.7 percent C (Boring and others 2018). Finally, relative to 0–20-cm upland soils (1.29 ± 0.6 percent C), bottomland soils were threefold higher (4.79 ± 5.61 percent C) (Silviera and others 2009). The VNIR calibrations should be able to detect these size differences.

Relative to our primary interest in map units and slope steepness, surface soil C (0–2, 9–11, or 0–20 cm) did not vary consistently with slope (fig. 4). In the 0–2-cm layer, soil C increased with slope steepness but not significantly. Only in 9–11 cm was slope significant, with the medium steepness in the Coastal Plain showing the highest soil C, which is not consistent with our original hypothesis. Whether variance in these map units with slope steepness can inform changes in DSP during LLP regeneration or reforestation depends on the variance in the units (or strata) compared to the overall landscape variance. When measuring 186 samples in an upland-to-bottomland gradient study previously noted above, the coefficient of variation (CV) for soil C was 144 percent over all samples and 50 and 118 percent in the upland and bottomland, respectively (Silviera and others 2009). In our study, CV of percent C for all soil samples in 0–2-, 9–11-, and 0–20-cm depths was 127, 92, and 58 percent, respectively ($n = 22$ per depth increment). Pooled across regions, the slope classes of flat ($n = 10$), medium ($n = 5$), and steep ($n = 7$) had CV for soil C of 49, 28, and 150 percent within 0–2 cm, respectively. In 9–11 cm, CV was 29, 68, and 46 percent, respectively. Finally, in the 0–20-cm sample, CV was 58, 70, and 47 percent, respectively. Only the 9–11-cm depth had smaller CV within all slope classes than the overall sample CV suggesting slope class was a useful stratum within this depth. Within the sample size constraints of our study, soil map unit phases did not greatly improve our ability to determine soil property change (i.e., DSPs) under LLP regeneration or restoration. There was too much variance within soil map unit phases for inclusion of slope to improve statistical tests of change over time.

CONCLUSIONS

We characterized 2-m profiles in adjoining map units to understand how well soil maps units, as delineated by polygons on soil maps, accurately capture variance over slope steepness and how soil variance across these units might impact our ability to quantify soil change. We also measured all soil with VNIR to assess how well this rapid field technique could measure soil attributes of interest both for field classification of soils and measurement of DSP over time. From these efforts, our study suggests that soil map unit phases capturing steepness of slope will not be a valuable stratification variable in analyzing DSP under LLP regeneration or restoration. Few significant differences were observed between slope classes at any depth (0–200 cm) for the measured variables (clay, C, or pH_{CaCl2}), and even in cases of observed differences there was not a clear monotonic pattern from flat to steep. Visible/near-infrared calibrations for percent clay demonstrated potential predictive value while those for C and pH_{CaCl2}, although not as strong, indicated some utility for field classification or monitoring of DSP.

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SOIL RESPIRATION AS RELATED TO ABIOTIC AND REMOTELY SENSED VARIABLES IN VARYING OVERSTORIES AND UNDERSTORIES IN A HIGH ELEVATION SOUTHERN APPALACHIAN FOREST

Rachel Hammer, John Seiler, Valerie Thomas, and Brian Strahm

Extended abstract—Forests capture carbon dioxide through the process of photosynthesis. However, forests also respire carbon dioxide into the atmosphere. Soil respiration (R_s) is a significant source of atmospheric carbon dioxide. A portion of R_s comes from the process of microorganisms breaking down carbon sources in the soil while another portion is from respiring roots (Gough and others 2008). Even small changes in R_s can have a significant impact on whether a forest will behave as a carbon source or a carbon sink (Schlesinger and Andrews 2000). Therefore, considerable attention has recently been focused on accurate predictions of R_s.

Vegetation affects the soil microclimate, the amount and quality of litter deposited, and the rate of root respiration (Akburak and Makineci 2013). Recent studies have developed relatively good predictions of R_s and carbon cycling in managed forest systems, including pine plantations. There are substantially fewer studies focused on natural hardwood systems. Hardwood systems often have mixtures of species that abruptly change across small spatial scales, adding a level of complexity we have yet to understand.

Our study compared R_s, soil temperature, and soil moisture under four different vegetation types: eastern hemlock (*Tsuga canadensis* L. Carriere)-dominated overstory, mountain laurel (*Kalmia latifolia* L.)-dominated understory, hardwood-dominated overstory, and cinnamon fern (*Osmundastrum cinnamomuem* (L.) C. Presl.)-dominated understory with four replications of each. We calculated vegetation indices (normalized difference lignin index, normalized difference vegetation index, photochemical reflectance index, and normalized difference nitrogen index) on remotely sensed data from the National Ecological Observatory Network.

We found strong seasonal differences in R_s rates among our vegetation types (fig. 1). In the growing season, cinnamon fern had the highest R_s rate. Cinnamon fern was in abundance during the growing season; therefore, there was more belowground activity during this time. In the cooler dormant months, the hemlock plots had the highest R_s rate. Hemlock are evergreens and thus their needles persist in the dormant months which could lead to higher activity belowground as compared to other vegetation plots. The indices were weakly correlated with R_s rates in August and September. The spatial differences between the vegetation indices and R_s could explain the weak correlations we observed. Studies may want to focus on examining vegetation indices' ability to predict processes under broader spatial scales as well as get a better understanding of vegetation indices' spatial accuracy. Overall, vegetation type had a secondary effect on R_s rate seasonally.

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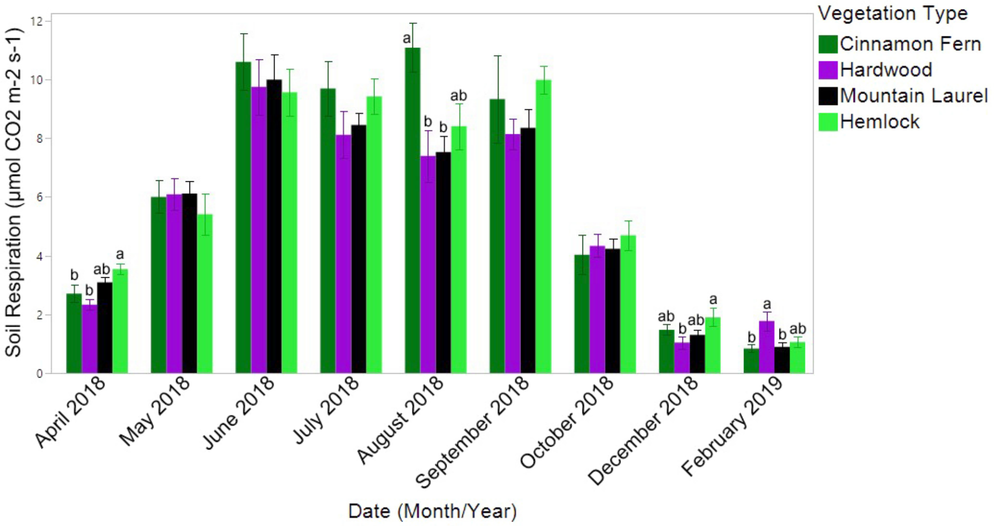

Figure 1—Average soil respiration (R_s) by sampling date for cinnamon fern, hardwood, mountain laurel, and hemlock vegetation types. Different letters signify a significant difference among vegetation types within sampling date.

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HYBRID SWEETGUM VOLUME EQUATIONS FOR A NORTH LOUISIANA AFFORESTED SITE FOLLOWING HERBICIDE APPLICATION

T. Eric McConnell, Curtis L. VanderSchaaf, Robert Hane, Joshua P. Adams, and Michael Blazier

Abstract—Investigating the suitability of hybrid sweetgum (*Liquidambar formosana* x *styraciflua*) as a biomass feedstock for Western Gulf forest industries requires information on stand yields. Using data from 2-year-old (1-0 seedling stock) hybrid sweetgum trees, equations were developed to estimate stem volume, comprising both wood and bark, on an afforested site in north Louisiana. Dummy variable statistical analyses concluded all data could be pooled across herbicide and varietal treatments to produce a single model system. Eighty-eight trees were measured for stem diameter at 1-foot increments from the groundline, and total stem height was determined from pole measurements. The volume of each section was calculated using Smalian's formula and summed to provide total stem volume. Eighty trees served as a model development set, with eight trees randomly withheld for validation. The square of groundline diameter (D_G^2) alone was determined to sufficiently predict stem volume, which could save managers time and effort when constrained by scarcity of resources at this stage of stand development. The validation set suggested our model over-predicted stem volume of smaller trees and under-predicted larger trees. Mean absolute deviation was 0.003 cubic feet, or 17 percent. Including tree height, form, and/or other variables as age increases will likely improve upon these estimates over time.

INTRODUCTION

Sweetgum (*Liquidambar styraciflua* L.) is a fast-growing hardwood species native to much of the Eastern United States (Martin and Harrell 1957). It is the most populous hardwood species growing on pine (*Pinus* spp.) sites in the South, but it grows fastest on bottomland sites (Koch 1985). Sweetgum quickly colonizes a site following disturbance, both naturally and by artificial regeneration.

Maintaining lumber quality through the drying process precludes sweetgum possessing any significant share of the appearance-grade hardwood marketplace, relegating it more commonly to lower-valued industrial products. Smaller, pulpwood-sized stems have long been a resource suited to pulping, with more limited use for oriented strand board production.

A relatively new practice becoming more commonplace is short rotation woody crop (SRWC) forestry, where the goal is to cultivate a crop of trees as rapidly as possible using techniques needed to improve growth rates (Kaczmarek and others 2012). Sweetgum is being investigated as a SRWC resource, but many questions related to SRWC need answering. Some, such as tolerance to cold and drought, resistance to disease, and fertilization requirements, must be considered prior to establishing a SRWC plantation (Kline and Coleman 2010); estimations of volume are also needed to predict yields in these stands.

The objective of this work was to develop stem volume equations using independent variables measured on an afforested field in north Louisiana. Tree measurements were conducted in a study examining the interactive effects of herbaceous competition control (two treatments) and hybrid sweetgum variety (five varieties) on yields using data from 2-year-old (1-0 seedling stock) hybrid sweetgum (*Liquidambar formosana* x *styraciflua*) trees.

METHODS

The study was located at Louisiana Tech University, South Campus (32° 30' 49.84" N. 92° 39' 11.59" W) in Ruston, LA. The study site was largely on an Angie fine sandy loam soil (Aquic paleudult), with a small portion on a Sacul very fine sandy loam (Aquic hapludult) (USDA NRCS 2019); no significant slope was present. The site had been used for grazing and hay production since 1990. During this time, horse manure was spread over the field occasionally as fertilizer. Prior to 1990, the

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site was the interior of a racetrack dating back to the late 1970s, during which time Christmas trees were periodically grown on the site.

No fertilizer treatment was applied prior to planting because of the site's history of manure fertilization (Scott and others 2004). In preparation for planting, the site was subsoiled (ripped) to a 24-inch depth in late summer. One week before planting, 3 quarts per acre of glyphosate was applied (Accord XRTII® [Dow, Indianapolis, IN]) via backpack sprayer to remove any herbaceous vegetation present.

Prior to planting, containerized seedlings were left outside under a covered awning and watered daily to prevent soil from drying out. Seedlings were planted in late October 2015, by hand. Five hybrid sweetgum varieties were tested (AGHS1, AGHS2, AGHS3, AGHS4, AGHS8). The study was laid out in a split-plot design, with herbicide being the main plot and genotype as the sub-plot. Five replications were installed. Each row of the study was considered one plot, receiving a random herbicide treatment. The rows were divided into sub-plots of eight seedlings of each genotype. The internal six seedlings of each sub-plot were considered the test sub-plot, while the seedling at either end of the sub-plot was considered a border tree and removed from analysis. A total of 640 seedlings was planted. The seedlings were planted 5 feet apart along the row, and rows were 10 feet apart.

The herbicide tested was sulfometuron methyl (Oust XP®). Oust XP® was applied in a 36-inch-wide band using a boom sprayer attached to a tractor at 2 ounces per acre directly over the seedlings. The rate of 2 ounces per acre of Oust XP® was selected in accordance with recommendations for sweetgum based on prior studies (Kushla and Self 2013). In this study two treatments were studied, a no herbicide control and a single application of Oust XP® applied on February 17, 2016. This treatment was in accordance with the chemical company recommendations for Oust XP® to prevent seedling damage while still controlling competing vegetation into the growing season.

Measurements were conducted after two growing seasons in November 2017. To determine if herbicide application and/or variety caused a change in growth characteristics of seedlings after 2 years, seedlings from each block were randomly measured. Height was measured in 1-foot increments using a height pole from the ground level up to the highest living bud present on the seedling. Diameter was measured using calipers at each increment on both the lower and upper ends of the stem section beginning at the groundline. Groundline-diameter (D_G) was measured at ground level unless roots were exposed above the ground, where instead D_G was taken at the root collar. Eighty-eight trees were measured (table 1).

Equations were developed to estimate the amount of standing stem volume using 80 trees as a model development set. Independent variables investigated included D_G, tree height, and additional diameters along the stem (Schlaegel 1984) in various combinations of both linear and exponential form. All variables were natural logarithm (ln) transformed to account for non-constant variance. Prior to final model-fitting, dummy variables were used to see if separate volume equations were needed by herbicide, variety, or herbicide and variety interaction. The results showed that separate equations were not necessary. Thus, all data were pooled across treatments to produce a single model with no dummy variables present at $\alpha = 0.05$. The equations were then evaluated qualitatively to gauge both their statistical (regression F test and coefficient t tests) and practical significance (model R^2). Validation of the final equation used the remaining eight trees from the study.

RESULTS AND DISCUSSION

The relationship between D_G and volume was not altered by genotype or herbicide. This is worthy of tracking over time because resource consistency is desired among manufacturers for predicting yields and conversion efficiencies. The equation we felt most practically

Table 1—Summary statistics for 2-year-old sweetgum trees at an afforested site in north Louisiana

Statistic	Groundline diameter	Volume
	inches	*cubic feet*
Model development set (n = 80)		
Mean	1.35	0.025
Standard deviation	0.32	0.013
Maximum	2.17	0.075
Minimum	0.74	0.006
Median	1.32	0.022
Validation set (n = 8)		
Mean	1.14	0.018
Standard deviation	0.25	0.010
Maximum	1.51	0.031
Minimum	0.67	0.004
Median	1.19	0.018

captured the significant effects that tree size and form had on stem volume was Equation 1 in ln form (fig. 1), or its arithmetic equivalent, Equation 2:

$$\widehat{\ln Vol} = -4.41 + \left(1.06 * \ln D_G^2\right) \tag{1}$$

$$\widehat{Vol} = e^{-4.41+(1.06*\ln D_G^2)} \tag{2}$$

where

Vol is in cubic feet and D_G is in inches.

This single-measurement regression was significant (F = 841.79, $p < 0.01$), with $R^2 = 0.92$. The intercept b_0 (t = -166.43, $p < 0.01$) and slope b_1 (t = 29.01, $p < 0.01$) coefficients were likewise highly significant. This equation was concluded to be as good (but perhaps not better) a predictor of stem volume than linear forms of diameter at any height and total height. While the inclusion of other independent variables accounted for slightly more variance in stem volume than simply using D_G^2, (D_G^2H and $D_G^2D_3H$, where an additional diameter measurement was taken at height = 3 feet and H is total height, for example), these equations required multiple measurements.

Validation Analysis

Our model system on average under-predicted volume for the validation trees (figs. 2 and 3). Under-prediction appeared greater for larger D_G of the woody stem, but at smaller diameters volume was slightly over-predicted. Perhaps for particular D_G, biomass is more efficiently produced. Including height in the model may be more important in terms of practical significance for prediction of future observations rather than focusing strictly on statistical significance during model development.

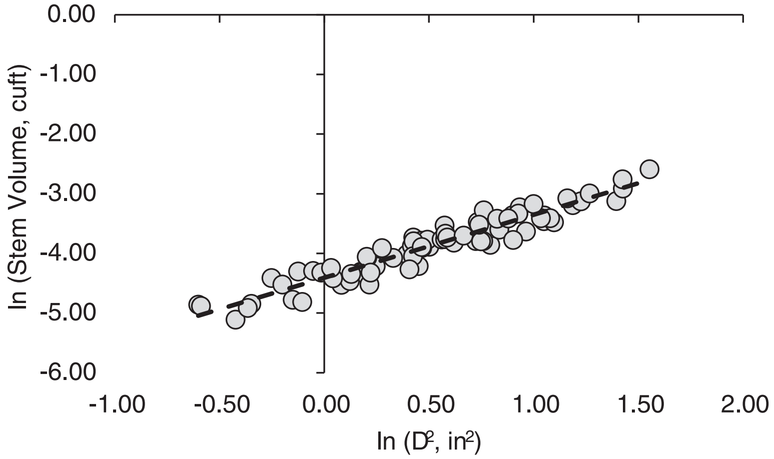

Figure 1—Plot of log-transformed stem volume versus the square of groundline diameter.

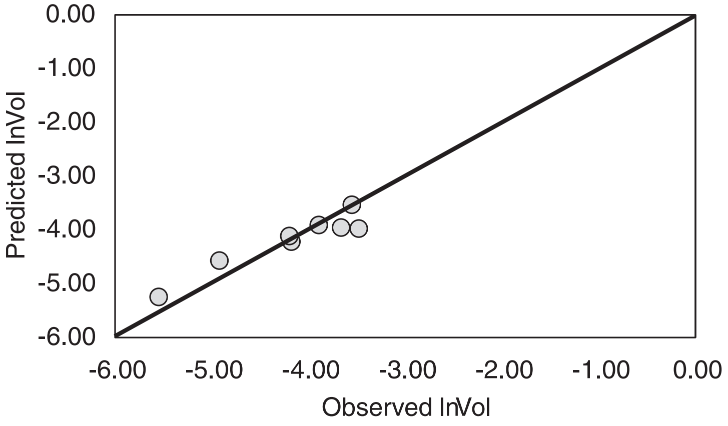

Figure 2—Comparison of predicted versus observed log-transformed stem volumes for the validation set.

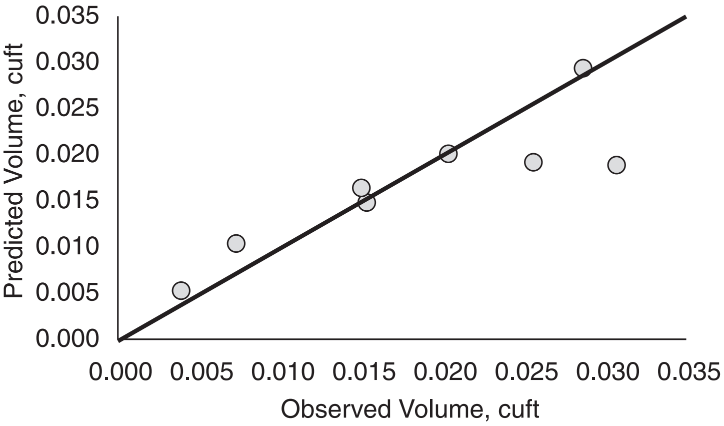

Figure 3—Comparison of predicted versus observed stem volumes for the validation set.

Using the Equation

The volume equation in arithmetic form represents the exponent to which the base is raised. This, however, returns a geometric mean rather than an arithmetic one. A correction factor, $\theta_2 = e^{s^2}/_2$ (Flewelling and Pienaar 1981), was applied to adjust for logarithmic transformation bias, where the regression variance, s^2, was equal to 0.0254. We calculated θ_2 as 1.0128.

Suppose one wants to predict the volume of a hybrid sweetgum tree with a D_G of 1.25 inches; the equation would be used as:

$$\widehat{Vol} = e^{-4.41+1.06*ln(1.25^2)} * 1.0128 = 0.0198\,ft^3$$

SUMMARY

Data from 2-year-old (1-0 seedling stock) hybrid sweetgum trees treated with herbicide were pooled across treatment effects to develop stem volume equations on an afforested site in north Louisiana. The efficiency provided by taking a single measurement of D_G to predict hybrid sweetgum stem volume could save managers time and effort, particularly if constrained by scarcity of resources at this stage of stand development. The practicality of a single diameter measurement, coupled with a basic knowledge of spreadsheet applications, can allow most parties interested in sweetgum SRWC—even nonindustrial private forest landowners—to conduct an individual-tree or stand-level assessment using this equation.

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TWENTY-FIVE-YEAR ANALYSIS ON THE EFFECTS OF ORGANIC MATTER REMOVAL AND SOIL COMPACTION ON A LONG-TERM SOIL PRODUCTIVITY STUDY SITE IN NORTH CAROLINA

Robert Eaton

Extended abstract—Forests are subject to large-scale disturbance by harvesting and site preparation. An important question is whether soils can sustain the long-term needs of forest stands under intensive site preparation, shortened rotations, and higher utilization standards (Powers and others 1990). The effects of harvest intensity and site preparation on soil properties and stand productivity are being analyzed as part of the U.S. Department of Agriculture (USDA), Forest Service, Long-Term Soil Productivity (LTSP) studies.

The site installation followed the clearcutting of a 60-year-old natural pine (*Pinus* spp.)-hardwood stand on the Lower Coastal Plain, near New Bern, NC, in 1991. Three blocks of nine treatment plots (0.4 ha each) were established and assigned a 3-m by 3-m factorial combination of organic matter removal [none/stem-only removal (OM0), moderate/whole-tree removal (OM1), and severe/whole-tree plus forest floor removal (OM2)] and compaction [none (C0), medium (C1), and severe (C2)] treatments. Treatment plots were split to include a total competition control (H+) and no competition control (H-) treatment. Thinning in March 2012 removed approximately one-half of the trees and understory, leaving the cut vegetation in place.

Height and diameter measurements of all trees in the measurement plots were recorded annually for the first 10 years of the study and at years 16, 18, 21, and 25. Analysis of variance was used to test for treatment impacts on tree height and diameter. An estimated site index curve was calculated based on information from the USDA Soil Conservation Service (Goodwin 1989).

There was a significant ($p < 0.05$) interaction between the competition control, organic matter removal, and compaction treatments for tree diameter. The trees in the OM0 and OM1 treatments were generally greater in diameter than in the OM2 treatments in the H+ plots for all years. Tree diameters in the H+ plots were always greater in the C2 plots and least in the C1 plots.

There was a significant ($p < 0.05$) interaction between organic matter removal, compaction, and competition control on height for most years. Further investigation indicated significant differences in tree height on the competition control plots was associated with organic matter removal. For example, the mean height in the H+ × OM removal plots was, until year 21, consistently greatest in the OM1 plots and lowest in the OM2 plots, while in H+ × compaction plots, C2 plots consistently had the greatest tree heights, until year 21, when they dropped to the least height. There was a large difference in the tree heights on the H+ plots when compared to the estimated tree heights generated by the site index curve, while all the organic matter removal treatments on the H- plots remained close to estimated heights (fig. 1). Using the H- treatment as an unmanaged treatment, comparison of tree heights by treatment against estimated tree heights (fig. 1) indicated that organic matter removal had no effect on tree height growth in this study up to year 21. From a year 25 perspective, the trend of increased height growth in year 20, compared to the site index curve, continued, and the OM0 and OM1 height responses mirrored the H+ plots in their separation from the OM2 plots.

The significant effect of organic matter on height and the consistently greater heights in the OM1 treatment may have been due to several factors. The OM0 treatment left the most biomass, but also allowed the highest amount of competition due to its low site disturbance. These treatments were generally cooler (Eaton 1996) in the summer months which some studies indicate can result in decreased growth (Heninger and White 1974). On the OM2 treatments, reduced nutrient levels may have initially reduced height growth. The consistently greater tree heights on the C2 treatment, in H- and H+ treatments, may have been due to a decrease in competitive vegetation in the plots. As discussed above, competing vegetation has a significant effect on height growth, and the C2 treatment reduced competition, especially when due to stump sprouting.

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When competition control was applied, tree growth increased above the site index estimation from approximately year 5, even in the OM2 plots. The effect of the competition control treatment was minimized when the thinning removed the competing trees and much of the understory. This trend continued through year 25. Further analyses indicated the impact of the main treatment effects was minimal in the presence of competition and significant once competition was removed. Based on site index comparisons, treatments did not reduce productivity as measured by tree growth, even in the most severe treatments. Thinning resulted in increased growth rate in all treatments, but continued assessment is needed to determine if this trend persists.

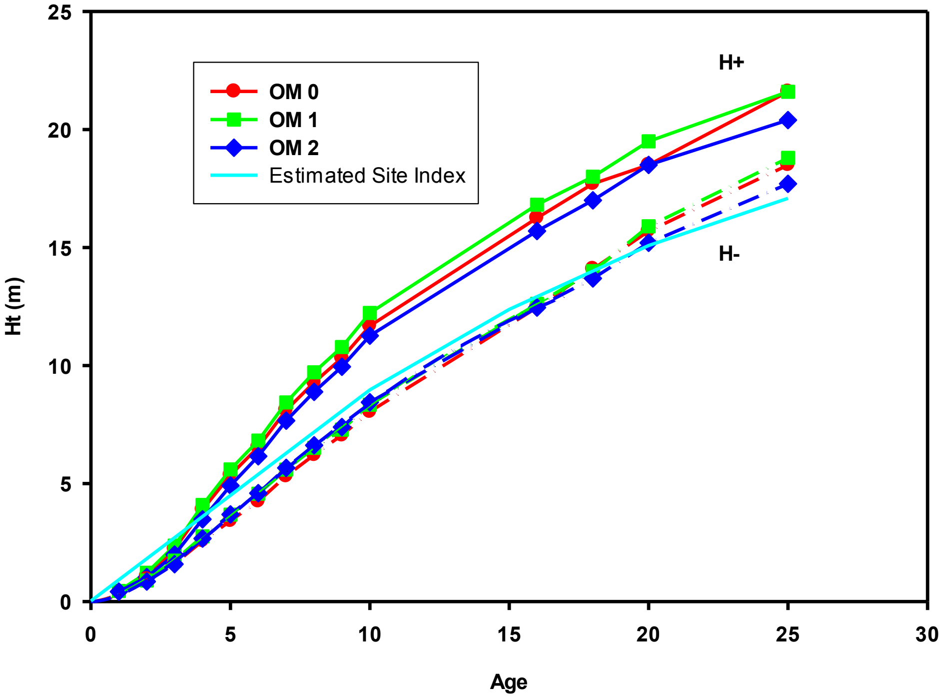

Figure 1—Height curves of organic matter removal treatments [none/stem-only removal (OM0); moderate/whole-tree removal (OM1); severe/whole-tree plus forest floor removal (OM2)] by competition control treatments [none (H-, dashed); total (H+, solid)] with estimated site index.

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EFFECTS OF FERTILIZATION AND IRRIGATION ON COMPONENTS OF SOIL CARBON EFFLUX AND SOIL RESPIRATION IN LOBLOLLY PINE PLANTATIONS

Peter H. Anderson and Christopher A. Maier

Extended abstract—Soil carbon dioxide (CO_2) evolution is a combined product of the metabolic activity of plant roots and both free-living and symbiotic heterotrophs. Soil CO_2 efflux (S_f) rates are the second largest carbon flux in the global carbon cycle and the largest terrestrial contributor of CO_2 (Raich and Schlesinger 1992). The components of S_f can be broken down into heterotrophic respiration (R_H) and autotropic root respiration (R_R). Quantifying S_f and understanding the contribution of R_H and R_R on intensively managed sites is fundamental to understanding the carbon cycle and implications for carbon sequestration (McElligott and others 2016).

Loblolly pine (*Pinus taeda*) is used extensively for commercial timber and fiber production in the Southern United States. Fertilization and, to a lesser degree, irrigation, are increasingly being used to raise productivity in managed pine stands. For example, 238,000 ha of southeastern pine forests were fertilized in 2016 (Albaugh and others 2018). While fertilization can dramatically increase stand productivity and leaf area (Albaugh and others 2004, Samuelson and others 2004a), the effects on belowground carbon allocation and S_f are equivocal. Changes in nutrient availability can have a differential effect on fine root production and microbial respiration, altering the relative contributions of R_R and R_H to S_f (Butnor and others 2003, Maier and Kress 2000, Samuelson and others 2004b).

We examined the effects of fertilization and irrigation on S_f in a 16-year-old loblolly pine plantation and quantified how root biomass, forest floor litter, and soil coarse organic fragments influenced S_f. The objectives of the study were to (1) examine the effect of fertilization and irrigation on S_f and (2) quantify component contributions of R_H and autotrophic root respiration R_R.

The main study had a randomized complete block design with a 2 × 2 factorial combination of nutrition (no addition, -F, and complete nutrition, +F) and irrigation (no addition, -I, and well watered, +I) replicated four times (Albaugh and others 1998). After 10 years of treatment, five 1-m^2 by 50-cm-deep organic matter treatment pits (O, subplots) were randomly installed in each treatment plot: control (C, no treatment); litter removed (L); roots removed (R); roots and mineral soil coarse organic fragments (>2 mm) removed (RX); and roots, coarse organic fragments, and litter removed (RXL). On 13 days between July 2001 and December 2002, measurements of S_f were taken using a LI-6400 (LI-COR, Lincoln, NE) portable photosynthesis system at two points per subplot. Soil CO_2 efflux was modeled as a function of

$$S_f = S_{f,20} {}^* e^{(q^*(T\text{-}20))} \qquad (1)$$

where

$S_{f,20} = S_f$ at 20 °C, q = temperature coefficient, and T = soil temperature at 10 cm.

The whole-plot (F and I), subplot (pits) and interactive effects of treatment and day of measurement on S_f were tested using repeated measures analysis of variance (Proc Mixed, SAS Institute Inc., Cary, NC, USA) with block as a random factor and treatments as fixed factors. A first-order autoregressive covariance structure (AR(1)) was selected based on AIC fit statistics. Treatments differences in LSMEANs were evaluated with Tukey's test.

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Fertilization and irrigation treatment increased S_f by 25 percent (p = 0.005) and 17 percent (p = 0.046), respectively, and there was no significant F x I interaction (p = 0.46). Irrigation increased S_f mainly during the growing season (I x Day p = 0.001). Average S_f was 2.14, 2.46, 2.74, and 3.40 μmol m^{-2} s^{-1} (SE = 0.23) in the -F-I, -F+I, +F-I, and +F+I treatments, respectively. Fertilization increased S_f, likely due to increased R_R from a nearly doubling of root biomass. In 2002, the fertilization treatments had an almost 2.4-fold greater coarse root biomass than non-fertilized treatments (Albaugh and others 2004), resulting in higher R_R.

Soil temperature explained 60 to 80 percent of the variation in S_f. $S_{f,20}$ increased with fertilization and irrigation, while q was increased by irrigation, but decreased with fertilization. There was no significant F x I on either parameter. There were significant whole-plot x pit interactions ($p < 0.05$) on $S_{f,20}$ (table 1). The responses of $S_{f,20}$ and q to the removal of organic matter varied with treatment.

The temperature sensitivity was similar among C, L, RX, and RXL pits, but were significantly higher in the R pits (fig. 1). On the other hand, $S_{f,20}$ was significantly greater in the C (no organic matter removal) pits than in pits where litter (L), roots (R), or coarse organic fragments (RX, RXL) were removed. $S_{f,20}$ in the L, R, and RX pits was 18, 23, and 24 percent lower, respectively, than in the C pits. This reduction in S_f due to R_R was similar to other studies in managed loblolly pine plantations (McElligott and others 2016). There was no significant difference in $S_{f,20}$ between R and RX treatments (p = 0.798), which suggest that the decomposition of coarse organic fragments contributed only a small amount of CO_2 to S_f.

There was a significant fertilization and irrigation interaction with organic matter treatment (F x O and I x O), likely caused by a larger +F and +I effect on S_f in the C and L pits that contained roots. This was likely due to increased R_R rather than R_H. Surprisingly, removal of roots, coarse organic matter, and litter (RXL) reduced $S_{f,20}$ by only 50 percent. This indicates that a considerable amount of S_f came from R_R and R_H from outside of the pit. Because of this, the root/coarse organic matter exclusion pit approach used here, by itself, is unlikely to produce robust estimates of the ratio R_R/S_f or R_H/S_f.

Table 1—ANOVA for treatment effects on parameters in equation 1

Treatment effect	$S_{f,20}$	q
	p-values	
Fertilization (F)	<0.001	0.023
Irrigation (I)	0.025	0.001
F x I	0.775	0.255
Organic matter (O)	<0.001	<0.001
F x O	0.002	0.915
I x O	0.007	0.243
F x I x O	0.124	0.562

$S_{f,20}$ is soil CO_2 efflux at 20 °C and q is the temperature sensitivity.

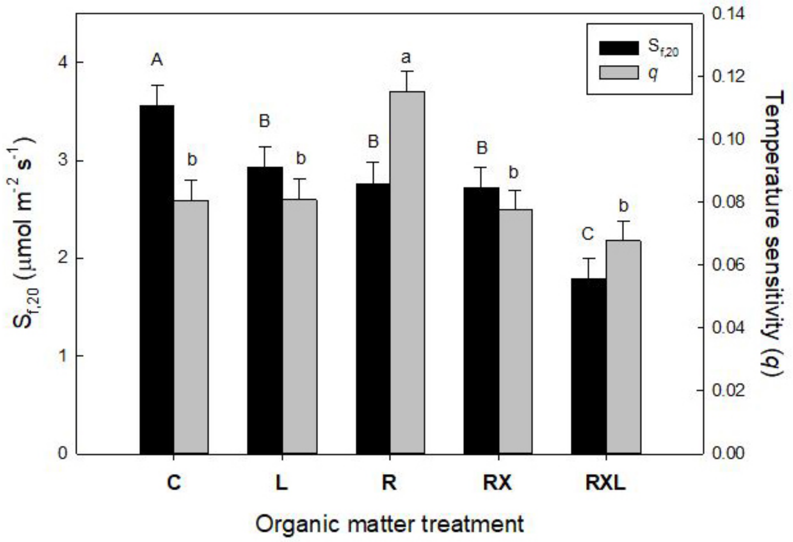

Figure 1—LSMEANs for soil CO_2 efflux at 20 °C ($S_{f,20}$) and temperature sensitivity (q) (equation 1). Organic matter treatments were C - no treatment; L - litter removed; R - roots removed; RX - roots and coarse organic fragments (>2 mm) removed; RXL - roots, coarse organic fragments, and litter removed. Means with the same letter (upper case for $S_{f,20}$, lower case for q) are not significantly different at α= 0.05.

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WINDS OF CHANGE: TORNADO AND HURRICANE IMPACTS ON LOUISIANA FORESTS

Michael K. Crosby

Abstract—Severe wind events have devastating impacts on forests throughout the United States. Events such as tornadoes and hurricanes can destroy standing timber, produce stresses that impact wood quality, and leave debris that leads to susceptibility to additional impacts. Data for tornado and hurricane occurrences was obtained and the width of these storms calculated using Geographic Information Systems software. The storm tracks were then used to extract impacted forested pixels in Louisiana to determine the acreage impacted, by forest type, within the State. Approximately 238,000 forested acres have been impacted by tornadoes (~3,000 acres per storm), with EF-2 tornadoes impacting the greatest acreage; hurricanes have impacted the State's forests multiple times, with tropical storm force winds impacting the greatest acreage. These preliminary results will be incorporated with inventory data and damage reports to develop a risk index to forests in Louisiana.

INTRODUCTION

Forests are vitally important to Louisiana's economy, comprising approximately 15 million acres and making a $13 billion impact on the State's economy (Tanger 2018). Extreme wind events, for example, tornadoes and hurricanes, have devastating impacts on forests. These events damage and destroy standing timber, produce stresses that impact wood quality, and leave debris that leads to a greater susceptibility to additional impacts, such as wildfire (Cooke and others 2007). Damage can be influenced by terrain (Cannon and others 2016) and forest type and density relative to wind speeds (Zeng and others 2009, 2010). Damaged and destroyed timber can become a carbon source and affect forest productivity for years (Zeng and others 2009) by reducing timber availability for mills within impacted areas (McConnell and Shmulsky 2009). This loss, in turn, may influence the type of product those mills produce in future if they remain active.

Given the importance of forestry to Louisiana's economy and the varying scale of impacts caused by extreme wind events, an accurate approximation of areal impacts from these storms can be incorporated with damage assessments and volume estimates leading to a relative risk index for various forest types and isolated by area within a State or region. The objectives of this study are to 1) determine the number of tornadoes and hurricanes that have affected Louisiana and 2) quantify the acreage affected by these storms.

MATERIALS AND METHODS

Data were obtained from the National Oceanic and Atmospheric Administration's National Weather Service (https://www.spc.noaa.gov/gis/svrgis/) for all tornadoes occurring between 1950 and 2016. Data for hurricane tracks was obtained from the National Climate Data Center (https://www.ncdc.noaa.gov/ibtracs/index.php?name=ibtracs-data) for all hurricanes in the North Atlantic Basin. Forest cover types were obtained from the Forest Service, U.S. Department of Agriculture (Ruefenacht and others 2008).

Using GIS software, all datasets were extracted using the boundary for the State of Louisiana. To determine the impact of tornadoes and hurricanes on forests in Louisiana, buffers were generated using tornado widths and radii of maximum winds for hurricanes. The tornado and hurricane buffers were used as a mask to extract forested pixels that intersected them. The impacted pixels were then summed by forest type for each wind-speed classification for tornadoes (using the Enhanced Fujita scale) and hurricanes (using the Saffir-Simpson hurricane wind scale).

RESULTS AND DISCUSSION

Forested Area Impacted by Tornadoes

There were 1,900 tornadoes that impacted Louisiana between 1950 and 2016 and affected 238,209 total acres (table 1). Of these tornadoes, approximately 95 percent were EF-0 to EF-2, accounting for 64 percent of the impacted acreage. This was not entirely surprising

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Table 1—Acreage impacted by forest type by EF (Enhanced Fujita scale) classification for each tornado in Louisiana between 1950 and 2016

Forest type*	EF-0 (618)	EF-1 (870)	EF-2 (308)	EF-3 (94)	EF-4 (9)	EF-5 (1)	Total
Longleaf pine	0	31	93	0	46	0	170
Slash pine	432	2,564	3,707	649	216	0	7,568
Loblolly pine	4,834	42,641	57,143	50,101	11,506	0	166,224
Shortleaf pine	0	0	46	124	0	0	170
Shortleaf pine/oak	0	31	15	0	0	0	46
Loblolly pine/hardwood	587	3,181	4,386	4,309	680	0	13,143
Slash pine/hardwood	0	15	0	0	0	0	15
Other pine/hardwood	0	0	0	15	0	0	15
Post oak/blackjack oak	0	108	46	62	0	0	216
White oak/red oak/hickory	263	2,471	2,085	1,761	417	0	6,996
Yellow-poplar/white oak	15	0	77	0	0	0	93
Sweetgum/yellow-poplar	15	139	108	741	0	0	1,004
Red maple/oak	0	108	15	0	0	0	124
Mixed upland hardwoods	0	154	62	587	31	0	834
Swamp chestnut oak/cherrybark oak	15	263	124	46	0	0	448
Sweetgum/Nuttall oak/willow oak	417	3,938	7,892	6,564	541	170	19,521
Overcup oak/water hickory	154	1,189	2,255	1,622	185	0	5,405
Baldcypress/water tupelo	77	1,081	2,641	1,390	402	0	5,591
Sweetbay/swamp tupelo/red maple	15	124	124	0	0	0	263
Cottonwood	0	62	62	46	0	0	170
Willow	0	62	31	77	15	0	185
Sycamore/pecan/American elm	0	15	154	108	62	0	340
Sugarberry/hackberry/elm/green ash	510	2,363	4,510	1,637	355	139	9,514
Cherry/ash/yellow-poplar	0	0	93	0	0	0	93
Other exotic hardwoods	0	15	46	0	0	0	62
Total	7,336	60,556	85,715	69,838	14,456	309	238,209

The number of tornadoes in each category are in parentheses.

*Longleaf pine = *Pinus palustris*, slash pine = *P. elliottii*, oak = *Quercus* spp., post oak = *Q. stellata*, blackjack oak = *Q. marilandica*, white oak = *Q. alba*, red oak = *Q. rubra*, hickory = *Carya* spp., yellow-poplar = *Liriodendron tulipifera*, red maple = *Acer rubrum*, swamp chestnut oak = *Q. michauxii*, cherrybark oak = *Q. pagoda*, Nuttall oak = *Q. texana*, willow oak = *Q. phellos*, overcup oak = *Q. lyrata*, water hickory = *Carya aquatica*, sweetbay = *Magnolia virginiana*, swamp tupelo = *Nyssa biflora*, cottonwood = *Populus* spp., willow = *Salix* spp., sycamore = *Platanus* spp., pecan =*Carya illinoinensis*, American elm = *Ulmus americana*, sugarberry = *Celtis laevigata*, hackberry = *Celtis occidentalis*, elm = *Ulmus* spp., green ash = *Fraxinus pennsylvanica*, cherry = *Prunus* spp., ash = *Fraxinus* spp.

as the higher category tornadoes (EF-3 and greater) are typically larger in width and on the ground for greater periods of time. The most acreage impacted by forest type, based on 2008 forest type data, was loblolly pine (*Pinus taeda*), accounting for 70 percent of the affected acreage; loblolly pine accounts for nearly 56 percent of forested acres in Louisiana. However, as a percentage of forest type cover, baldcypress (*Taxodium distichum*)/ water tupelo (*Nyssa aquatica*) forest type had 9 percent of its area impacted and shortleaf pine (*Pinus echinata*) saw approximately 6 percent of its area touched by a tornado during the time period covered by the data. The greatest acreage of loblolly pine forest type impacted was impacted by EF-2 and EF-3 tornadoes, likely because these tornadoes were distributed throughout the central to north-central portions of Louisiana (fig. 1).

The tornado dataset dates from 1950. During this time, and through the 1970s, the forest composition in Louisiana looked different that it does presently (Delcourt and others 1981, Murphy 1975). While fewer than half of the tornadoes considered occurred between 1950 and 1980, the bias in reporting and potential errors in estimation of track widths could (and likely does) lead to an underrepresentation of impacts to historical forest cover in the State. For example, 273 tornadoes have impacted the Florida parishes in eastern Louisiana since 1950. There were 101 tornadoes in these parishes between 1950 and 1980, when much of this area was longleaf pine (*Pinus palustris*) (but has since been converted to loblolly pine plantations).

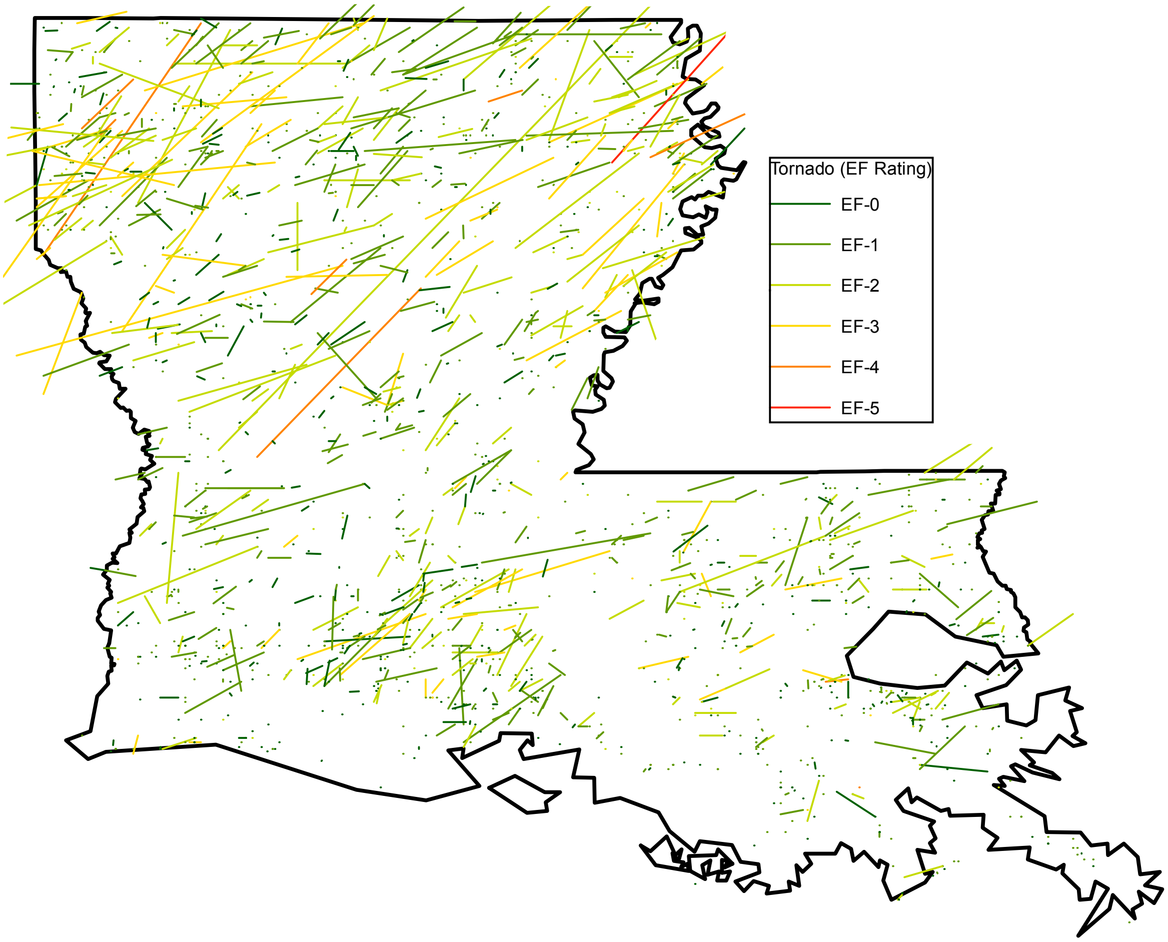

Figure 1—Tornadoes impacting Louisiana, 1950-2016.

Forested Area Impacted by Hurricanes

Analysis of the impacts of hurricanes on forests was limited by data availability. Of the 147 hurricanes impacting the State between 1854 and 2012 (fig. 2), only 13 storms (all making landfall between 2002 and 2012) had reliable data for radius of maximum winds with which buffers could be created. Of the storms used in assessing impacted acreage, it was determined that (in terms of total acreage impacted), loblolly pine was the most affected forest type with approximately 2.9 million acres affected (table 2). It is important to note that, as a percentage of forest impacted, some forest types were repeatedly impacted—most notably baldcypress/water tupelo, commonly found in coastal/wetland areas. Sweetgum (*Liquidambar styraciflua*) forests were also impacted (greater than 750,000 acres total), likely because of where they are located in the southern part of the State.

Most areas/forest types were impacted more than once in the analysis but they were still counted cumulatively to indicate how often the forest areas are impacted. As a total, roughly one-half of Louisiana forests were affected by the 13 storms that had wind radii reported in the data set. It is important to distinguish between impact and damage as this study only quantifies acreage impacted and is not an indication of damage. Coastal forests in Louisiana are dominated by wetland species, with baldcypress and water tupelo dominant and among the 10 most common species in the State (Oswalt 2016). However, baldcypress and water tupelo saw little damage from Hurricane Katrina (Middleton 2009) while pine and sweetgum were damaged (Oswalt and others 2008). It will be useful in subsequent research to determine areas that have been repeatedly impacted by this type of system. Determination of probabilistic damage of species classes within forest types will drive future research efforts to build a stand-level damage model for forests throughout the region.

It bears repeating that, particularly for the estimated areas impacted by tornadoes, the data used is for current forest cover types (Ruefenacht and others 2008). While this will lead to an underestimation of impact on historic forest types by tornadoes, it does provide a preliminary estimate of area impacted by tornado magnitude. The hurricane impacts are closer to true estimate of cover type during the time of impact of

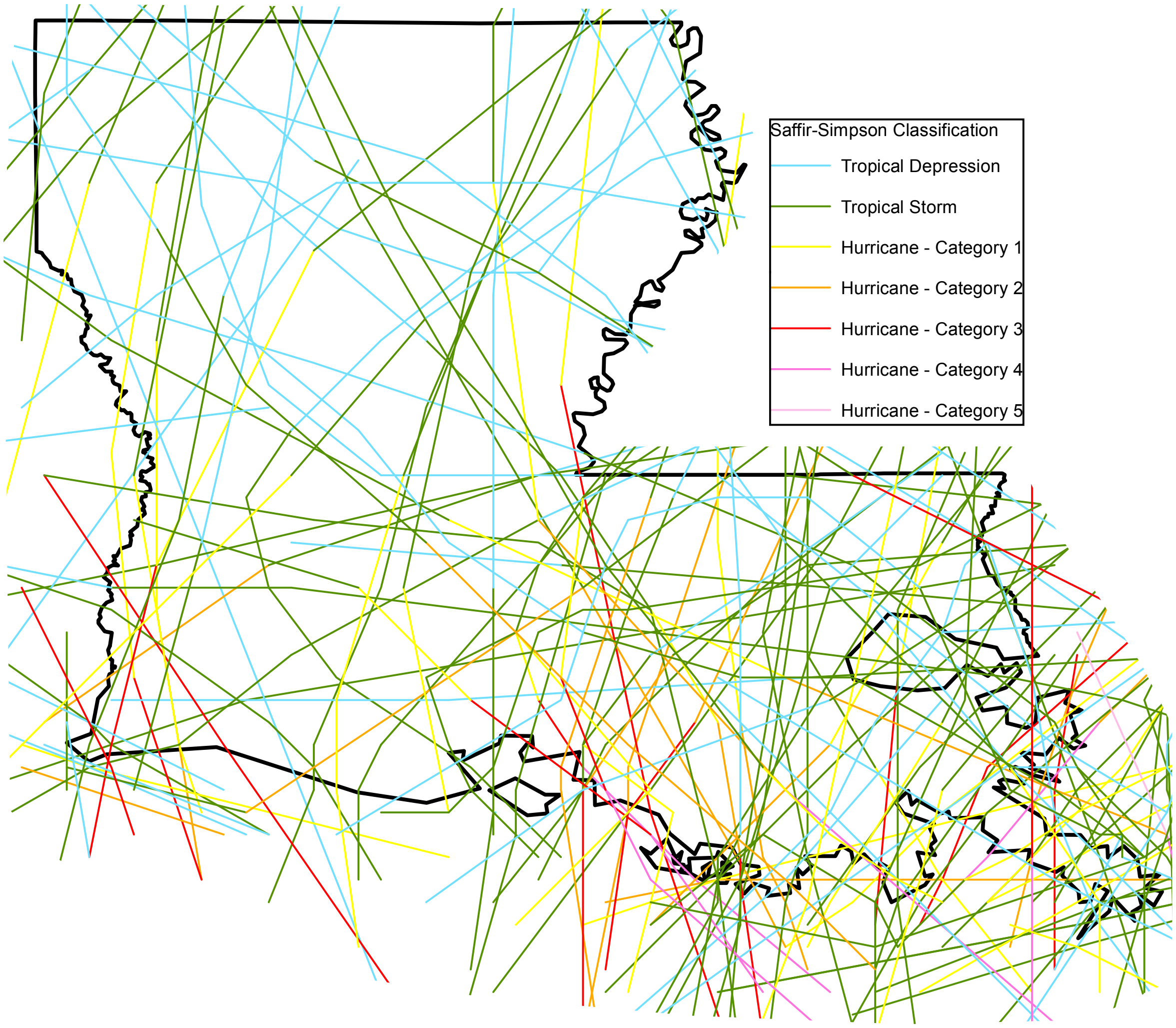

Figure 2—Land-falling tropical hurricanes impacting Louisiana, 1854-2012; this study only considered storms from 2002-2012 with complete track length and width attributes.

each storm, but there were only 13 storms for which consistent track data was available. Future work could build on such estimates, elucidate historic impacts of types, combine with inventory data, and attempt to estimate potential biomass losses of historic storms.

CONCLUSIONS

This initial assessment provides information that will be used in subsequent analyses. If reliable damage assessment data can be found it could be leveraged with remotely sensed data to develop a risk-rating of probabilistic damage by forest type. This methodology could then be applied to a broader area—regionally or nationally—and utilized to assess annual damage risk from tornadoes and land-falling tropical systems.

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Table 2—Acreage impacted by forest type by Saffir-Simpson hurricane wind scale for 13 hurricanes in Louisiana between 2002 and 2012

Forest type	Tropical depression	Tropical storm	Category 1	Category 2	Category 3	Category 4	Total
Longleaf pine	2,286	9,759	672	185	463	0	13,365
Slash pine	43,246	269,958	69,406	54,981	22,571	0	460,163
Loblolly pine	394,735	2,312,758	63,799	124,495	20,178	0	2,915,964
Shortleaf pine	49	537	3	0	0	0	589
Sand pine	12	16	0	0	0	0	28
Eastern redcedar	3	6	0	0	0	0	9
Longleaf pine/oak	83	95	0	0	0	0	179
Shortleaf pine/oak	6	222	0	0	0	0	228
Loblolly pine/hardwood	62,308	290,048	22,031	52,626	1,274	0	428,286
Slash pine/hardwood	442	458	10	0	77	0	987
Other pine/hardwood	723	1,209	0	0	15	0	1,948
Post oak/blackjack oak	6	547	0	0	0	0	553
White oak/red oak/hickory	44,680	117,840	867	3,660	100	0	167,148
Yellow-poplar/white oak	49	1,650	566	154	39	0	2,459
Sweetgum/yellow-poplar	9,195	17,708	39	981	0	0	27,923
Chestnut oak/black oak/scarlet oak	0	39	0	0	0	0	39
Red maple/oak	544	1,498	368	178	46	0	2,634
Mixed upland hardwoods	34,354	51,191	407	2,394	15	0	88,361
Swamp chestnut oak/cherrybark oak	10,508	19,182	528	1,290	2,440	0	33,947
Sweetgum/Nuttall oak/willow oak	222,873	430,704	10,777	99,244	14,000	232	777,830
Overcup oak/water hickory	37,532	135,608	1,109	28,873	239	0	203,362
Baldcypress/water tupelo	477,293	578,057	128,502	329,267	14,355	541	1,528,016
Sweetbay/swamp tupelo/red maple	23,997	29,508	927	749	12,988	15	68,184
River birch/sycamore	99	223	15	0	0	0	337
Cottonwood	1,319	5,286	0	1,699	8	0	8,312
Willow	23,855	27,725	2,528	22,131	162	31	76,432
Sycamore/pecan/American elm	32,192	38,548	69	37,313	0	0	108,122
Sugarberry/hackberry/elm/green ash	163,228	279,195	7,578	98,726	1,900	77	550,704
Red maple/lowland	65	110	51	0	0	0	227
Cottonwood/willow	3,351	3,833	28	4,270	0	0	11,483
Cherry/ash/yellow-poplar	1,313	1,909	0	0	0	0	3,222
Other exotic hardwoods	1,375	1,729	36	263	8	0	3,409
Total	1,591,721	4,627,158	310,318	863,478	90,881	896	7,484,450

Slash pine = *P. elliottii*, loblolly pine = *P. taeda*, shortleaf pine = *P. echinata*, sand pine = *P. clausa*, eastern redcedar = *Juniperus virginiana*, post oak = *Quercus stellata*, blackjack oak = *Q. marilandica*, white oak = *Q. alba*, red oak = *Q. rubra*, hickory = *Carya* spp., yellow-poplar = *Liriodendron tulipifera*, sweetgum = *Liquidambar styraciflua*, chestnut oak = *Q. montana*, black oak = *Q. velutina*, scarlet oak = *Q. coccinea*, red maple = *Acer rubrum*, swamp chestnut oak = *Q. michauxii*, cherrybark oak = *Q. pagoda*, Nuttall oak = *Q. texana*, willow oak = *Q. phellos*, overcup oak = *Q. lyrata*, water hickory = *Carya aquatica*, baldcypress = *Taxodium distichum*, water tupelo = *Nyssa aquatica*, sweetbay = *Magnolia virginiana*, swamp tupelo = *Nyssa biflora*, river birch = *Betula nigra*, sycamore = *Platanus* spp., cottonwood = *Populus* spp., willow = *Salix* spp., pecan = *Carya illinoinensis*, American elm = *Ulmus americana*, sugarberry = *Celtis laevigata*, hackberry = *Celtis occidentalis*, elm = *Ulmus* spp., green ash = *Fraxinus pennsylvanica*, cherry = *Prunus* spp., ash = *Fraxinus* spp.

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GENETIC MARKERS FOR IDENTIFICATION OF SOUTHERN PINE SPECIES

Rabiu Olatinwo, D. Paul Jackson, Shi-Jean S. Sung, Alex Mangini, Brian Strom, and James P. Barnett

Abstract—The chloroplast DNA (cpDNA) is paternally inherited in pine species (*Pinus* spp.), hence potentially useful in developing genetic markers for four common southern pine species [longleaf pine (*P. palustris* Mill.), loblolly pine (*P. taeda* L.), shortleaf pine (*P. echinata* Mill.), and slash pine (*P. elliottii* Engelm.)]. In this study, we (a) developed a simple DNA tool to accurately distinguish pure longleaf pine seeds or seedlings from other pine species, a critically important aspect of any longleaf pine restoration effort, and (b) validated the accuracy of identified genetic marker/specific primer combinations that uniquely identify the four pine species. Four genetic markers identified in this study correctly distinguished the four southern pine species based on the evaluation of over 200 tissue samples from multiple sources in Arkansas, Louisiana, and Mississippi that were tested. This DNA-based tool will enable routine and timely detection of natural hybridization when screening for seeds or seedlings intended for the restoration of pine ecosystems in southern region of the United States.

INTRODUCTION

The longleaf pine (*Pinus palustris* Mill.) restoration efforts (Guldin and others 2016) in the Southern Region have led to an increased demand for longleaf seeds from different sources, including seed orchards in Louisiana and Mississippi. Although most longleaf pine seeds collected from established orchards are pure longleaf, a small percentage are hybrids. Generally, a level of less than 3 percent of hybrids in any longleaf pine seedlot or seedling crop is considered acceptable. However, in recent years, there are indications that longleaf pine seedling lots have demonstrated less desirable traits (Barnett and others 2020), and have been presumed to be a naturally occurring hybrid between longleaf pine and loblolly pine (*Pinus taeda* L.) known as Sonderegger pine (*Pinus x sondereggeri* H.H.Chapm.) (Chapman 1922). For decades, such hybrids have been considered much less desirable than either of the parent species (longleaf or loblolly) because of their susceptibility to pests and extra-large branches (Barnett and others 2002, Wakeley 1954), thereby creating a need for an accurate detection of and timely determination between longleaf and Sonderegger pines. The issue of natural hybridization is a problem not restricted to longleaf, but found in other southern pine species, including shortleaf pine (*Pinus echinata* Mill.) hybridizing with loblolly pine (Stewart and others 2012).

How can managers accurately distinguish a pure longleaf from a Sonderegger hybrid or any of the other southern pine species? Although morphological determination may be possible between parent pine species and hybrids, it may be subjective and inconsistent (fig. 1). Can the true identity of southern pine seeds/seedlings/saplings/trees be determined using DNA techniques? The objective of the study was to develop a DNA-based tool to accurately distinguish "pure" longleaf pines (seeds or seedling/sapling/tree) from other southern pine species by using the chloroplast DNA (cpDNA), which is paternally inherited in pine species via pollen (Chen and others 2002, Neale and Sederoff 1989). Our objectives were to (a) identify genetic markers and develop a simple DNA tool to accurately distinguish a pure longleaf pine seed or seedling/sapling/tree from other southern pine species, and (b) validate the accuracy of selected sets of genetic marker/specific primer combinations that uniquely identify each of the four southern pine species. By achieving these objectives, markers identified in this study could serve as a critically important tool in detecting any natural hybridization within seed sources and accurately identifying pine species intended for restoration efforts.

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a. Loblolly b. Sonderegger c. Longleaf

d. Loblolly buds e. Sonderegger buds f. Longleaf buds

Figure 1—Stem elongation and bud morphology have been traditionally used to distinguish loblolly, longleaf, and their hybrid (Sonderegger) pine trees in the nursery (a-c) and field (d-f).

MATERIALS AND METHODS

Pine Tissue Samples

In this study, a total of 231 pine tissue samples obtained from multiple sources in Arkansas, Louisiana, and Mississippi were evaluated. A total of 64 needle samples were collected from 29 pine seedlings grown from stored longleaf pine seeds from the LA 2014 seedlot (U.S. Department of Agriculture, Forest Service, Stuart Seed Orchard, Bentley, LA), 17 seedlings from the MFC 2014 seedlot (Mississippi Forestry Commission Seed Orchard), and 18 seedlings from the MFC 2013 seedlot. Fifty needle samples were obtained from 25 mature loblolly and 25 longleaf pine trees at the Stuart Seed Orchard, while a similar set of 50 needle samples were obtained from trees on the Mississippi Forestry Commission Seed Orchard. Eighteen stem cambial tissue samples from different pine species located at the Crossett Experimental Forest in Crossett, AR, were included in the evaluation. Twenty-two needle samples from seedlings grown from a mixed slash pine (*P. elliottii* Engelm.) seed sources from Louisiana were included in the genetic marker evaluations. Additional needle samples were obtained from a Sonderegger hybrid study plot (18 suspected hybrids and 3 longleaf saplings) established in 2010 and six saplings from another study established in 2010 on the Palustris Experimental Forest within the Kisatchie National Forest in Rapides Parish, LA. Measurements of total height (cm), ground-line diameter (mm), and diameter at breast height (mm) were made between 2011 and 2015 at the Sonderegger hybrid site. Data analysis was conducted in SAS-JMP v. 13.0 statistical software based on determination of the pine species or hybrid according to the chloroplast DNA markers.

Genetic Markers Identification

Variation in the complete chloroplast DNA sequences, specifically the single nucleotide polymorphism (SNP), was explored and used for developing unique DNA markers for each of four southern pine species: longleaf pine, loblolly pine, shortleaf pine, and slash pine. The complete chloroplast genome sequences of pine species including the four southern pine species were obtained from the National Center for Biotechnology Information (NCBI) GenBank database (http://blast.ncbi.nlm.nih.gov/Blast.cgi). Multiple aligned sequences were analyzed to obtain suitable fingerprints (DNA markers) for each of four southern pines (table 1). The GenBank accession for reference sequences for #1, #2, #3, and #4 markers were, respectively, JN854176 (longleaf pine), KC427273 (loblolly pine), JN854202 (slash pine), and JN854204 (shortleaf pine) (table 1). Forward and reverse polymerase chain reaction (PCR) primers were designed for each of the four markers to produce either a positive band or a null amplification (negative) on gel electrophoresis (table 2).

DNA Extraction

DNA was extracted from all pine tissue samples obtained for this study using the Qiagen DNeasy® Plant Mini Kit (Qiagen Inc., Valencia, CA) according to the manufacturer's protocol. The DNA from previously verified and known longleaf, loblolly, shortleaf, and slash pine tissue samples were included in the PCR amplifications as positive checks for the corresponding set of specific markers identified and evaluated in this study.

PCR Amplification

The PCR amplification of the DNA template was performed in a 10 µl PCR reaction in an Eppendorf Mastercycler® Pro PCR machine (Eppendorf AG Hamburg, Germany). The PCR was performed using the following conditions: 94 °C for 2 minutes → 94 °C

Table 1—Chloroplast DNA (cpDNA) markers identified for the detection of four southern pine species: longleaf pine, loblolly pine, shortleaf pine, and slash pine

cpDNA marker	Southern pine species	Reference seq. accession number	Single nucleotide polymorphism site	Start position
#1	Longleaf	JN854176	$(TTCCGA)^2$	119023
#2	Loblolly	KC427273	ATATATC*	96129
#3	Slash	JN854202	TACC	68085
#4	Shortleaf	JN854204	$(CCATT)^2$	42451

*Absent/missing in loblolly but present in the other southern pine species.

Table 2—Information on sets of specific PCR primers used for the detection of four southern pine species: longleaf pine, loblolly pine, shortleaf pine, and slash pine

Chloroplast DNA marker	Southern pine species	PCR sequence, 5' - 3'	Single nucleotide polymorphism target
#1	Longleaf	Forward: CTCATCATTTTCCGA**TTCCG** Reverse: GGAAATGAAACACCGGAAGA	$(TTCCGA)^2$
#2	Loblolly	Forward: GTTCGAAAGAACAACAAGTAATATAG Reverse: CATAGCCAGGTTTTCCCAAA	**ATATATC***
#3	Slash	Forward: GTCAACTAAAAAGAAGTAAAAA**TACC** Reverse: CATTTTATTCATAAGATAGATGCCAGA	TACC
#4	Shortleaf	Forward: AAATCATTTCCATTC**CATTCATT** Reverse: TCGATAACGAATCCTATTCATCC	$(CATT)^2$

*Absent/missing in loblolly but present in the other southern pine species.

PCR = Polymerase chain reaction.

for 30 seconds, 59 °C for 30 seconds, 72 °C for 1 minute, 30 cycles → 72 °C for 15 minutes, 4 °C hold, for amplification. The gel electrophoresis of 5 µl of each amplified PCR products was conducted on 1-percent agarose gel. The agarose was stained with ethidium bromide after 20 minutes of electrophoresis, and the resulting bands were visualized under ultraviolet (UV) illumination. Presence of a band on a gel indicates positive amplification, while no band indicates negative. A positive band with the longleaf marker identifies a sample as a longleaf pine, while a negative (no band) with longleaf marker indicates the sample is not a pure longleaf pine. Similarly, a positive band with any of the specific markers (i.e., #1, #2, #3, and #4) confirms the identity of the targeted pine species sample, while a negative or null band indicates the sample is not that pine species targeted. The accuracy of markers was validated with samples from different pine tissues obtained from multiple sources in Arkansas, Louisiana, and Mississippi.

RESULTS

Four species-specific DNA markers and specific primers developed to amplify these markers accurately detected the corresponding four southern pine species based on the chloroplast DNA from pine tissue samples collected from multiple sources in Arkansas, Louisiana, and Mississippi. The genetic markers #1, #3, and #4 specifically detected longleaf, slash, and shortleaf pines, respectively; whereas marker #2 detected loblolly pine (paternal DNA) as shown in figures 2, 3, and 4. Of 18 cambial tissue samples from Arkansas, samples #1, 4, 5, 7, 8, and 10-12 were loblolly pine and the rest of the samples were shortleaf pine (fig. 2). The longleaf pine marker did not produce positive bands with these cambial tissue samples (fig. 2). The DNA classification results corroborated the tree species where the samples were obtained. The DNA classification results for 22 needle samples from seedlings of a mixed slash pine seedlot showed that samples #12, 14, 16, 17, and 20 were of loblolly pine, with the rest being slash pine except for #8 (fig. 3). Sample #8 was subsequently identified as slash pine when re-extracted DNA was tested for the four markers. Among 27 needle samples from the hybrid study plot in Louisiana, samples #13, 22-23, and 26-28 were identified as longleaf pine (fig. 4). The results from the 67 samples presented represent a cross section of the 231 samples evaluated.

Based on a longleaf marker (cpDNA Marker #1) classification of 21 pine saplings from the suspected "Sonderegger hybrid" plot, total heights of the

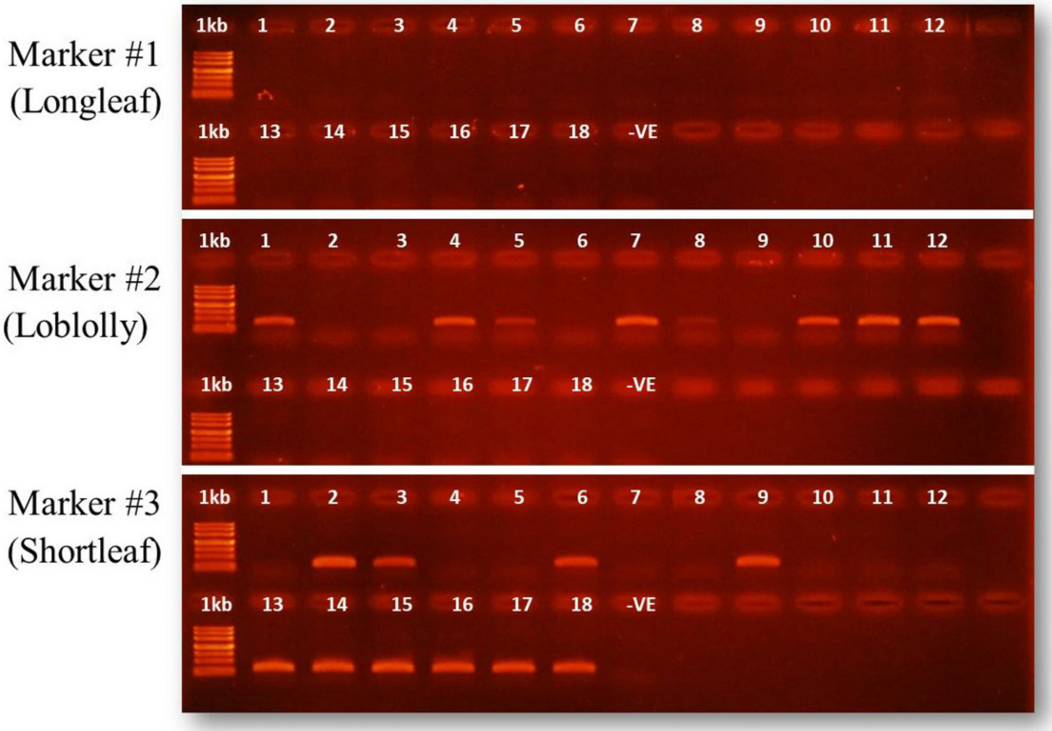

Figure 2—Detection of loblolly and shortleaf pines using three species-specific chloroplast DNA markers on DNA extracted from 18 pine stem cambium tissue samples from Crossett, AR.

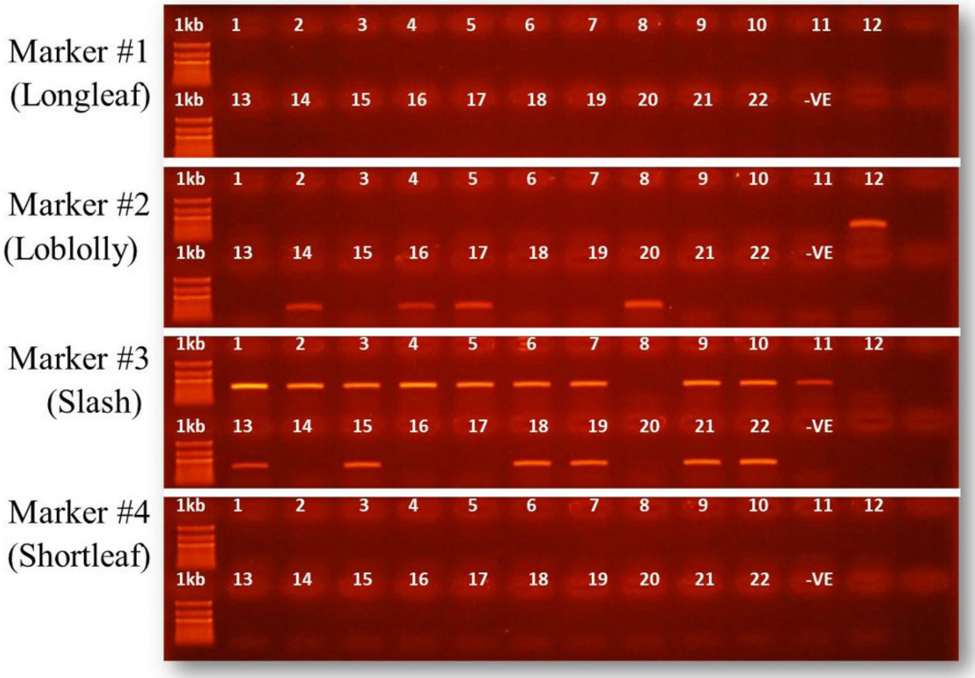

Figure 3—Detection of loblolly and slash pines using four species specific chloroplast DNA markers on DNA extracted from needle tissue samples of 22 seedlings from a mixed slash pine seedlot from Louisiana. Sample #8 was subsequently identified as slash pine when re-extracted DNA was tested for the four markers.

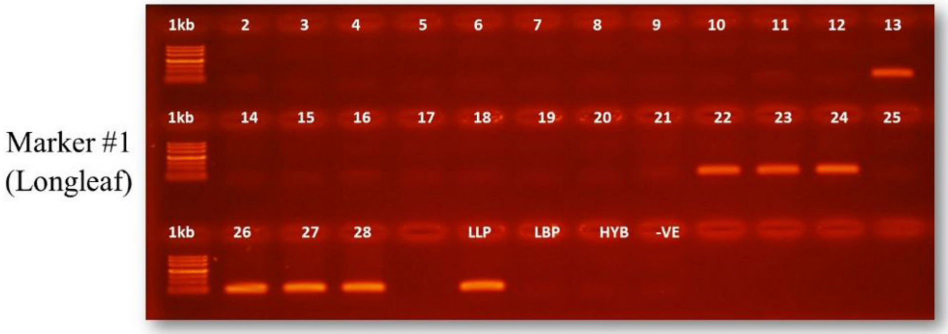

Figure 4—Identification of longleaf pine among 7- or 8-year-old Sonderegger hybrid saplings with a longleaf paternal marker (chloroplast DNA Marker #1) using DNA extracted from needle tissue samples collected from a Sonderegger plot located on the Palustris Experimental Forest within the Kisatchie National Forest, Rapides Parish, LA. Saplings were outplanted in 2009 (#24-#28) and 2010 (#2-#23). LLP, LBP, and HYB are the checks for longleaf, loblolly, and the Sonderegger hybrid, respectively.

verified Sonderegger hybrid were significantly greater compared to that of longleaf pine up to 5 years after planting (fig. 5). The initial mean seedling total height for Sonderegger pine and longleaf pine were 6.9 cm and 3.8 cm, respectively. After 5 years, Sonderegger pine and longleaf pine saplings had mean total height of 387.5 cm and 270.3 cm, respectively (fig. 5). After 3 years, average ground-line diameter was significantly larger for the Sonderegger hybrid than the longleaf pine with an average of 59.5 mm and 51.4 mm, respectively (fig. 6). However, at the end of the fifth year, the average diameter at breast height (d.b.h.) of the Sonderegger pine saplings was no longer statistically significantly greater than that of the longleaf pine saplings (fig. 6).

DISCUSSION

In this study, we identified species-specific cpDNA genetic markers (paternal) and developed a DNA-based tool to differentiate a "pure" longleaf pine (seed or seedling/sapling/tree) from other southern pine species by targeting paternally inherited cpDNA passed to progeny via pollen. The genetic markers/gel electrophoresis method described here explored the genetic variation and SNP target sites identified within the available cpDNA sequences. This technology addresses the emerging issues of natural hybridization in the southern pine forests.

Growth measurements made on seedling/saplings of the Sonderegger hybrid plot showed that this hybrid between longleaf and loblolly pine had greater growth in total height and stem diameter compared to that of the longleaf pine (figs. 5 and 6). Schmidtling (1999) observed the height growth in hybrid seedlings started almost immediately after germination, with the early growth much better than for longleaf pine but possessing the undesirable characteristics of loblolly pine such as poor form and susceptibility to fusiform rust disease. Hence, we concluded that a longleaf seedling that begins height growth in the nursery is likely a hybrid. We have yet to observe our Sonderegger saplings possess any undesirable form up to 9 years after planting.

Many landowners may decline to plant a Sonderegger hybrid seedling based on the observations by Chapman (1922) and Schmidtling (1999). In the nursery operation, longleaf seedlings with some degree of stem elongation are typically culled due to the poor quality of plants attributed to hybridization (Wakeley 1954). Generally, trees classified as Sonderegger pines are considered inferior to pure longleaf pine. Therefore, such an attribute may have serious consequences on marketability of longleaf pine seedlings at the nursery, and perhaps on the overall quality of seedlings available for use in the longleaf restoration initiative efforts. However,

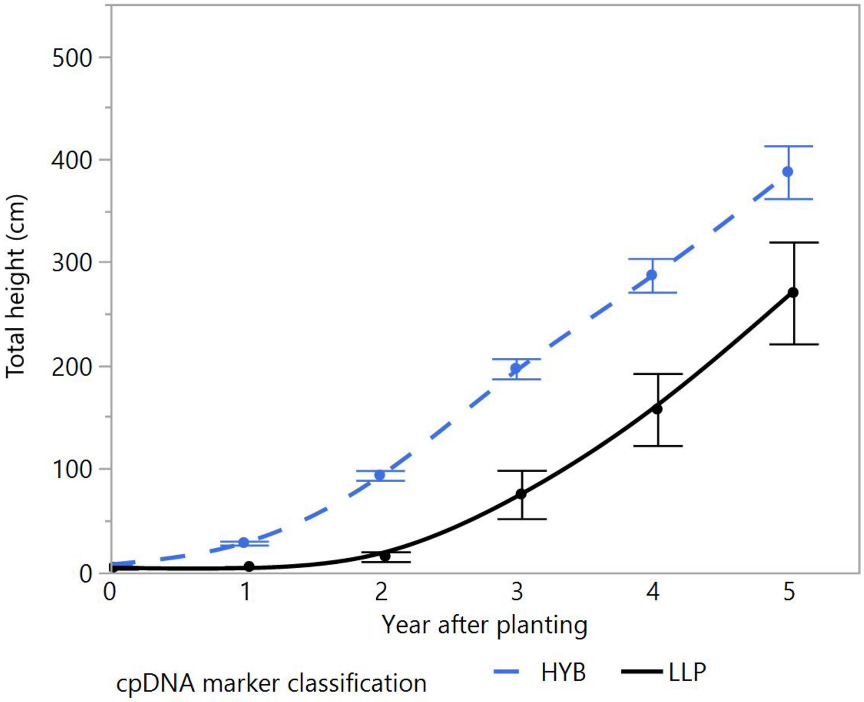

Figure 5—Total height of longleaf pine (LLP) and Sonderegger hybrid (HYB) saplings based on a longleaf marker (chloroplast DNA Marker #1) classification of 21 pine saplings from the Sonderegger hybrid plot on the Palustris Experimental Forest in the Kisatchie National Forest, Rapides Parish, LA.

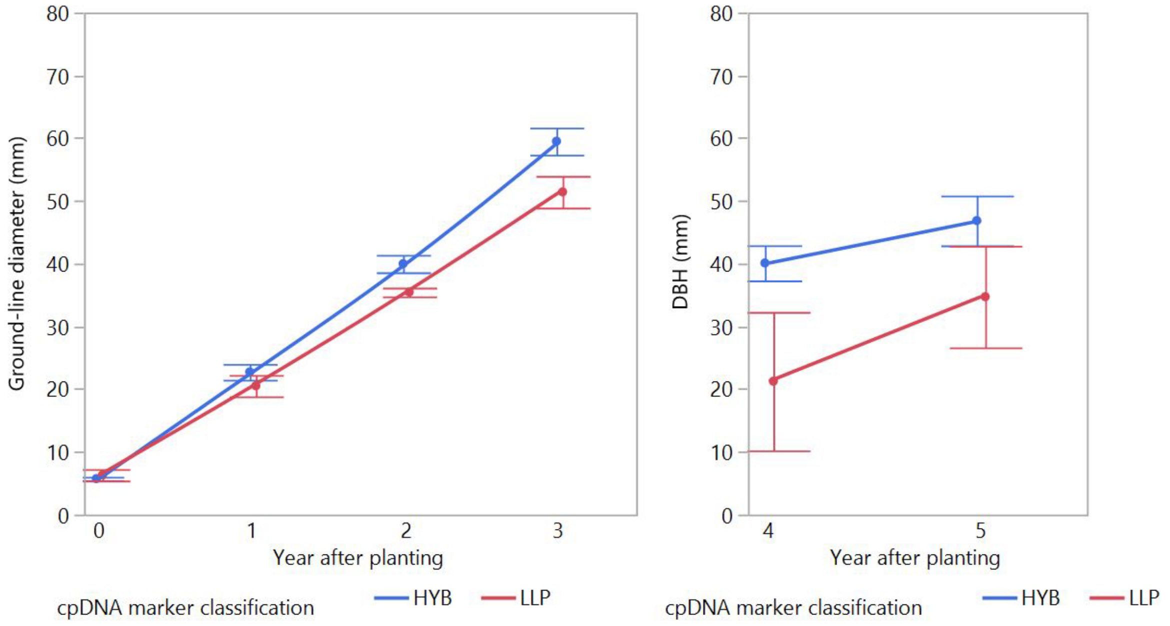

Figure 6—Ground-line diameter and diameter at breast height (d.b.h.) of longleaf pine (LLP) and Sonderegger hybrid (HYB) saplings based on longleaf marker (chloroplast DNA Marker #1) classification of 21 pine saplings from the Sonderegger hybrid plot on the Palustris Experimental Forest in the Kisatchie National Forest, Rapides Parish, LA.

measurements from trees evaluated at the Sonderegger hybrid plot at the Palustris Experimental Forest indicate that the average total height and stem diameter in Sonderegger hybrid pines were significantly greater than those of longleaf pines.

On the regional level, the U.S. Department of Agriculture, Forest Service, Southern Region initiated an ongoing effort of genotyping seed orchard clones and seedlots, which is an attempt to identify and eliminate the hybrid types from further contributing to the next generation of seed orchard seed crops and forest tree nursery seedling crops (Stewart and others 2016). Interestingly, one positive attribute of hybridization, at least in shortleaf pine × loblolly pine hybrids, is that they are more resistant to diseases compared to either parent. Shortleaf pine is susceptible to little leaf disease (caused by *Phytophthora cinnamomi*), and loblolly pine is susceptible to fusiform rust (caused by *Cronartium quercuum* f.sp. *fusiforme*) (Stewart and others 2016), while shortleaf x loblolly hybrids are less susceptible to these diseases (Benson and others 1982, Kraus 1986). Shortleaf pine x loblolly pine hybrids have also grown as well as or even better than one or both parents and have shown increased resistance to cold and ice damage (LaFarge and Kraus 1977).

Overall, identification of new DNA markers and improving the existing molecular tools will enable a better understanding of genetic diversity of southern pines. Findings from this investigation offer a simple and relatively quick, but accurate, detection approach that will facilitate routine detection of “suspect longleaf pine,” namely Sonderegger hybrids, among pure longleaf pine seeds and seedlings. This method offers a way to estimate the extent of hybrid contamination in seedlots, in crops of pine seedlings at the nurseries, and in pine stands.

CONCLUSIONS

The genetic markers and the specific primers we developed accurately identified the four southern pine species evaluated in this study. We anticipate this DNA tool will facilitate routine detection of natural hybridization when screening for seeds or seedlings intended for the restoration of longleaf pine ecosystems in southern region of the United States.

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6. Hardwood Regeneration

Moderators:

Michael Blazier and Brian Lockhart

CHERRYBARK OAK 7-YEAR GROWTH RESPONSE IN INTERMIXED SPECIES, COMPETITIVE NEIGHBORHOODS

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Abstract—In 2009, 6.5 acres on the University of Tennessee's Cumberland Forest in Morgan County, TN, were identified for hardwood afforestation. Twenty-seven plots were planted in one of three species of hardwoods: yellow-poplar (*Liriodendron tulipifera*), black cherry (*Prunus serotina*), and sweetgum (*Liquidambar styraciflua*) at three spacings. Cherrybark oak (*Quercus pagoda*) was intermixed in these plantings such that each oak was completely surrounded by a competitor species. These unique, species-specific neighborhoods act on oak growth and development particular to variations in competitor crown architecture. After 7 years, oak survival ranged from 84.8 percent in 6-foot by 6-foot sweetgum plots to 100 percent survival in the 10-foot by 10-foot yellow-poplar plots. Oak diameter at breast height (d.b.h.) showed significant effects within spacing ($p = 0.0002$) and species ($p = 0.0015$), but not their interaction ($p = 0.9110$). Total mean cherrybark oak d.b.h. was 1.6 inches, ranging from 1.4 inches in the 6-foot by 6-foot yellow-poplar plots to 2.17 inches in the black cherry 10-foot by 10-foot plots. There were significant effects of spacing on cherrybark oak height growth ($p = 0.0164$) but no significant differences at the species level ($p = 0.2410$) or in the interaction of spacing and species ($p = 0.7451$). Comparisons of mean plot heights by spacing indicates significant cherrybark oak height differences between the 10-foot by 10-foot spacing (16.6 feet) and the 6-foot by 6-foot spacing (13.4 feet; $p = 0.0091$) but not between the 6-foot by 6-foot and 8-foot by 8-foot (14.9 feet; $p = 0.3901$) or the 8-foot by 8-foot and 10-foot by 10-foot spacings ($p = 0.2905$).

INTRODUCTION

Although oaks (*Quercus* spp.) are typically the most dominant trees in the overstory of the Central Hardwood region, they are not consistently regenerating, especially on better sites (Abrams 2003, Fei and others 2011, Moser and others 2006, Thomas-Van Gundy and others 2014). This apparent oak regeneration crisis, a "paradox of a species that is dominant on the landscape, yet difficult to regenerate" (Crow 1988: 19) has confounded forest managers for decades. The long-term effect of this paradox on stand dynamics is a decline of an oak-dominated overstory with other species taking their place (Fei and others 2011, Luppold and Bumgardner 2018).

In response, work has been done to mimic historical fire regimes that might effectively perpetuate the establishment of oak regeneration and subsequent recruitment in size class. These efforts have had mixed results with some studies showing prescribed fire promoting oak regeneration by successfully reducing vegetative competition (Brose 2010, Brose and Van Lear 1998, Huddle and Pallardy 1999, Royse and others 2010, Signell and others 2005). Others have found little positive impact of fire on oaks or minimal negative impact on its competitors (Albrecht and McCarthy 2006, Alexander and others 2008, Gilbert and others 2003 Granger and others 2018, Green and others 2010, Hutchinson and others 2005). Other work has focused on developing thinning regimes, midcanopy removals, or a variety of basal area reductions (Albrecht and McCarthy 2006, Fahey and others 2016, Loftis 1990, Parrott and others 2011) and utilizing various regeneration harvest techniques such as shelterwood, seed tree, femelschlag, etc. (Beckage and others 2000, Granger and others 2018, Kellner and Swihart 2016, Loftis 1990 Motsinger and others 2010) to encourage oak establishment and development.

But whether exploring fire regimes, stand manipulation, or some combination of these broad treatment types, it is evident that there is a need to investigate interspecies-specific competition and its explicit impact on the development of oak. It is foundational to understand long-term competitor interactions with oak and impacts on the growth and development of oak crowns and subsequently their general form and function before exploring oak response to other confounding factors such as fire or prescriptive removals.

The rich diversity of taxa throughout the eastern hardwood forests forming the competitive

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neighborhoods with which oak interacts in its ontogeny suggests a vast array of unique competitive influences on oak. What role does competitor species crown architecture play in shaping the growth environment for oak and does that interaction change over time? For example, the excurrent form of sweetgum (*Liquidambar styraciflua*) has been shown to allow cherrybark oak (*Quercus pagoda*) to assume latent dominance in natural (Clatterbuck and Hodges 1988) and artificial mixed stands (Lockhart and others 2012).

We hope to 1) quantify the unique competitive pressures inherit to oak in mixed stands, 2) assess cherrybark oak response to these pressures, and 3) develop practical guidelines for quality oak management for landowners and natural resource practitioners. This is a first step in these efforts and this paper reports on 7-year survival, height, and d.b.h. of intermixed cherrybark oak and assesses early interspecies interactions with cherrybark oak in Tennessee.

METHODS

Study Site

In 2009, 6.5 acres of slightly rolling land on the University of Tennessee's Cumberland Forest in Morgan County, TN, were identified for afforestation. This area was located at latitude N36$^{\text{O}}$ 3.116' and longitude W84$^{\text{O}}$ 28.952' on a broad upland interfluve at an elevation of 1340 feet above sea level (Griffith and others 1998, Smalley 1982). The climate was characterized by long, moderately hot summers and short, mild winters. Average annual temperature ranged from a January mean minimum of 27.5 °F to a July mean maximum of 80.6 °F with an annual daily average of 57.3 °F. Average annual precipitation was 57.5 inches which was fairly evenly distributed throughout the year (Logan and others 1990). Soils were classified as Lonewood silt loam (LoB) with 2 to 5 percent slopes. These tended to be well drained with moderate permeability and high available water capacity with strongly to very strongly acidic soil pH. Depth to soft sandstone bedrock was 40 to 60 inches or more (Davis and Yaeger 2007, Evans 1992). Site indexes ranged from 75 feet at base age 50 years for shortleaf pine (*Pinus echinata*) and white oak (*Quercus alba*), 80 feet for northern red oak (*Quercus rubra*), 90 feet for sweetgum and eastern white pine (*Pinus strobus*), and 100 feet for yellow-poplar (*Liriondendron tulipifera*) on the Wartburg Basin – Jellico Mountains subregion (Smalley 1982). The area had been left fallow for 8 years following a white pine and loblolly pine (*Pinus taeda*) salvage harvest. It was bush hogged and burned annually during that time. While generally homogenous, some microsite variability existed in the form of two linear depressions that carried overland flow in significant rain events. By avoiding these depressions, 6.5 acres were delineated as plot land for this project. Immediately prior to establishment, the area was disked.

Planting Design and Establishment

This study used cherrybark oak, one of the most highly valued and quickly growing of the red oaks (Section *Lobatae*), as the focal tree. It was intermixed in plantings of yellow-poplar, sweetgum, or black cherry (*Prunus serotina*) as trainer trees in part to utilize the unique crown characteristics these competitor species provide. Aside from being one of the most common regional competitors of oak, yellow-poplar is also one of the most quickly growing trees in the Eastern United States with broad leaves that shade out competition underneath a dense canopy. It also sprouts vigorously when cut. Although expected to quickly overtop the cherrybark oak, its physiological characteristics allow investigation of oak crown response to severe competition at crown closure and affords opportunity to develop a complimentary thinning regime thereafter. Sweetgum's excurrent crown architecture should allow cherrybark oak to occupy the space above the base and widest section of the sweetgum crowns regardless of the overall height of the sweetgum. Black cherry is a fast-growing pioneer species like yellow-poplar but differs in that its sparse crown and small leaves result in a low light extinction rate through its canopy allowing cherrybark oak to assume latent dominance. Yellow-poplar and black cherry 1-0 seedlings were purchased from the Indiana Department of Natural Resources State nursery at Vallonia in southern Indiana. Cherrybark oak and sweetgum seedlings were purchased from the Tennessee Division of Forestry nursery located in Delano, TN.

In March 2009, the seedlings were planted on 27 plots. Each was planted with one competitor species and cherrybark oak. Odd numbered rows consisted purely of the competitor and even rows alternated with cherrybark oak such that every oak was surrounded by eight trees of a trainer species. Three replicates of each competitor were planted at three spacings (6-foot by 6-foot, 8-foot by 8-foot, and 10-foot by 10-foot). Six-foot by 6-foot plots were 0.19 acre in size (15 rows) with 49 cherrybark oak intermixed with 176 competitors. Eight-foot by 8-foot plots were 0.25 acre (13 rows) with 36 cherrybark oak and 133 competitors. The 10-foot by 10-foot plots were 0.28 acre in size (11 rows) with 25 cherrybark oak trees in 96 competitors (fig. 1). After planting, glyphosate was applied by backpack sprayer between rows three times during the first growing season, twice in the second growing season, and once during the third growing season to minimize ingrowth.

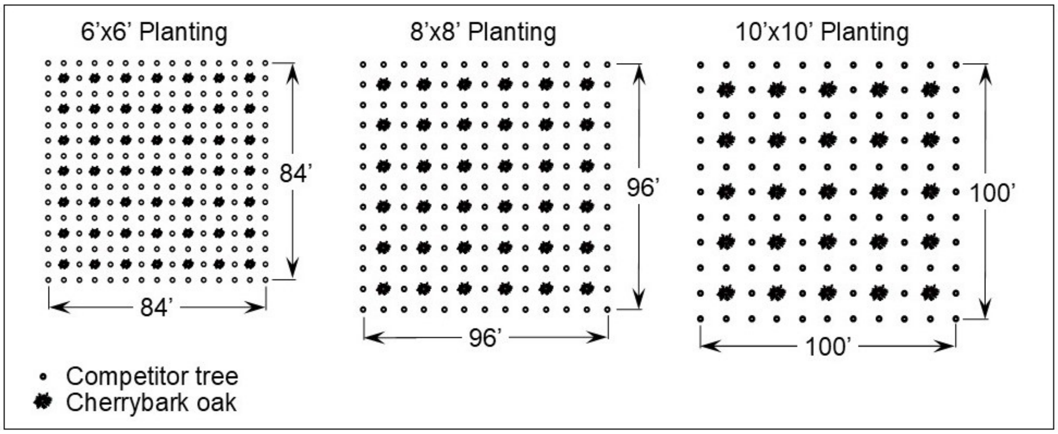

Figure 1--Mixed cherrybark oak and competitor species experimental unit layouts. From left to right: 6-foot by 6-foot spacing, 8-foot by 8-foot spacing, and 10-foot by 10-foot spacing.

Two linear depressions precluded blocking on spacing/species replicates. Maximizing uniformity within plots, the study was blocked on spacing with replicates of species within spacing blocks. This allowed distribution of the smaller 6-foot by 6-foot plots in conformity to the known site restrictions and resulted in the greatest plot homogeneity.

Early Treatments

It was expected that cherrybark oak would not successfully compete with yellow-poplar especially at closer spacings. By the end of the fourth growing season, in the 6-foot by 6-foot spacing, the cherrybark oak averaged 4.9 feet tall and were completely overtopped by the yellow-poplar (mean 17 feet total height) (Clatterbuck 2016). The yellow-poplar was systematically thinned, removing every poplar in each cardinal direction to a cherrybark oak. In that way, the four yellow-poplars closest to each cherrybark oak were removed and the four ordinal yellow-poplar remained. The cut yellow-poplar was removed from the plot by hand, minimizing damage to the stumps and residual stems. No chemical was applied allowing the yellow-poplar to coppice. Successful timing of the thinning application would prevent increased mortality and reduce growth inhibition caused by the complete yellow-poplar crown closure above the oak.

Measurements

Survival, total height, and diameter at breast height (d.b.h.) were measured for every tree in the study during the winter of 2016 after seven growing seasons. Diameters to the nearest tenth of an inch were measured using calipers and total heights to the nearest tenth of a foot were estimated using ocular estimation of tree tops next to height poles. These data were collected prior to additional release treatments conducted in late winter of 2016.

Analysis

Statistical analysis of the 995 cherrybark oak diameters and heights across all spacings and species were conducted using R software (R Core Team 2012). Although part of a larger investigation into tree crown development and interactions in which each cherrybark oak and its surrounding competitors were considered individual experimental units, this iterative analysis treated the plot as the experimental unit and therefore was treated as a completely randomized design with species plot replication within spacing. Cherrybark oak d.b.h. and heights were therefore averaged for each species x spacing x replicate plot and an analysis of variance performed with subsequent pairwise comparisons using t-tests with pooled standard deviations and Bonferroni's *p* value adjustment method.

RESULTS

Survival

Cherrybark oak seedling survival across the entire study ranged from a low of 84.8 percent in the 6-foot by 6-foot sweetgum to a high of 100 percent survival of cherrybark oak in the 10-foot by 10-foot yellow-poplar (table 1). Despite being overtopped by the end of four growing seasons, the oak in the thinned 6-foot by 6-foot yellow-poplar treatment exceeded that of the 6-foot by 6-foot black cherry and sweetgum treatments.

Diameter at Breast Height

Total mean cherrybark oak d.b.h. after 7 growing seasons was 1.6 inches, ranging from a low of 1.4 inches in the 6-foot by 6-foot yellow-poplar treatment to a high of 2.2 inches in the black cherry 10-foot by 10-foot treatment (fig. 2). Cherrybark oak d.b.h. showed significant effects within spacing ($p = 0.0002$) and species ($p = 0.0015$) but not the interaction term ($p = 0.9110$). The 10-foot by 10-foot spacing trees had

Table 1—Seven-year survival of planted cherrybark oak intermixed in competitor species plantings by spacing

Spacing	Plot size	Competitor	Planted	Surviving	Survival
	acres		*number*	*number*	*percent*
6 x 6	0.19	YEP	147	143	97.3
		SWG	147	125	84.8
		BLC	147	135	91.9
8 x 8	0.25	YEP	108	107	99.1
		SWG	108	104	96.3
		BLC	108	104	96.3
10 x 10	0.28	YEP	75	75	100.0
		SWG	75	73	97.3
		BLC	75	73	97.3

YEP = yellow-poplar, SWG = sweetgum, BLC = black cherry.

Planted = initial number of cherrybark oak planted.

Surviving = number of cherrybark oak that were alive at the time of measurement.

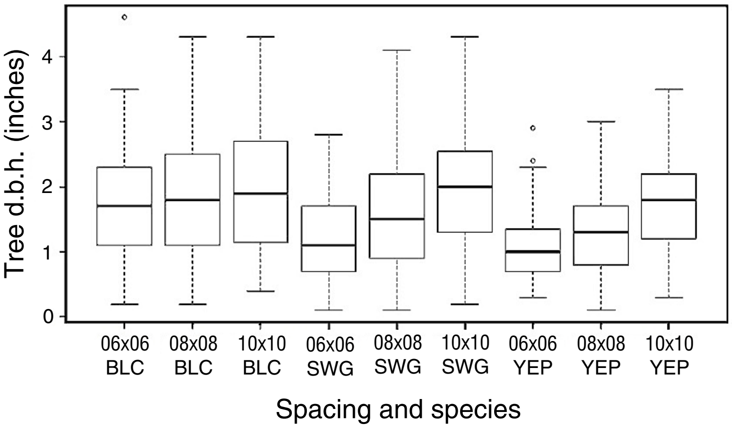

Figure 2—Boxplots of d.b.h. of cherrybark oak distributions after 7 years, by spacing and competitor species. YEP = yellow-poplar, SWG = sweetgum, BLC = black cherry.

a significantly larger average d.b.h. than the cherrybark oak in the 6-foot by 6-foot (p = 0.0007) or in the 8-foot by 8-foot spacing (p = 0.0446). There was no statistically significant difference between d.b.h. in the 6-foot by 6-foot and the 8-foot by 8-foot spacings (table 2).

Cherrybark oak also had significantly greater average diameter growing with black cherry compared to yellow-poplar (p = 0.0170). There was no significant differences between cherrybark oak in the black cherry mixture as compared to the sweetgum mixture (p = 0.1960) or between the sweetgum and yellow-poplar mixtures (p = 0.8540) (table 2).

Total Height

Mean height for cherrybark oak after 7 years was 15.0 feet with maximum heights approaching 30 feet (fig. 3). Significant effects of spacing on cherrybark oak height were evident (p = 0.0164) but not at the species level (p = 0.2410) or in their interaction (p = 0.7451). Comparisons of mean heights by spacing indicated significant differences between the 10-foot by 10-foot spacing and the 6-foot by 6-foot spacing (p = 0.0091) but no statistically significant differences between the 6-foot by 6-foot and 8-foot by 8-foot (p = 0.3901) or the 8-foot by 8-foot and the 10-foot by 10-foot spacings (p = 0.2905) (table 2).

Table 2—Mean d.b.h. and height by spacing and species

	d.b.h.				Height			
Treatment	Yellow-poplar	Sweetgum	Black cherry	Total	Yellow-poplar	Sweetgum	Black cherry	Total
6 x 6	1.07	1.21	1.67	1.3 ± 0.37 a	11.6	14.7	13.9	13.4 ± 2.4 a
8 x 8	1.32	1.54	1.87	1.6 ± 0.27 a	14.1	16.1	14.6	14.9 ± 1.9 ab
10 x 10	1.78	1.98	2.17	2.0 ± 0.32 b	16.6	16.6	16.6	16.6 ± 1.8 b
Total	1.38 ± 0.34 a	1.57± 0.35 ab	1.9 ± 0.40 b	1.6 ± 0.41	14.1± 2.7 a	15.8 ± 1.8 a	15.1 ± 2.7 a	15.0 ± 2.4

Total means (± standard deviation) followed by the same letter are not significantly different.
d.b.h. = diameter at breast height.

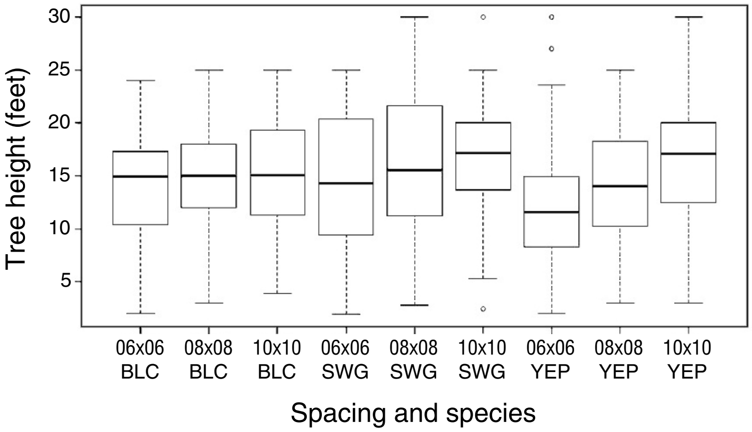

Figure 3—Boxplot of heights (feet) of cherrybark oak distributions after 7 years, by spacing and competitor species. YEP = yellow-poplar, SWG = sweetgum, BLC = black cherry.

DISCUSSION

Yellow-poplar outgrows most commercial species on productive sites in the Southeastern United States. After four growing seasons, yellow-poplar overtopped the oak in the 6-foot by 6-foot spacing such that complete yellow-poplar crown closure occurred over the oak. The thinning treatment implemented to release the cherrybark oak in this species and spacing combination was successful given the high survival of the oak in the 6-foot by 6-foot poplar treatment 3 years after the removal in comparison to the survival of the oak in the sweetgum and black cherry 6-foot by 6-foot treatments. Yellow-poplar coppice from the thinning reached a mean height of 4.9 feet in the subsequent 3 years and added pruning pressure from below to the oak crowns (Clatterbuck 2016). While there were no significant differences in height between cherrybark oak growing in these treated yellow-poplar neighborhoods, oak d.b.h. in the 6-foot by 6-foot poplar treatment was significantly smaller than the black cherry treatment with the same spacing.

Black cherry, though also a quick-growing species on productive sites, had a low light extinction rate through its canopy due in part to its small leaves, their arrangement, and its branching pattern. These characteristics were evident in the even growth distribution of the cherrybark oak regardless of the initial planting density. A potential issue arising in this mixture is the recruitment of weeds such as honeysuckle (*Lonicera* spp.) after initial herbicide treatments were concluded. This would explain the difference in the survival of the oak intermixed with black cherry in comparison to yellow-poplar.

The excurrent crown form of sweetgum afforded the slower-developing oak growing space above the widest part of the sweetgum crowns which was roughly equal in height to the base of their live crowns. The relatively low survival of the 6-foot by 6-foot sweetgum can be partially attributed to early vole (*Microtus* spp.) damage in these treatments. The lagging oak survival in the 6-foot by 6-foot sweetgum plantings is also indicative that sweetgum crown closure occurred above the height of the oak crowns. This suppressive action is evident in the d.b.h. and height distributions of the oak in these sweetgum neighborhoods at this density. The height and diameter growth of the oak at the 8-foot by 8-foot and 10-foot by 10-foot spacings would seem to align with the complimentary natural and artificial cherrybark oak/sweetgum stand development as reported by Clatterbuck and Hodges (1988) and Lockhart and others (2012).

CONCLUSIONS

Intraspecies competitive neighborhoods appear to play an important role in the development of cherrybark oak as they begin to express themselves at an early age. Differences in these competitor species' influence can have dramatic complimentary or adverse impacts over time. Continued investigation of these influences and additional parameters exploring cherrybark oak crown development within these plots are needed to better quantify these interactions.

ACKNOWLEDGMENTS

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STATUS OF PLANTED OAK MONOCULTURES ON A COASTAL PLAIN MINOR BOTTOM IN THE FIFTH DECADE AFTER ESTABLISHMENT

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Abstract—In the mid-1970s, four oak (*Quercus* spp.) species adapted to bottomland sites, cherrybark oak (*Q. pagoda*), Nuttall oak (*Q. texana*), swamp chestnut oak (*Q. michauxii*), and water oak (*Q. nigra*), were planted in monocultures at several spacings to evaluate species and spacing effects on stand dynamics. The present investigation extends this study out to the fifth decade by comparing the oak monocultures planted at the two widest spacings (8 by 8 feet and 12 by 12 feet). A thinning in March 1996 provided an opportunity to assess potential effects of a single tending treatment. Results suggest that the original species and spacing treatments continue to influence development at individual-tree and stand levels. Red oak species were larger than swamp chestnut oak, while trees at the wider spacing (12 by 12 feet) were larger than trees established at the narrower spacing (8 by 8 feet). The effect of spacing on stems per acre was not statistically significant, but stand-level basal area was greater at the wider spacing. Both live-crown ratio and survival since 1996 were greater in stands that were treated with a one-time thinning. This study reinforces how decisions made at the time of stand establishment and early stand tending can have lasting effects on the development of planted bottomland oak stands.

INTRODUCTION

Although short-term studies of forests under active management can provide meaningful insights that help inform management decisions, the longevity of tree species and the multi-decadal nature of stand dynamics require a longer-term perspective to fully evaluate consequences of interventions in managed forests. Longitudinal investigations based on designed silviculture experiments can be particularly valuable to enriching our understanding of managed forests since they offer opportunities to address long-term impacts of deliberate manipulations of a stand within a statistically rigorous framework.

In the mid-1970s, the Forest Service, U.S. Department of Agriculture initiated a hardwood plantation experiment on a minor bottom in southeast Arkansas owned at that time by Georgia-Pacific Corporation. The experiment was installed to evaluate effects of species and spacing on the dynamics of planted hardwood monocultures. As part of this study, four oak (*Quercus* spp.) species were planted: three types of red oak (cherrybark oak (*Q. pagoda*), Nuttall oak (*Q. texana*), and water oak (*Q. nigra*)) and one white oak (swamp chestnut oak (*Q. michauxii*)). The present investigation compared these four species planted at the two widest spacings in the fifth decade after stand establishment. Approximately half of the planted oaks were treated with a precommercial thinning. Therefore, the potential effect of this one-time thinning was also assessed. The objective of this investigation was to evaluate long-term effects of species, spacing, and thinning on oak plantation development at the individual-tree and stand levels.

METHODS

The 75-acre study site is located on what is now Weyerhaeuser Company property in Drew County, Arkansas, on a terrace adjacent to a minor stream bottom in the Western Gulf Coastal Plain. The poorly drained Amy Series (a fine-silty loam) is the dominant soil at this site. Prior to initiating the study, the site supported a mixed hardwood-pine (*Pinus* spp.) stand that was harvested, cleared, root raked, and disked in the fall of 1975 (Carlson and Goelz 1998).

The original study consisted of a factorial of eight hardwood species planted at five spacings with treatment combinations replicated four times in a randomized complete block design (see Carlson and Goelz (1998) for details). The site was planted in May

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1976. The present investigation considered only the cherrybark, Nuttall, swamp chestnut, and water oak plantings established at the two widest spacings: 8 by 8 feet (hereafter, "narrow") and 12 by 12 feet (hereafter, "wide"). Deployment of these spacings on a per acre basis scaled up to 680 and 302 trees, respectively. Each experimental unit consisted of a block of 169 trees (13 rows by 13 columns). This design established stands of 0.25 acres at the narrow spacing and 0.56 acres at the wide spacing.

Following stand establishment, the study site was treated mechanically to control competing vegetation. Mechanical release was done by mowing between rows for the first 14 years. A precommercial thinning was applied in March 1996 to a subset of the stands. Stands were free thinned to either B-level stocking or to 50 percent stocking based on Goelz (1995), whichever was higher, by targeting volunteers and poorly formed planted trees. The intensity of thinning was variable among stands due to differences in the abundance of volunteers. For example, the reduction in basal area per acre (BA) from thinning ranged from 13 to 63 percent. The thinning treated 1 to 3 replicates of the oak species-spacing combinations. Thus, the thinning produced an unbalanced experimental design with only 1 or 2 replicates for most of the 16 three-way treatment combinations.

In the summer of 2017, all 32 stands of the oak species planted at narrow and wide spacings (4 species x 2 spacings x 4 replications) were revisited for sampling. Each sample was a nested-plot array consisting of a single, 0.10-acre plot (hereafter, "large plot") established at the center of each plantation to capture trees at least 3.5 inches in diameter at breast height (d.b.h.) and a single, 0.05-acre plot (hereafter, "small plot") centered within each large plot to capture trees 0.5 to 3.4 inches d.b.h. Species, d.b.h., total height, height to crown base, and condition were recorded for each sampled tree. Grade of the first 16-foot log was determined following the assessment by Rast and others (1973) for all planted trees greater than 10 inches d.b.h.

Analysis of variance (ANOVA) was used to assess the effects of species, spacing, and thinning on planted tree and stand attributes. Tree responses included mean d.b.h., mean height, and mean live crown ratio (LCR) of planted trees. Responses of planted trees at the population level consisted of mean BA, mean number of trees per acre (hence, stem density), two estimates of survival, and log grade of the first log. Planted-tree survival was calculated based on the stem density of live trees recorded in 2017 expressed as a percentage of 1) initial planting density for unthinned stands only (IPD) and 2) the immediate post-thinning density in 1996 (PTD). Several estimates of the number of grade-quality first logs (those receiving a grade of 1, 2, or 3) were estimated and analyzed including, mean density of grade 1 and 2 first logs per acre (sum of grades 1 and 2), mean density of grade 3 first logs per acre, and mean density of graded first logs (sum of grades 1, 2, and 3) expressed as both an absolute density (number of graded first logs per acre) and relative density (percent of total planted trees per acre). The mean BA of all trees (planted + volunteer) was used for assessing stand-level response as well as the mean BA of volunteer pine, hardwood, and both individually. Because the thinning created an unbalanced experimental design with low replication for most three-way treatment combinations, only the main effects and two-way interactions of species, spacing, and thinning were considered. Significance of ANOVA models was assessed at an alpha level of 0.05 and treatment means were compared using Tukey's HSD. All analysis was performed in SAS 9.4.

RESULTS

Tree Attributes

ANOVA detected significant main effects of species and spacing on mean d.b.h. ($p = 0.049$ and 0.015, respectively) and mean height ($p = 0.001$ and 0.034, respectively) (table 1). Mean separation comparing d.b.h. among species and spacings revealed cherrybark oak was larger in diameter than swamp chestnut oak and trees planted on a 12- by 12-foot spacing were larger in diameter than trees on a narrow spacing. Comparisons of species based on height revealed cherrybark oak was taller than swamp chestnut oak and Nuttall oak, and water oak was taller than swamp chestnut oak. Mean separation of spacings based on height found trees planted on a wide spacing were taller than trees on a narrow spacing. An effect of thinning on mean LCR was detected ($p = 0.022$). Trees in thinned stands had larger LCR than those in unthinned stands. No significant interactions were detected.

Stand and Population Attributes

Species had a significant effect on both the BA ($p = 0.018$) and stem density ($p = 0.021$) of planted oaks (table 2). Cherrybark oak and water oak had significantly greater BA than Nuttall oak. For stem density, there were significantly fewer stems of Nuttall oak than swamp chestnut oak. There was no effect of spacing on stem density but spacing did affect BA ($p = 0.013$). Basal area of planted oak was greater at the wide spacing than the narrow spacing. An effect of thinning on stem density was detected ($p = 0.021$) and mean separation revealed a higher density of stems in unthinned than thinned stands. Spacing was a significant factor in ANOVA models of long-term survival in unthinned stands (IPD; $p = 0.002$), but species was not ($p = 0.058$). IPD was greater at the wide spacing (55.1 ± 2.9 percent) than the narrow spacing (27.8 ± 3.2 percent). Spacing ($p = 0.023$) and thinning ($p = 0.012$) had an effect on post-thinning

Table 1—Least squares means and standard errors of tree-level attributes (d.b.h., height, and LCR) for main effects of species, spacing, and thinning in a 41-year-old bottomland hardwood plantation experiment in southeast Arkansas

Attribute	Oak species		Spacing		Thinning	
			inches			
d.b.h.	Cherrybark	12.0 ± 0.6 a	Narrow	9.8 ± 0.4 b	Unthinned	10.0 ± 0.5
	Nuttall	10.7 ± 0.6 ab	Wide	11.4 ± 0.4 a	Thinned	11.1 ± 0.4
	Swamp chestnut	9.3 ± 0.6 b				
	Water	10.3 ± 0.6 ab				
			feet			
Height	Cherrybark	86.3 ± 2.6 a	Narrow	71.5 ± 3.3 b	Unthinned	72.9 ± 2.1
	Nuttall	73.4 ± 4.3 bc	Wide	79.2 ± 2.5 a	Thinned	77.4 ± 1.7
	Swamp chestnut	64.1 ± 3.9 c				
	Water	77.6 ± 2.2 ab				
			percent			
LCR	Cherrybark	49.5 ± 1.9	Narrow	48.0 ± 1.3	Unthinned	47.9 ± 1.3 b
	Nuttall	50.1 ± 1.9	Wide	51.5 ± 1.4	Thinned	52.2 ± 1.3 a
	Swamp chestnut	49.3 ± 1.9				
	Water	51.5 ± 1.9				

d.b.h. = diameter at breast height, LCR = live crown ratio, narrow = 8- by 8-foot spacing, wide = 12- by 12-foot spacing.

Tukey's HSD results are included comparing attribute means within a column. Means followed by the same letter were not significantly different at 0.05 level.

Table 2—Least squares means and standard errors of population-level attributes (BA, density, and PTD) for main effects of species, spacing, and thinning in a 41-year-old bottomland hardwood plantation experiment in southeast Arkansas

Attribute	Oak species		Spacing		Thinning	
			square feet per acre			
BA	Cherrybark	111.3 ± 8.2 a	Narrow	84.5 ± 5.6 b	Unthinned	100.3 ± 6.3
	Nuttall	74.5 ± 7.6 b	Wide	107.2 ± 5.8 a	Thinned	91.1 ± 5.0
	Swamp chestnut	90.8 ± 8.2 ab				
	Water	106.9 ± 8.2 a				
			stems per acre			
Density	Cherrybark	136 ± 15 ab	Narrow	165 ± 10	Unthinned	177 ± 12 a
	Nuttall	121 ± 14 b	Wide	144 ± 11	Thinned	133 ± 10 b
	Swamp chestnut	182 ± 15 a				
	Water	180 ± 15 ab				
			percent			
PTD	Cherrybark	70.5 ± 6.7	Narrow	61.9 ± 4.6 b	Unthinned	60.8 ± 5.1 b
	Nuttall	67.7 ± 6.3	Wide	78.6 ± 4.8 a	Thinned	79.6 ± 4.1 a
	Swamp chestnut	72.7 ± 6.8				
	Water	70.0 ± 6.8				

BA = basal area, PTD = post-thinning density in 1996.

Tukey's HSD results are included comparing attribute means within a column. Means followed by the same letter were not significantly different at 0.05 level.

survival (PTD). PTD was greater in the wide spacing than the narrow spacing and in thinned stands than unthinned stands. Species was a significant factor in the ANOVA model for volunteer pine basal area ($p = 0.026$) (table 3). Pine basal area was higher in Nuttall oak and swamp chestnut oak stands than planted stands of cherrybark oak and water oak. No effects were detected in ANOVA models for volunteer hardwood basal area, total volunteer basal area, or total stand-level basal area (planted plus volunteer). No significant interactions were detected.

Log Grade Assessment

Species was the only significant factor in the ANOVA models for relative ($p = 0.002$) and absolute ($p = 0.003$) density of graded first logs (sum of grades 1, 2, and 3). Mean separation revealed that both the relative density and absolute density of graded first logs were higher for cherrybark oak (table 4) than Nuttall oak, swamp chestnut oak, and water oak. No differences in relative density or absolute density of graded first logs were found among Nuttall oak, swamp chestnut oak, and water oak. Only species had an effect ($p < 0.001$) on the absolute density of grade 1 and grade 2 first logs (sum of grades 1 and 2). Cherrybark oak stands supported a higher absolute density of grade 1 and 2 first logs than Nuttall oak, swamp chestnut oak, and water oak. No differences in absolute density of grade 1 and grade 2 first logs were detected among the Nuttall oak, swamp chestnut oak, and water oak. None of the factors tested had an effect on the absolute density of grade 3 first logs. No significant interactions were detected.

DISCUSSION

Treatments implemented as part of the original experiment continue to explain differences among the planted oak monocultures. A salient finding of earlier reports was that swamp chestnut oak stems were generally smaller than stems of planted red oak species (Kennedy and others 1988). Our study observed a similar difference in tree size between oak species groups. The smaller size of swamp chestnut oak compared to the red oaks, particularly cherrybark oak and water oak, is consistent with growth differences between species of the red oak and white oak sections under open canopy conditions observed in upland oak ecosystems. In

Table 3—Least squares means and standard errors of basal area (square feet per acre) for volunteer trees and total stand basal area (planted + volunteer) sorted by stands planted to the four oak species in a 41-year-old bottomland hardwood plantation experiment in southeast Arkansas

	Volunteer basal area			
Oak species	Pine	Hardwood	Total	Stand basal area
Cherrybark	3.6 ± 2.7 b	26.1 ± 6.2	29.6 ± 10.8	141.9 ± 11.0
Nuttall	23.1 ± 5.1 a	35.1 ± 5.7	58.2 ± 14.0	138.3 ± 10.1
Swamp chestnut	22.3 ± 7.2 a	22.8 ± 6.2	45.2 ± 13.3	153.4 ± 11.0
Water	2.1 ± 2.1 b	17.6 ± 6.2	19.8 ± 8.3	126.7 ± 11.0

Tukey's HSD results are included comparing means within a column. Means followed by the same letter were not significantly different at 0.05 level.

Table 4—Least squares means and standard errors of absolute (stems per acre) and relative (percent of live planted trees) densities of graded first logs (grades 1+2+3), density of grades 1+2 first logs (stems per acre), and density of grade 3 first logs (stems per acre) sorted by the four planted oak species in a 41-year-old bottomland hardwood plantation experiment in southeast Arkansas

	Graded first logs			
Oak species	Absolute density	Relative density	Grades 1+2	Grade 3
Cherrybark	72 ± 7 a	53 ± 5 a	25 ± 6 a	47 ± 7
Nuttall	36 ± 6 b	30 ± 5 b	1 ± 1 b	35 ± 7
Swamp chestnut	35 ± 7 b	18 ± 5 b	2 ± 2 b	33 ± 7
Water	43 ± 7 b	23 ± 5 b	4 ± 2 b	38 ± 7

Tukey's HSD results are included comparing means within a column. Means followed by the same letter were not significantly different at 0.05 level.

the Missouri Ozarks, red oak saplings have a height growth advantage over white oak saplings at residual overstory densities less than 22 square feet per acre (Vickers and others 2014). The red oak species included in this study are shade intolerant (Meadows and Stanturf 1997) and capable of rapid growth in high light environments (Filer 1990, Krinard 1990, Vozzo 1990). Swamp chestnut oak, on the other hand, is moderately shade intolerant (Meadows and Stanturf 1997) with a moderate growth rate (Edwards 1990). Slower growth of swamp chestnut oak may be a trade-off for higher shade tolerance. There was also a high BA of volunteer loblolly pine (*Pinus taeda*) recorded in swamp chestnut oak stands. Furthermore, swamp chestnut oak was often in subordinate crown classes beneath the pine. The slower growth of swamp chestnut oak may have predisposed these stands to overtopping by volunteer pine, which may have exacerbated size differences with the red oaks.

Hydrology varied considerably across the 75-acre study area and the effect of species on planted tree BA and density (stems per acre) may have reflected interspecific differences in adaptability to bottomland landforms. Cherrybark oak and water oak are adapted to a wide range of soils (Krinard 1990, Vozzo 1990). These species were among the top performing in terms of tree-level growth and stand production at stand age 20 years (Carlson and Goelz 1998) and out to the fifth decade among the four oaks. Nuttall oak, however, had low BA and density compared to the other species. This species is often associated with wetter bottomland landforms (Filer 1990) and, of the oak species considered, is the least adaptable from a habitat perspective. Early reports noted high variability of Nuttall oak survival across the study site (Carlson and Goelz 1998, Kennedy and others 1988). Variability in Nuttall oak survival and poor performance at the population level may be linked to soil heterogeneity across the study area, yet also may be associated with high volunteer pine BA and interspecific competition.

Species had an effect on densities of graded first-logs, but spacing or thinning did not. This effect was attributable to cherrybark oak stands outproducing the other species, especially in yielding higher-valued grade 1 and 2 butt logs. Differences in butt-log grade among species was largely due to species-specific variation in stem quality and size. For example, the greater number of defects in both Nuttall oak and water oak contributed to lower densities of butt logs receiving a grade of 3 or better, while the smaller size of swamp chestnut oak stems limited the number of first logs that could receive a grade. Defects on Nuttall oak were mainly surficial bumps from occluded branch stubs and likely would be more correctable as tree size increases. In the case of water oak, however, many stems exhibited heavy decay originating from large dead branches and would be less likely to improve with time. Spacing did not affect log grade in this study. Quality growth has been linked to stand density, spacing, and the timing of crown closure (Sonderman 1985). The relatively low crown base heights in 10- to 20-year-old bottomland red oak plantations planted on a 12- by 12-foot spacing was likely due to delayed crown closure (Stoll and Frey 2016). It is possible that a spacing effect was detectable at a younger stand age when stems were smaller, but that it diminished as diameter growth dampened the visual impact of stem defects.

Although competition control was performed for over a decade post-establishment, this effort focused on treating the area between rows, while leaving competition within rows largely unchecked. By stand age 20 years, the BA of volunteers in oak stands ranged from 4 to 42 percent of total BA (planted plus volunteer), which is comparable to the 16 to 42 percent observed in 2017. The report on 20-year results alluded to potential negative effects of volunteer ingrowth on planted tree survival (Carlson and Goelz 1998). Our results suggest that volunteer encroachment, especially loblolly pine, may have contributed to the poor performance of swamp chestnut oak and Nuttall oak. Similar to findings at stand age 20 years, total BA in 2017 did not vary among the planted oaks despite significant variation in planted tree and volunteer BA. Carlson and Goelz (1998) speculated that similarity in total BA across treatments could be a reflection of stands growing at the site's carrying capacity. These authors also predicted that total BA would vary among species in the future due to the impacts of autecological differences in the planted species on stand dynamics. This prediction is consistent with the transitioning of an even-aged stand from the stem exclusion stage to the understory reinitiation stage of development (Oliver and Larson 1996). Results out to stand age 41 years indicate this prediction has not played out. Given time, density-independent factors, such as longevity, may still affect structural development in a species-specific manner.

Spacing effects on tree-level attributes noted in earlier reports have also persisted. The influence of initial spacing can be explained by stand dynamics concepts relating spacing and stand density to growing space allocation, tree growth, and self-thinning. All things being equal, crown closure will happen earlier in stands planted at a narrower spacing, leaving each tree with less space in the developing canopy, which, in turn, limits growth by restricting crown and leaf area development (Oliver and Larson 1996). Earlier onset of crown closure likely explains the smaller average stem diameter in stands at the 8- by 8-foot spacing compared to the 12- by 12-foot spacing. Larger stem diameter in the wider spacing may not be just a legacy effect of rapid early growth. A separate analysis based on this study found that individual-tree growth over the last 20 years was positively associated with spacing, suggesting that growth differences between these spacings have persisted. Higher survival at the wider spacing was likely linked to greater canopy space allocation and lower competitive stress at the individual-tree level. The higher rate of self-thinning in stands planted at the narrower spacing eliminated initial differences in population density. This difference in self-thinning also helps explain the higher BA in stands planted at the wider spacing, which, by age 41 years, supported planted populations of comparable density to the narrower spacing, but with a larger average stem diameter. Trees were also significantly taller in stands established at a 12- by 12-foot spacing. This result is interesting since height is generally assumed to be relatively independent of stem density (Oliver and Larson 1996). Considering initial density of the 8- by 8-foot spacing was over twice that of the 12- by 12-foot spacing (680 versus 302 stems per acre), it is plausible the height disparity observed between spacings is associated with density-dependent factors, including competitive pressure.

The precommercial thinning over 20 years ago explained variability in tree and population-level attributes of oak monocultures detected at stand age 41 years. Tree-level growth enhancement after thinning is largely the result of providing residual trees with access to additional canopy space for crown expansion and leaf area development (Oliver and Larson 1996). In this study, live crowns, but not stem diameters, were larger in thinned stands. Although not a significant factor in the model for tree diameter, the *p*-value for thinning was still relatively low ($p = 0.075$), suggesting a possible weak association in the third decade post-thinning. Another analysis of this study found that thinning enhanced tree-level basal area increment in the first decade after thinning but not the following decade. Thinned stands also had higher post-thinning survival than unthinned stands. Improved survival in thinned stands was likely related to enhanced tree vigor, as evidenced by a larger LCR, as well as the thinning's effectiveness in removing trees likely to succumb to mortality.

CONCLUSIONS

Research on the dynamics of older oak plantations, such as this study, enriches our understanding of managed oak ecosystems. This study reinforces how silvicultural actions can have long-term consequences on stand development at the individual-tree and stand levels. When growing bottomland oak plantations, stand establishment options, including what species to plant and at what spacing, should consider landowner objectives, site characteristics, and establishment costs. For example, if timber production is an objective on similar sites, then planting cherrybark oak at either spacing could meet management objectives. However, planting at the wider 12- by 12-foot spacing would cut the number of seedlings by more than half and reduce the cost of stand establishment. It is worth stating that this study assessed tree grade based on standing timber and, therefore, these results may not apply to effects of spacing on lumber grade. Early vegetation management to control competition both between and within rows is also likely warranted on similar sites. An early thinning could also benefit similar planted oak stands, especially where undesirable volunteer encroachment is severe. Finally, similar oak stands would likely benefit from a second thinning to enhance tree growth and improve stand quality that may also generate revenue.

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THE POTENTIAL FOR EXTENDING THE NATURAL RANGE OF CHERRYBARK OAK ON APPROPRIATE SITES

Wayne K. Clatterbuck and Evan McDivitt

Abstract—Five cherrybark oak (*Quercus pagoda*) plantations outside its native range spanning 10 to 50 years in age were studied to determine survival, growth rates, and projected yields. The plantations were located from southern Indiana to eastern Tennessee on former agricultural fields or cleared areas adjacent to minor drainages. Soils of these plantations were evaluated to determine if they had similar characteristics to common soils within the cherrybark oak range using the Baker and Broadfoot (1979) site evaluation guide. Plantations were well-stocked with present volumes of 8,000 to 14,000 board feet per acre (International ¼ Rule) depending on age. Plantations were free from insects or disease symptoms. Oak bole quality in these pure species plantations was a concern with branch scars still occluding on the upper butt log. Diameter growth rates were about 3 inches per decade. Cherrybark oak plantings appeared promising on sites east of its native range in Tennessee on suitable sites, but less so on sites north of its native range in southern Indiana due to susceptibility of frost cracks.

INTRODUCTION

Cherrybark oak (*Quercus pagoda*) is a cherished and highly valued tree in the red oak family known for its fast growth, straight form, wood quality, and acorn production (Belanger and Krinard 1990). The species occurs in major and minor river bottoms of the Atlantic and Gulf Coastal Plains and the northern Mississippi River Valley to southern Illinois on loamy sites of first bottom ridges and well-drained terraces, primarily alfisol and inceptisol soils (fig. 1) (Broadfoot 1969, 1976). Until the early 1990s, cherrybark oak was considered a variety of southern red oak (*Q. falcata*) instead of a separate species (fig. 1) (Belanger and Krinard 1990). Sites supporting cherrybark oak transition to and overlap southern red oak as sites become more upland and drier. Because cherrybark oak is a preferred timber tree, managers have questioned whether the distribution of the species could be extended on suitable sites outside of its natural range, primarily in minor stream valleys. Minor stream bottoms may be distinguished from major bottoms of the Mississippi River as those floodplains and terraces where soils are of local origin (Hodges 1997).

Unfortunately, little is known about adaptability of cherrybark oak beyond its natural range on suitable sites. Considering that the range of cherrybark oak is rather narrow and discontinuities exist between the Atlantic and Gulf Coastal Plains, influence of geographic and climatic variability on cherrybark oak is unknown. Factors that generally impact geographic variability of a species include size of a species' range, amount of environmental diversity within the species' natural range, and extent of range discontinuities (Wright 1976). Schmidtling (2001) suggested the most important climatic variable related to growth and survival of southern pines (*Pinus* spp.) is annual average minimum temperature. Typically, species can be moved west to east and vice versa with similar moisture and temperature regimes (similar isotherms), but south to north transfer influences rate of growth, date of bud break, length of growing season, and resistance to cold temperatures (Schmidtling 2001, Wright 1976). Sporadic weather events such as ice storms, late season frosts, and sudden fluctuations in temperature can also impact tree health when species are moved from southern to northern latitudes.

This study explored the growth of cherrybark oak plantations beyond the species' natural range. Location and substrates of each planting were carefully considered to align with site-species productivity parameters and common soils for sites within the species' natural range. Site evaluation guidelines for cherrybark oak of Baker and Broadfoot (1979) were used to compare site properties and plantation growth outside the natural range to those expressed within the natural range.

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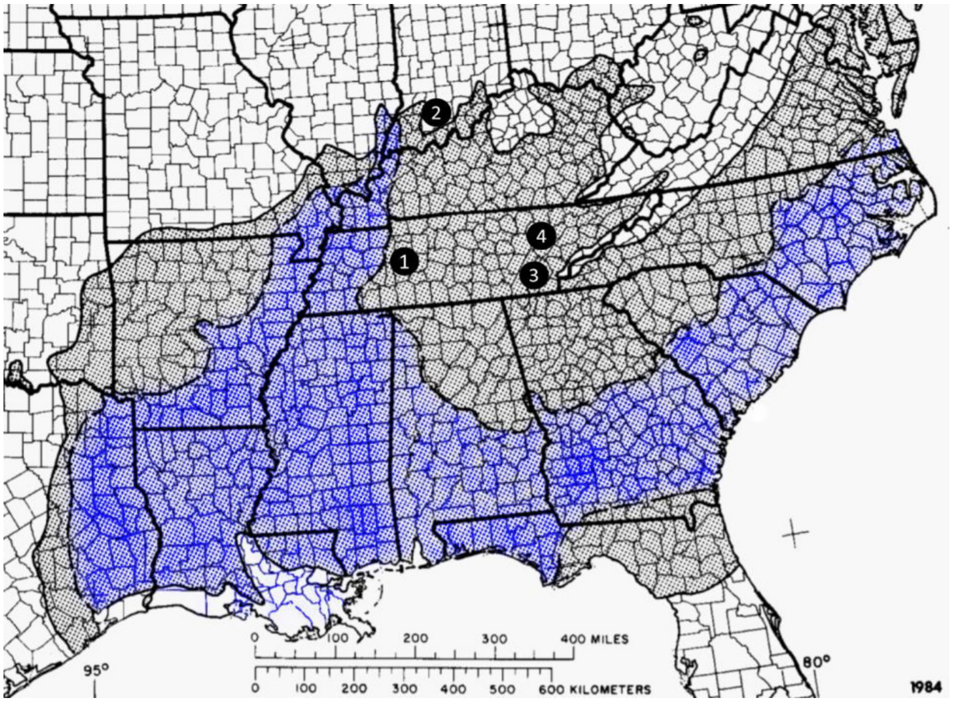

Figure 1—Locations of sampled plantations for the cherrybark oak geographic range study. 1: Natchez Trace State Forest, 2: Pike State Forest, 3: Tennessee State Nursery, and 4: University of Tennessee Cumberland Forest. The blue area represented in the Coastal Plain and the Mississippi Alluvial Plain is the geographic range for cherrybark oak (*Quercus pagoda*) and the more upland gray area is the geographic range for southern red oak (*Quercus. falcata*). Map Source: Belanger and Krinard (1990)

METHODS

Study Sites

Five cherrybark oak plantations were addressed in this study (table 1). All locations were outside the natural cherrybark oak range as designated in Belanger and Krinard (1990). Plantations were located within floodplains of minor streams with entisol or inceptisol soils except for the UT Cumberland Forest that was on the lower slope of an ultisol. Most of the sites were on old fields containing herbaceous vegetation. The exceptions were the PSF sites which had young woody stems and brush that were cut and removed prior to planting. Herbicides were used before planting for site preparation and several times after planting to control competing herbaceous vegetation. Sample plantations infrequently flooded (averaging once every 5 to 10 years) and when they did, duration was just a few days. Area of each plantation was small, ranging from 0.5 to 2.0 acres. Spacing was some variate of 8 feet by 8 feet to 10 feet by 10 feet. Seedling survival from surveys collected a few years after planting exceeded 80 percent for each plantation.

Data Collection

Each plantation was visited in the summer 2018. Diameter at breast height (4.5 feet, d.b.h.) of each tree was measured, total height on a subset of five dominant or codominant trees was tallied, and trees that had succumbed since planting were recorded. Stem analysis was conducted on three to five trees in each plantation to determine height growth rates. Though not presented in this paper, these data were used to corroborate height and diameter measurements. Bole quality as designated by log grade of the butt log for those stems greater than 12 inches d.b.h. was measured in older plantations (Hanks and others 1980). Soils, topography, and drainage were noted on each site and evaluated using soil survey reports and the online web soil survey. From these data, plantation volumes, basal area, and trees per acre were calculated.

Once vegetative and substrate information for each plantation were collected, a site evaluation guide (Baker and Broadfoot 1979) was used to determine if planted locations were suitable for cherrybark oak plantations. This guide uses four soil-site factors for determining site index for various hardwood species. Point values were assigned for various components and added together to establish total site index. A synopsis of factors and components for cherrybark oak are outlined in table 2, but for more detailed information on assessment of each factor/component, reference the Baker and Broadfoot (1979) publication. Point-scored site index values were then compared between plantations with their respective average tree measurements and site conditions to

Table 1—Location and description of the five cherrybark oak plantations

Study site	Location	Managed by	Age	Soil series	Site index for cherrybark oak	Age thinned
			years		*feet at 50 years*[a]	
Natchez Trace State Forest (NTSF) thinned	Henderson County, TN	Tennessee Department of Agriculture, Division of Forestry	50	Iuka (thermic Aquic Udifluvent)	105	Age 24
NTSF unthinned	Henderson County, TN	Tennessee Department of Agriculture, Division of Forestry	49	Bibb (thermic Typic Fluvaquent)	95	Not thinned
East Tennessee (TN) State Nursery	Polk County, TN	Tennessee Department of Agriculture, Division of Forestry	20	Toccoa (thermic Typic Udifluvent)	95	Not thinned
Pike State Forest (PSF) (2 locations 1.5 miles apart)	Pike County, IN	Indiana Department of Natural Resources, Division of Forestry	38	Steff (mesic Fluvaquentic Dystrochrepts)	97	Age 38
University of Tennessee (UT) Cumberland Forest	Morgan County, TN	University of Tennessee, Forest Resources Research and Education Center	10	Lonewood (mesic Typic Hapludults)	87	Not thinned

[a] Clatterbuck (1987)

provide an informed assessment of appropriateness of these sites to extend the natural range of cherrybark oak. Site index for four of the five sampled cherrybark oak plantations was also determined with total height-age relationships of dominant and co-dominant trees using site index curves formulated in minor bottoms of Mississippi (Clatterbuck 1987). The fifth plantation at UT Cumberland Forest was omitted because of its young age (10 years).

RESULTS

Data collected from each cherrybark oak plantation suggested that within their particular age and development timeline, growth trajectories and tree size statistics were remarkably similar (table 3). The NTSF plantation thinned at 24 years had greater diameter and volume, but the plantation that was not thinned had greater basal area and trees per acre. Grade of butt logs (first 16 feet) was greater in thinned plantations averaging a log grade of two due to greater diameters, while butt logs in the unthinned plantations averaged a grade of three because of smaller diameters and exposed branch scars. Both plantations had more numerous surface defects on logs in the upper 8 feet than the lower 8 feet.

The cherrybark oak plantation at the TN State Nursery exhibited phenomenal growth and merchantable volumes after 20 years. Diameter and height growth rate averaged 4 inches and 20 feet per decade, respectively (table 3). These growth rates are expected to diminish somewhat as growing space becomes more limited and trees are increasingly affected by competition from adjacent trees. A thinning to maintain growth rates should take place within the next 5 years.

The PSF cherrybark oak plantations were thinned in the winter of 2017-2018 and the remaining trees measured during the summer of 2018. Table 3 depicts the information after thinning. Growth and volume accumulations were excellent after 38 years with diameter growth rates exceeding 3 inches per decade. Substantial frost cracks were apparent on 32 percent of dominant or codominant trees in one of the two

Table 2—Synopsis of the soil-site properties expressed by the site evaluation guide for cherrybark oak (Baker and Broadfoot 1979)

Factor	Description	
Factor 1	Physical condition (maximum of 31 points; minimum of 19 points)	
	Soil-site properties:	Soil depth and presence of artificial or inherent pan
		Soil texture in the rooting zone
		Soil compaction in the upper one foot of soil
		Soil structure in the rooting zone
		Past use and present cover
Factor 2	Moisture availability during the growing season (maximum of 38 points; minimum of 21 points)	
	Soil-site properties:	Water table depth
		Artificial or inherent pans
		Topographic position
		Microsite
		Soil structure in rooting zone
		Soil texture in rooting zone
		Flooding
		Past use and present cover
Factor 3	Nutrient availability (maximum of 25 points; minimum of 14 points)	
	Soil-site properties:	Geologic source
		Past use and present cover
		Organic matter (A-horizon)
		Depth of topsoil (A-horizon)
		Soil age
		pH in the rooting zone
Factor 4	Aeration (maximum of 31 points; minimum of 16 points)	
	Soil-site properties:	Soil structure in the rooting zone
		Swampiness
		Mottling
		Soil color in rooting zone

The maximum number of points (site index in feet, base age of 50 years) is 125, while the minimum number of points is 70.

Table 3—Summary stand statistics (means) for each sampled plantation for the cherrybark oak geographic range study

Plantation	Age	d.b.h.	Total height	Trees per acre	Basal area	Volume per acre[a]
	years	*inches*	*feet*	*number*	*square feet per acre*	*board feet*
NTSF thinned	50	13	104	145	125	13,500
NTSF unthinned	49	10	98	196	137	10,800
TN State Nursery	20	8	62	248	98	8,600
PSF	38	12	84	114	92	10,200
UT Cumberland Forest[b]	10	3	29	---	---	---

d.b.h. = diameter breast height at 4.5 feet, NTSF = Natchez Trace State Forest, TN = Tennessee, UT = University of Tennessee, PSF = Pike State Forest.

[a] International ¼ log rule.

[b] Mixed species plantation.

plantations (fig. 2). Based on stem analysis, frost cracks occurred sometime during 2006 to 2008 when the trees were 26 to 28 years old.

The UT Cumberland Forest plantation is a mixed species planting research study (Clatterbuck 2016, Schubert and others 2020) with a focus on growth and development of cherrybark oak, presently 10 years old. Although overall (stand) plantation data for the mixed species planting were not directly comparable to the other four pure species plantations measured in this study, diameter and height growth rates of cherrybark oak averaged 3 inches per decade and 3 feet per year, respectively (table 3).

All plantations appeared free from insects and disease. Each plantation was well-stocked to overstocked (basal area ranged from 90 to 140 square feet per acre) with present volume ranging 8,000 to 14,000 board feet per acre (International ¼ Rule). Except for frost cracks encountered at PSF and bole surface defects when assessing log grade, no other tree damage was observed.

The Baker and Broadfoot (1979) site evaluation guide for cherrybark oak was used as another approach to estimate site index. Based on four major soil factors expressed in the guide, a site index range was formulated for each plantation. Site index ranges for each cherrybark oak plantation averaged 95 to 100 feet after 50 years following this guide (table 4). Using Clatterbuck (1987), site index for cherrybark oak was also found to be 95 to 105 feet at 50 years for all plantations, suggesting site productivity was comparable across plantations (fig. 3).

DISCUSSION

Land managers and organizations that planned and planted the sampled cherrybark oak plantations years ago were successful in locating appropriate sites for growth of the species outside its natural range. By selecting sites similar to those found in its natural range, growth trajectories (table 3) and site productivities (fig. 3 and table 4) were similar. Both direct measurement of tree growth using site index curves and use of the Baker and Broadfoot (1979) site evaluation guide yielded similar site productivities. Entisol and inceptisol soils in sampled plantations were slightly less productive (less than 10 to 15 feet in site index) than their counterparts within the cherrybark oak natural range. The difference is probably attributable to soils not being as deep and well-drained as those in Coastal Plain areas. However, the ultisol soil at UT Cumberland Forest was just as productive for cherrybark oak as soils at other sites, but it was also the youngest plantation sampled (10 years). Additional time will be necessary to determine whether early growth rates correspond with growth at later stages or times.

Figure 2—Frost crack (cross section and vertical surface) of a 38-year-old sample tree at Pike State Forest, Indiana. Photo Credit: Wayne K. Clatterbuck (author)

Table 4—Baker and Broadfoot (1979) site index estimations for sampled plantations based on soil-site factors for the cherrybark oak geographic range study

Plantation	Site index
	feet at 50 years
NTSF thinned	100-110
NTSF unthinned	95-100
TN State Nursery	95-105
PSF	95-100
UT Cumberland Forest	85-90

NTSF = Natchez Trace State Forest, TN = Tennessee, PSF = Pike State Forest, UT = University of Tennessee.

Diameter and height growth were comparable at the different chronological times among the five plantations (table 3). The NTSF plantation was thinned (26 years ago) allowing an assessment of the response to the thinning. Both PSF plantations were thinned during the growing season prior to data collection and the future response to thinning is not known. The goal of thinning was to reduce stocking by removing unacceptable growing stock trees. Except for the PSF plantations, all other sampled locations were approaching or were overstocked. Without density control, diameter growth will be reduced. Estimated volume per acre for each plantation corresponds with number of trees, diameter, and basal area (table 2).

The planted, pure stands of cherrybark oak had little, if any crown stratification. Most trees were growing at the same rate and retained lower branches until sunlight became limited at which point branches died and were shed. The branch scars were occluded very slowly because diameter growth was protracted in the excessively stocked stands with little room for additional crown expansion and growth. While the first 6 to 8 feet of most butt logs were relatively clear with few surface blemishes, the upper 8 feet of logs still had defects yielding a log grade of two as the best grade. Although thinning would increase diameter growth rates and occlude branch scars more quickly, most stands had not been thinned, leaving tall, lanky trees of small diameters.

Crowns of mixed species stands often stratify because different species have different growth rates resulting in multi-canopy stands. These stratified stands with differential growth rates often promote better bole grade with slower-growing trees shaping branch-free oak boles. Once oak crowns emerge and ascend above neighboring trees, larger crowns are produced with greater diameter growth rates to occlude the branch scars faster (Clatterbuck and Hodges 1988, Lockhart

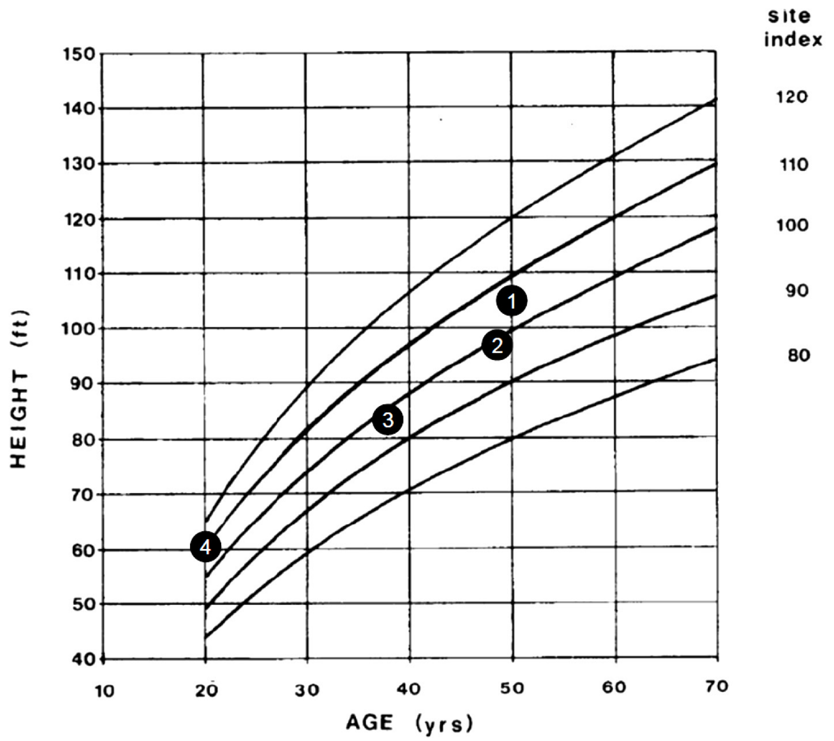

Figure 3—Site index curves for cherrybark oak on minor stream bottoms with site index estimations from Baker and Broadfoot (1979) of the sampled plantations in the cherrybark oak geographic study (1: Natchez Trace State Forest - thinned, 2: Natchez Trace State Forest – unthinned, 3: Pike State Forest, and 4: Tennessee State Nursery. Site Index Curve Source: Clatterbuck (1987)

and others 2006). Because trees in a monoculture usually grow at the same rate, the opportunity for better log grades is diminishing. Thinning at the appropriate time will increase diameter growth rates and could improve log grade, but branch pruning and occlusion of large-diameter branch scars often wanes because branches are retained longer when more growing space is available. Mixed species plantings should be established to encourage crown stratification for better grade of oaks.

Based on similar growth trends of the five cherrybark oak plantations investigated in this study, the range of cherrybark oak may be extended from west to east on appropriate sites, even though site productivities may be slightly less than those in the natural range. Shifting of range northward should be carefully considered due to cooler and shorter growing seasons. Frost cracks were encountered on some trees at the southern Indiana site. Tree growth was not hampered on the northern site, but log grade was reduced permanently with frost cracks. Future northward expansion studies could be useful to assess extent and severity of frost cracking along a cooler temperature gradient, especially with the advancing climate variability.

CONCLUSIONS

West to east expansion of the natural cherrybark oak range appears feasible on appropriate sites, at least in Tennessee. South to north expansion is problematic with cooler temperatures during the early growing season and possibilities of freezing temperatures having detrimental effects on the tree, such as frost cracks. However, tree and plantation growth were not adversely affected at the location in southern Indiana. For plantings to be successful, suitable sites for cherrybark oak should be determined through objective site evaluation and soils information. Although site productivities are slightly less outside the natural range of cherrybark oak compared to Coastal and Alluvial Plain sites, site index (95 to 105 feet in 50 years) was within bounds for successful growth of cherrybark oak. This study is further evidence that mixed species stands may be more advantageous to develop better log grade in cherrybark oak through crown stratification than pure oak plantations.

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EFFECTS OF CANOPY STRUCTURE ON WATER CYCLING: IMPLICATIONS FOR CHANGING FOREST COMPOSITION

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Abstract—In upland oak (*Quercus* spp.) forests of the Eastern United States, shade-intolerant, fire-tolerant oaks are being replaced by shade-tolerant, fire-sensitive species due to changes in forest management and fire regimes. In these mixed-species forests, rainwater redistribution by the forest canopy is determined by tree species traits as well as canopy position. To better understand how shifting forest composition could impact rainwater partitioning, we quantified differences in canopy structure and the resultant net flux of water to forest soils in a series of experiments across the Southeastern United States. Non-oak species had denser canopies than oaks and intercepted more rainwater, reducing throughfall by more than 15 percent. Conversely, stemflow water inputs were more than four times greater beneath non-oaks, which had smoother bark compared to rougher-bark oaks. This study demonstrates the link between aboveground tree structure and interspecific water fluxes. It supports the hypothesis that a shift in forest composition could influence future ecosystem function in southeastern upland oak forests.

INTRODUCTION

Upland oak (*Quercus* spp.) forests in the Eastern United States have been undergoing a shift in composition due to changes in forest management (Abrams 2003). The suppression of the natural fire regime is a driving factor that has led to the proliferation of fire-sensitive species in the understory and midstory that are out-competing fire-tolerant oak species (Nowacki and Abrams 2008)often increasing fire occurrence (e.g., in northern hardwoods. These species, broadly termed "mesophytes," create an understory environment with cooler, damper, and more shaded conditions. This environment in turn is more suitable for survival and succession of mesophytes and less suitable for oak regeneration (Palus and others 2018).

Hypothesized mesophytes, such as red maple (*Acer rubrum*), hickories (*Carya glabra* and *C. ovata*), and winged elm (*Ulmus alata*), tend to be shade-tolerant and exhibit a suite of physical characteristics that may divert more water to soils surrounding these individuals. For example, smooth-bark mesophytes divert more water to stemflow than co-occurring oak species (Alexander and Arthur 2010, Barbier and others 2009). Mesophytes may also have smoother leaf surfaces, which help shed rainwater, thus reducing canopy interception and increasing throughfall to the forest floor (Pypker and others 2005).

Current restoration efforts use prescribed fire to increase light availability to oak seedlings (Fan and others 2012, Vander Yacht and others 2019) under the assumption that dense, mesophytic subcanopy layers are the principal force inhibiting oak regeneration. However, the redistribution of water resources (Alexander and Arthur 2010), leading to changes in moisture and flammability by mesophytes (Dickinson and others 2016, Kreye and others 2013), may be just as important based on preliminary findings and the limited success of restoration activities to date (Arthur and others 2015, Keyser and others 2019). As such, the objectives of this study were to determine how canopy structure influences canopy water partitioning and subsequent soil moisture availability.

MATERIALS AND METHODS

Study Sites

This study summarized findings from two upland oak stands in Mississippi: Sessums Natural Area and Spirit Hill Farm. Sessums Natural Area was located in

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Starkville, MS (33.4247 N, 88.7607 W) and Spirit Hill Farm was located southwest of Holly Springs, MS (34.6661 N, 89.7004 W). Both stands were considered oak-hickory forests with similar basal areas and stem densities, although the specific species distribution was slightly different (table 1). All hickory species were grouped together and termed "hickory," all oak species from the Section *Quercus* were termed "white oaks," and all oak species from the Section *Lobatae* were termed "red oaks."

Measurements

At both sites, a mixture of oak and non-oak species were selected for measurements. Species were selected based on their contrasting physical characteristics (e.g., canopy structure, bark morphology) in different canopy positions (e.g., overstory and midstory). At Sessums Natural Area, 18 trees (3 individuals across 6 species: *C. glabra, C. ovata, Q. alba, Q. falcate, Q. pagoda,* and *Q. stellata)* were monitored from September 2014 through November 2017. At Spirit Hill Farm, 81 trees (9 individuals across 4 species in the overstory: *A. rubrum, C. glabra, Q. alba,* and *Q. stellata;* 9 individuals across 5 species in the midstory: *A. rubrum, C. glabra, Q. alba, Q. stellata,* and *U. alata*) were monitored from October 2017 through November 2018.

Tree structural characteristics including canopy area, basal area, bark thickness, and bark roughness were measured for all study trees and standardized for tree size. Leaf water storage capacity under calm and windy conditions was determined over three replicate leaves of each species using the water displacement method (Llorens and Gallart 2000). Briefly, leaves were weighed, submerged in water, and then weighed again to determine the change in mass (i.e., water retention) on a per unit area basis. Windy conditions were created by shaking each leaf three times after submersion in water prior to weighing. *In situ* study trees were outfitted with stemflow collars constructed from 2.5-cm-inner-

Table 1—Stand conditions at the study sites

Feature	Sessums Natural Area	Spirit Hill Farm
Basal area (m^2 ha^{-1})	Overstory: 33.6 Midstory: 3.4	Overstory: 17.6 Midstory: 4.4
Density (stems ha^{-1})	Overstory: 207 Midstory: 1,636	Overstory: 123 Midstory: 2,608
Dominant oak species		
White oak section	Post oak White oak	Post oak
Red oak section	Cherrybark oak Shumard oak	Southern red oak
Dominant non-oak species	Pignut hickory Shagbark hickory White ash Winged elm	Blackgum Pignut hickory Sweetgum Winged elm
Soil series[a]	Kipling silt loam	Providence silt loam
Precipitation (mm)[b]	1,402	1,460
Temperature (°C)[b]	6.8 (DJF) to 26.6 (JJA)	7.9 (DJF) to 15.1 (JJA)

Blackgum = *Nyssa sylvatica* Marsh., cherrybark oak = *Quercus pagoda* Raf., pignut hickory = *Carya glabra* P. Mil., post oak = *Q. stellata* Wangenh., shagbark hickory = *C. ovata* Mil., Shumard oak = *Q. shumardii* Buck., southern red oak = *Q. falcata* Michx., sweetgum = *Liquidambar styraciflua* L., white ash (*Fraxinus americana* L., white oak (*Q. alba* L., winged elm (*Ulmus alata* Michx.

[a] USDA NRCS (2015).

[b] National Centers for Environmental Information (Arguez and others 2010).

DJF = December, January, February; JJA = June, July, August.

diameter polyethylene tubing cut longitudinally and sealed around the trunk of each tree above the girdling and inoculation site with aluminum nails and silicone caulk. Collars drained into 20-L polyethylene bins and stemflow volume was measured manually. Funneling ratio (FR) is a measure of the contribution of outlying canopy areas to stemflow generation (Herwitz 1986) and was calculated as

$$FR = \frac{SF}{\left(P_g \times BA\right)} \tag{1}$$

where

FR is the funneling ratio, SF is stemflow volume, P_g is gross rainfall as a depth equivalent, and BA is the basal area of the tree.

When FR is greater than 1, the outlying canopy is contributing to additional stemflow production beyond what would be expected by the basal area occupied by the tree trunk alone. Throughfall collectors were constructed from 3.8-L polyethylene collectors fitted with a 12.5-cm-diameter funnel and placed underneath individual tree crowns. Soil moisture was measured at three distances from tree boles (0.5 m, 1.0 m, 1.5 m) and at three depths (3.0 cm, 7.0 cm, 12.0 cm) (FieldScout 150 TDR probe).

Data Analysis

Canopy structural traits and leaf water storage capacity data were normally distributed, thus differences in sample means were tested using analysis of variance. In the overstory, red maple was omitted from statistical analysis due to limited sampling pool (red maple were infrequent in the overstory). Stemflow and throughfall data were not normally distributed, so a generalized linear model was used to determine differences in these variables among species. These tests were performed using the lme4 package (Bates and others 2014) in R version 3.5.1 (R Core Team 2018). Principal components analysis (PCA) was performed on field-measured variables using the prcomp function in R. Principal components with eigenvalues greater than or equal to 1 were retained following the Kaiser criterion.

RESULTS

Tree Structural Traits

In the midstory, oaks had rougher and thicker bark compared to non-oak species (fig. 1a, b) while non-oaks had greater canopy area per unit basal area (fig. 1c). White oak leaves held more water per unit leaf area than non-oaks under calm conditions, but no differences between species were evident during windy (shaken) conditions (fig. 1d).

Canopy Hydrology

In the overstory, hickories and red oaks generated the largest percent stemflow, which was 5.1 and 3.8 times greater than white oaks, respectively (table 2). Overstory hickories were also the most efficient at generating stemflow, with FR values more than two times greater than oaks. In the midstory, all species partitioned approximately the same amount of rainfall into stemflow, although red maple and winged elm were more efficient in stemflow generation relative to their size with FR values of 23.4 and 15.2, respectively (table 2). Over a 1-year period, this is equivalent to an additional 3,000 L m^{-2} of stemflow around overstory hickories and an additional 30,000 L m^{-2} of stemflow around midstory red maple compared to oak species. The order of magnitude difference in midstory stemflow generation can be attributed to the extremely high FR, with all midstory trees being more efficient at generating stemflow over a given basal area (table 2). For throughfall, there were no differences in the percent throughfall partitioning in the overstory ($p = 0.411$), while midstory throughfall under midstory winged elm was more than 10 percent less than under red oaks (table 2).

Principal Components Analysis

Principal components analysis was used to visualize the relationships between tree structural characteristics, canopy hydrology, and soil moisture. In the midstory, two principal components explained 87 percent of the variation (table 3). The distribution of variables across PC1 separated species with large crowns and high funneling ratios (red maple) from species with high throughfall partitioning, rougher bark, and high soil moisture near the tree bole (red oaks). The distribution of variables across PC2 separated species with thick bark (white oaks) and high soil moisture at the crown edge (hickories and winged elm). With regards to non-oak species influence on water availability, red maple was associated with the greatest stemflow partitioning and funneling ratios while hickory was associated with higher soil moisture (fig. 2).

In the overstory, two principal components explained 90 percent of the variation (table 3). The distribution of variables across PC1 separated species with high throughfall partitioning and rough and thick bark (red oaks) from species with high soil moisture, especially at the crown edge (red maple). PC2 separated species with high stemflow partitioning and funneling ratios (hickories) from species with high leaf water storage capacities (white oaks). In the overstory, hickories were correlated with the greater stemflow production while red maples were correlated with higher soil moisture, opposite of the trends observed in the midstory for these species (fig. 2).

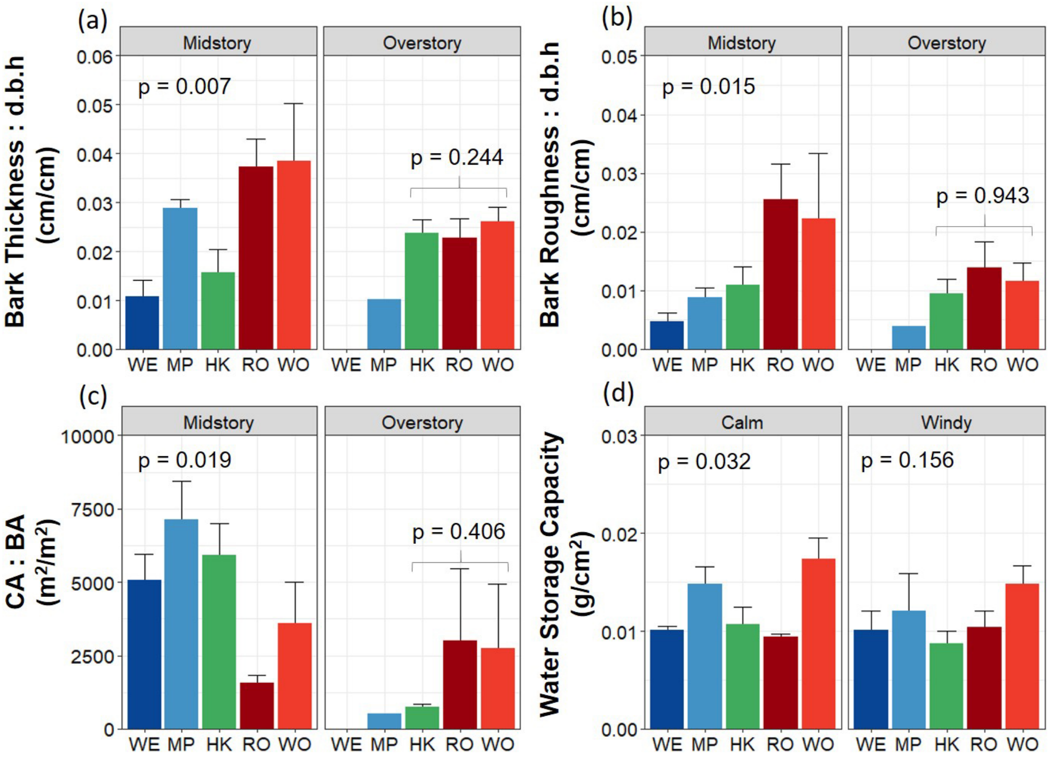

Figure 1—Barplot with standard errors for midstory and overstory tree characteristics including (a) bark thickness standardized to diameter at breast height (d.b.h.), (b) bark roughness standardized to d.b.h., (c) canopy area (CA) standardized to basal area (BA), and (d) leaf water storage capacity under calm and windy (shaken) conditions. WE = winged elm, MP = red maple, HK = hickory, RO = red oak, WO = white oak.

Table 2—Mean canopy hydrology fluxes with standard errors for overstory and midstory species

Fluxes	Red maple	Hickory	Winged elm	Red oaks	White oaks
Overstory					
Stemflow (%)	0.35 ± 0.05 b	0.81 ± 0.08 a	-	0.61 ± 0.05 a	0.16 ± 0.01 c
Stemflow (FR)	0.95 ± 0.14 bc	2.45 ± 0.16 a	-	1.62 ± 0.11 b	0.87 ± 0.07 c
Throughfall (%)	77.0 ± 1.37 a	79.4 ± 0.79 a	-	80.0 ± 0.77 a	79.1 ± 0.98 a
Midstory					
Stemflow (%)	0.42 ± 0.04 a	0.32 ± 0.02 a	0.27 ± 0.04 a	0.22 ± 0.03 a	0.35 ± 0.06 a
Stemflow (FR)	23.37 ± 2.64 a	7.10 ± 0.50 b	15.15 ± 3.55 ab	3.32 ± 0.55 b	6.94 ± 1.38 b
Throughfall (%)	78.3 ± 1.53 ab	79.1 ± 2.60 ab	75.9 ± 1.52 b	86.3 ± 3.41 a	80.4 ± 1.61 ab

FR = funneling ratio.

Winged elm were not observed in the overstory.

Means in a row followed by the same letter are not statistically different.

Table 3—Eigenvector loadings from principal components analysis

	Midstory		Overstory	
Variable	PC1	PC2	PC1	PC2
Variance explained (%)	63.95	22.99	56.76	34.07
Canopy area:basal area	-0.39	0.06	0.23	0.33
Bark thickness:d.b.h.	0.22	-0.57	0.36	0.18
Bark roughness:d.b.h.	0.36	-0.35	0.36	0.15
Stemflow (%)	-0.32	-0.40	0.19	-0.45
Funneling ratio	-0.37	-0.05	0.24	-0.39
Throughfall (%)	0.38	-0.17	0.40	0.02
VWC @ bole	0.36	-0.01	-0.21	0.40
VWC @ mid-canopy	0.32	0.22	-0.14	0.49
VWC @ edge	0.24	0.55	-0.40	0.02
Leaf water storage – calm	-	-	-0.36	-0.18
Leaf water storage – windy	-	-	-0.28	-0.24

d.b.h. = diameter at breast height, VWC = volumetric water content.

Leaf water storage experiments were only performed on leaves from overstory trees.

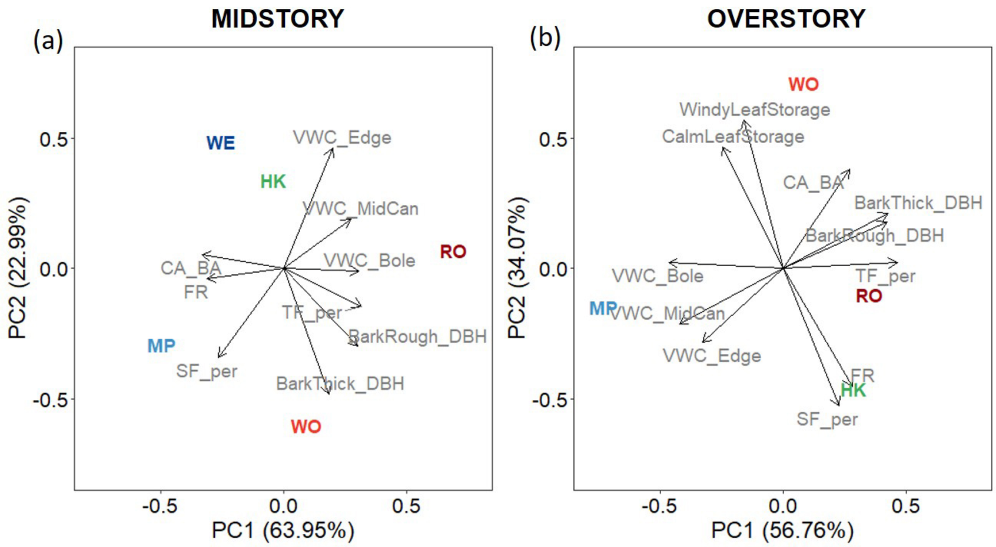

Figure 2—Principal components analysis of midstory and overstory tree traits, water partitioning, and soil moisture where CA_BA is canopy area per basal area; FR is funneling ratio, SF_per is percent stemflow partitioning, TF_per is percent throughfall partitioning, VWC_Bole is volumetric water content at tree bole, VWC_MidCan is volumetric water content at the mid-canopy, VWC_Edge is volumetric water content at the canopy edge, BarkRough_DBH is bark roughness standardized for d.b.h., BarkThick_DBH is bark thickness standardized for d.b.h., CalmLeafStorage is leaf water storage capacity under calm conditions, and WindyLeafStorage is leaf water storage capacity under windy (shaken) conditions. WE = winged elm, MP = red maple, HK = hickory, RO = red oak, WO = white oak.

DISCUSSION

Non-oak species including red maple, hickory, and winged elm have physical characteristics that facilitate mesic conditions in upland oak forests. These mesophytes have thinner and smoother bark compared to oak species, which enhances stemflow generation and consequently greater distribution of water in the vicinity of tree stems. Smoother bark provides uninterrupted flowpaths for stemflow (McGee and others 2019, Siegert and Levia 2014), in conjunction with thinner bark, which has lower water storage capacity (Levia and Herwitz 2005, Van Stan and others 2016). In contrast, the canopy area of mesophytes was greater than that of oak species, especially in the midstory. As such, denser mesophyte crowns will provide additional foliar surfaces for canopy interception, which serves to limit throughfall partitioning (Vrugt and others 2003). However, denser crowns may also reduce light availability to the forest floor, which simultaneously limits survival of shade-intolerant oaks (Larsen and Johnson 1998) and reduces forest floor evaporation.

The trade-off between increased stemflow and decreased throughfall underneath mesophyte crowns appears to favor wetter soil moisture conditions, but the strength of this response is not consistent across species. Instead, the net effect on soil moisture is likely determined by physical traits that change with tree size and canopy position. Our results suggest that even though red maple is capable of generating more stemflow in the midstory, hickory and winged elm are correlated with wetter soil conditions. In the overstory, the opposite is true. Hickories generated the greatest quantities of stemflow while red maple were correlated with the wettest soils. However, there is a caveat to the findings of this study: soil moisture is not the same as fuelbed moisture. It is likely that the same physical traits that lead to higher soil moisture will also maintain high moisture levels in the fuelbed, but there are suite of other characteristics that are important in fuelbed moisture retention (bulk density, specific leaf area, depth, etc.) (Dickinson and others 2016, Varner and others 2015). As such, this study provides preliminary mechanisms in which species-specific aboveground structures alter the forest floor underneath individual tree crowns.

CONCLUSIONS

In this study, we empirically demonstrated the link between aboveground tree architecture and the effects on the redistribution of rainwater to the forest floor. This relationship highlights another pathway in the complex process of mesophication through which non-oak species are creating stand-level conditions unsuitable for natural oak regeneration.

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OAK COMPETITIVE STATUS IN 27-YEAR-OLD GROUP OPENINGS IN A WEST GULF COASTAL PLAIN PINE-HARDWOOD FOREST

Colby E. Mohler, Mohammad M. Bataineh, Don C. Bragg, Robert L. Ficklin, Matthew H. Pelkki, and Matthew G. Olson

Abstract—Due to their high ecological and economic value, oaks (*Quercus* spp.) are a desirable species group for mixedwood management. However, little information exists on oak competitiveness at the local, neighborhood scale in harvest gaps beyond the first few growing seasons. The objective of this research is to determine if oak competitive status is related to neighborhood composition and gap size. A total of 156 oak stems at least 3.5 inches in diameter at breast height and their respective neighborhoods were sampled in nine experimental harvest gaps (ranging in size from 0.25 to 1.0 acre) on the Kisatchie National Forest. Using neighborhood species importance values, a cluster analysis identified five neighborhood types: pine (*Pinus* spp.), pine-sweetgum (*Liquidambar styraciflua*), pine-oak, mixed hardwood-pine, and oak. No significant effects of neighborhood type or gap size were detected for subject tree heights or competition index; however, gap size was a significant factor in explaining red oak (section *Lobatae*) live crown ratio, and neighborhood type was a significant factor in predicting live crown ratio of all oaks. Red oaks in smaller gaps had significantly higher live crown ratios when compared to those in medium or large gaps. Oaks in pine neighborhoods had significantly lower live crown ratios when compared to neighborhoods with a greater hardwood component. These results suggest that managers should consider implementing timber stand improvement earlier in gap development to release oaks from pine and other shade-intolerant competition if earlier canopy recruitment of oak is desired. Alternative research approaches may be required to fully evaluate oak competitive status in gap cohorts initiated by group selection, such as stem analysis of oak subjects and neighbors and including oaks of all size classes.

INTRODUCTION

Mixedwoods, defined as stands composed of hardwood and softwood species in which neither group comprises more than 70 to 80 percent of the total stand basal area (Cavard and others 2011, Kabrick and others 2015), are a covertype that can offer many ecological and societal benefits. For example, mixedwoods tend to have greater structural heterogeneity and biodiversity than either hardwood- or softwood-dominated stands, and this offers more niche space for a variety of wildlife (Hunter 1999, Kabrick and others 2015). Mixedwood stands may be more resilient to the impacts of climate change and associated factors, such as increased insect pest outbreaks, drought, and severe weather (Griess and Knoke 2011, Guldin 2011, Jactel and Brockerhoff 2007). Mixedwood forests could also help mitigate the impacts of climate change, as ecosystems with more species are more efficient in resource uptake due to different strategies (Kirby and Potvin 2007), suggesting a positive relationship between biodiversity and carbon sequestration (Bunker and others 2005, Caspersen and Pacala 2001). Forest carbon stocks may be enhanced by management promoting compatible species mixtures where productive early-successional and long-lived, late-successional species coexist (Caspersen and Pacala 2001). Managing for mixedwoods may also be an attractive option on small, nonindustrial private holdings and public lands as it offers many ecological and recreational benefits while still being economically viable (Perry and Waldrop 1995, Phillips and Abercrombie 1987, Trammell and others 2017).

Oaks (*Quercus* spp.) are a desired species group for mixedwood management in the West Gulf Coastal Plain due to their high ecological and economic values. An array of flora and fauna depend on oaks for habitat, food, and nutrient recycling (Dey 2014). Oak crown structure, mast production, and leaf litter provide favorable conditions for diverse herbaceous understories which enhance cover and food for important insects and

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small mammals (Dey 2014, Fralish 2004, Phillips and Abercrombie 1987). Maintaining an oak component in mixed pine (*Pinus* spp.)-hardwood forests can help retain soil moisture and reduce soil erosion following heavy cutovers due to remaining oak root mats that provide suitable conditions for stand regeneration (Phillips and Abercrombie 1987). The hydraulic function of the deep root systems of oaks has also been shown to facilitate the survival of co-occurring species during drought conditions (Pretzsch and others 2013). Oaks are also an important timber-producing genus that contributes high commercial value to mixed stands and diversifies timber markets for landowners (Trammell and others 2017). For example, TimberMart-South reported fourth-quarter 2018 stumpage prices for oak sawtimber in southern Arkansas were an average of $378 per thousand board feet (Scribner), compared to pine sawtimber average prices at $183 per thousand board feet (TimberMart-South 2019). Although the production period for oak may be much longer than pine, the nontimber values of oak are often enough for landowners (Haymond 1988, Shelton and Murphy 1997). Some timber-oriented landowners may still reject the idea of retaining an oak component because of the risk of losing pine sawtimber growth. However, oak retention of 15 and 30 square feet per acre in southern Arkansas had no significant effect on total stand merchantable growth and the hardwoods even improved loblolly pine (*Pinus taeda*) stem quality by acting as trainers to the larger pines and contributed to the total merchantable volume growth in a 35-year-old natural stand (Shelton and Murphy 1997).

Understanding neighborhood-scale patterns and competitive status of mixed oaks and pines in the West Gulf Coastal Plain is essential to manipulating a stand for a desired future composition that satisfies landowner objectives. After all, trees in mixedwoods experience a wide range of interactions based on species (for example, inter- and intraspecific competition), successional status, neighboring tree size, and nutrient requirements and uptake strategies than found in monospecific stands (Zhao and others 2006). For example, in closed canopy forests, light is often the most common limiting factor (Hanson and Lorimer 2007, Oliver and Larson 1996, Trammel and others 2017), placing high importance on tree height relative to neighbors. Proximity of competitors also plays a major role in tree competitiveness, especially in high-stocked, even-aged stands where above- and belowground competition may be great (Coates and others 2009, Hanson and Lorimer 2007, Montgomery and others 2010, Wimberly and Bare 1996). In aboveground competition, close proximities restrict an individual's capacity for crown growth, both horizontally and vertically. A considerable amount of research has been conducted to relate live crown ratio (the ratio of crown length to total tree height) to tree vigor (Dyer and Burkhart 1987, Perry and Thill 2003, Rose and others 2012). In southern pine-hardwood stands, pines trade the development of dense crown for height growth to establish an early height advantage, while the slower growing oaks develop denser, laterally expanding crowns to collect sufficient sunlight through the pine upper canopy (Canham and others 2004, Oliver and Larson 1996).

Unfortunately, there is little information on the effects of interspecific competition from neighboring trees on oak competitive status in younger stands, especially in southern pine-hardwood forests. Therefore, the objective of this study is to investigate neighborhood-scale competitive status of oak species in harvest gaps 27 years after gap creation. Specifically, this research will determine if (1) oak competitiveness (explained by total and relative heights, live crown ratio, and percentage of oak subjects in upper canopy positions) is related to neighborhood composition and (2) if that relationship is affected by gap size.

METHODS

Original Study Design

The study site was a 120-acre, second-growth pine-hardwood stand in the Winn District of the Kisatchie National Forest in Grant Parish, LA. The site has an elevation of approximately 130 feet above sea level with 2 to 12 percent slope. The soil type is primarily Cadeville very fine sandy loam with minor components of Mayhew and Metcalf series (USDA NRCS 2017). This soil is moderately well drained with a site index of about 90 feet at a base age of 50 years for loblolly pine. Common pine species from this study were loblolly and shortleaf pine (*P. echinata*). Some common hardwood species were southern red oak (*Quercus falcata*), sweetgum (*Liquidambar styraciflua*), post oak (*Q. stellata*), red maple (*Acer rubrum*), white oak (*Q. alba*), hickory (*Carya* spp.), and blackgum (*Nyssa sylvatica*).

The original experiment (Cain and Shelton 2001) employed a randomized complete block design with three replications of a 3x3 factorial treatment combination with the gap as the experimental unit, yielding 27 experimental units (gaps). The blocks were approximately 40 acres and based on proximity to an intermittent drainage. Each block consisted of nine group openings of three sizes: three 0.25-acre gaps, three 0.625-acre gaps, and three 1-acre gaps. The three opening sizes were selected to create gaps with diameters being about 1.2, 2.0, and 2.5 times the height of the dominant pines on the gap edge (95 feet). Three site preparation methods were tested: chemical, mechanical, and untreated (control). Combinations of gap size and method of site preparation were randomly assigned to gap locations in each block and separated by at least 100 feet from the nearest opening. In October 1991, all merchantable pines and hardwoods were removed to create the harvest gaps. A thinning of only pine sawtimber was conducted in the area between the gaps (in other words, no pine pulpwood or hardwoods were removed) to a residual pine basal area of 75 square feet per acre. Hardwood basal area between gaps averaged 54 square feet per acre.

Current Study Design

We first updated our estimates of expanded gap size by mapping the gap perimeters using a Garmin® GPSMAP® 64s unit (table 1). Expanded gaps consist of the canopy gap plus the adjacent area extending to the bases of canopy trees surrounding the canopy gap (Runkle 1982). Data collection for the present study began in the summer of 2018 in the nine untreated (harvested, no site preparation) gaps. These were chosen because if a private landowner were to seek oak recruitment as part of a mixedwood cohort, they would not spray herbicides or bulldoze within harvest gaps to control hardwoods and promote pine establishment. Crews conducted an exhaustive search for all oak stems at least 3.5 inches in diameter at breast height (d.b.h.), which, hereafter, are called subject trees, in the expanded-gap area of untreated harvest gaps and marked their location with a Garmin® GPSMAP® 64s unit.

For each subject tree (n = 156), species, d.b.h., height (total height and crown base height), and Kraft crown class (dominant, codominant, intermediate, overtopped; Kraft 1884) were recorded, as well as whether the subject tree was of a sprout group. Next, the neighborhood of each subject tree was determined by selecting all trees with crowns immediately competing with the crown of the subject tree. Further, to be considered a neighbor, the top of the competing tree's crown must be equal to or taller than the subject tree's crown base. This implies that if the subject tree is already overtopping a neighbor, then its dominance over that neighbor has already been achieved and, therefore, the neighbor is not influencing the amount of crown space or light received. Hence, we assumed light is the most important limiting factor in this fairly productive site (Coates and others 2009, Hanson and Lorimer 2007, Montgomery and others 2010, Oliver and Larson 1996). Species, d.b.h., height (total height and crown base height), Kraft crown class, and distance from subject tree were also recorded for each neighbor. Heights and distances were measured using a Haglöf vertex IV hypsometer. D.b.h. was measured to the nearest 0.1 inch, and height and distance from subject tree to each neighbor were measured to the nearest 0.1 foot.

Analysis

A cluster analysis was conducted based on the importance values of competitors in each neighborhood to quantitatively determine the appropriate number of differing neighborhood types. Importance value was calculated as:

$$IV_i = \left(\frac{pBA_i + pTPA_i}{2} \right) \qquad (1)$$

where

IV = importance value for species i,
pBA_i = relative basal area (from 0 to 1) within each neighborhood, and
$pTPA_i$ = relative density (from 0 to 1) within each neighborhood.

Relative basal area and relative density were calculated by dividing a species group's basal area and density, respectively, by the sum of all species' basal area and density within each neighborhood. A hierarchical clustering procedure was performed using Euclidean Distance and Ward's Linkage Method. The resulting dendrogram was used to identify multiple clustering solutions based on pruning the longest stems, which yielded three alternatives of three, five, and seven clusters. Following Dufrêne and Legendre (1997), indicator species analysis was used to objectively select a cluster solution. This procedure selects the cluster solution that yields the lowest average p-value and highest number of significant p-values from the Monte Carlo test of significance of observed maximum indicator values. Based on this procedure, a five-cluster solution was selected. The indicator values from the indicator analysis were compared to the importance values of competitors within each respective cluster to reveal strong similarities between the indicator values and importance of species within each cluster. Neighborhood types were based on importance values.

Table 1—Kisatchie National Forest average gap metrics based on actual gap sizes measured in 2016 and 2017

Gap size	Gap area	Gap diameter	Canopy height	Diameter:Height
	acres	*feet*	*feet*	
Small	0.33	137	100	1.37
Medium	0.70	203	108	1.88
Large	1.15	259	108	2.40

Effects of neighborhood composition (neighborhood type) and gap size on the status (competition index, total height, relative height (the height of subject tree relative to the mean height of neighbors), and live crown ratio (the ratio of crown length to total tree height)) of red oaks (section *Lobatae*), white oaks (section *Quercus*), and all oaks combined were assessed (see table 2 for species in red and white oak groups). Unfortunately, this study lacked sufficient sample size and balance to rigorously test for interactions between gap size and neighborhood type; therefore, interpretations were based on observation of main effects. Hegyi's (1974) distance-dependent competition index was chosen as it has been shown to be an effective method for evaluating crowding in fully stocked, mixed-species stands (for example, Holmes and Reed 1991, Lorimer 1983, Wimberly and Bare 1996):

$$CI = \sum_{j=1}^{n} \frac{D_j / D_i}{\mathrm{DIST}_{ij}} \tag{2}$$

where

CI = competition index,
D_j = diameter of competitor tree *j,*
D_i = diameter of subject tree *i,*
DIST_{ij} = distance between trees *i* and *j, and*
n = total number of competitors.

Competition index, gap size, and neighborhood type were used to explain effects on relative height and live crown ratio for all oaks combined and red oaks and white oaks separately. Generalized linear models were run in R 3.4.3 using a quasi-binomial distribution and an alpha level of 0.05. The three predictor variables were also used to explain effects on subject tree total heights using PROC GENMOD in SAS® 9.4 with a normal distribution, identity link, and an alpha of 0.05.

RESULTS

A total of 156 subject trees and corresponding neighborhoods were recorded (85 red oaks, 71 white oaks; table 2) with an average competitive influence zone radius of 12.8 feet. Neighborhood types were determined by the species importance values that make up the majority of the neighborhood (table 3). Composition of the five neighborhood types from cluster analysis were defined as: pine, pine-sweetgum,

Table 2—Number of subject trees of each *Quercus* species and species group by gap size in the nine untreated gaps on the Kisatchie National Forest, Louisiana

	Gap size			
Species/group	Small	Medium	Large	Total
Q. alba	10	10	41	61
Q. stellata	1	7	2	10
White oak group	11	17	43	71
Q. falcata	0	1	1	2
Q. nigra	11	13	18	42
Q. pagoda	6	13	22	41
Red oak group	17	27	41	85

Table 3—Importance values and indicator values of species groups within each neighborhood type

	Neighborhood type				
Species group	Pine	Pine-sweetgum	Pine-oak	Mixed hardwood-pine	Oak
Importance value					
Pine	0.83	0.54	0.46	0.18	0.01
Sweetgum	0.04	0.20	0.05	0.10	0.03
All oaks	0.05	0.09	0.34	0.27	0.76
Tolerant hardwoods	0.08	0.16	0.12	0.43	0.19
Other	<0.01	0.01	0.02	0.03	0.01
Indicator value					
Pine	0.42	0.26	0.23	0.07	0.00
Sweetgum	0.04	0.45	0.05	0.12	0.02
All oaks	0.01	0.07	0.40	0.40	0.92
Tolerant hardwoods	0.07	0.20	0.14	0.87	0.14
Other	<0.01	0.03	0.08	0.06	0.03

The all oaks species group consisted of sampled oaks in the red oak group and white oak group.

Tolerant hardwoods included red maple, blackgum, and American holly, and a mix of red oaks and white oaks.

pine-oak, mixed hardwood-pine, and oak. The mixed hardwood component comprised mainly shade-tolerant hardwoods, including red maple, blackgum, and American holly (*Ilex opaca*), and a mix of red oaks and white oaks.

The number of red oak and white oak subject trees were fairly consistent among each neighborhood type (table 4). Each species group had the most subjects located in pine-oak neighborhoods. Each species group had the fewest subjects located in pine and oak neighborhoods; however, red oaks had double the number of subjects in pine neighborhoods compared to white oaks. As for pine-sweetgum and mixed hardwood-pine neighborhoods, the two species groups had no more than a difference of two subjects (table 4). Of the 156 neighborhoods, most were classified as pine-oak while far fewer pine and oak neighborhoods were recorded (table 4).

Heights of red oak and white oak subjects were generally equal to or slightly lower than the mean heights of their neighborhoods (fig. 1). Height distributions show oaks, including subject trees, mainly occupied the middle range of height classes from 25 to 75 feet (fig. 1). However, in oak neighborhood types, oak subjects reached into the 85-foot height class. Pines tended to dominate larger size classes, especially in pine-dominated neighborhoods, whereas pines were scarcer in larger height classes in hardwood-dominated neighborhoods. Tolerant hardwoods were concentrated in lower height classes. Sweetgum tended to occupy similar height classes as oak subjects; however, the number of sweetgum stems usually greatly outnumbered subjects in respective classes. Stems in the greater-than-85-foot height classes were border trees located on gap edges in the mature forest, or matrix, surrounding the gaps. These trees were not of the gap cohort. Pine-dominated neighborhoods contained the most border trees greater than 85 feet tall (these were usually pines). Hardwood-dominated neighborhoods contained fewer border trees, and these were usually hardwoods.

Results from the generalized linear models testing the effects of competition index, gap size, and neighborhood type on the relative height of subject red oaks, white oaks, and all oaks combined found no significant effects. However, gap size was a significant predictor of red oak live crown ratio, and neighborhood type was a significant predictor of all-oak live crown ratio ($p < 0.05$; table 5). Red oak live crown ratios were significantly greater in small gaps compared to large and medium gaps, averaging 0.52 compared to 0.43 and 0.42, respectively. For all oaks combined, subject tree live crown ratios were significantly lower in pine neighborhoods when compared to those in pine-sweetgum. Oak subject live crown ratios in pine neighborhoods averaged 0.41 when compared to 0.50 in pine-sweetgum, 0.49 in pine-oak, and 0.52 in oak. Subject live crown ratios in oak neighborhoods were significantly greater than in mixed hardwood-pine neighborhoods, averaging 0.52 versus 0.45, respectively.

DISCUSSION

The neighborhood types determined from the cluster analysis reflect the relatively diverse tree species composition of this pine-hardwood forest. These neighborhood types also reflect local, within-gap variation, as pockets of different species mixtures are distributed among the gap depending on gap size and position within the gap. This compositional variability is typical of earlier stages of secondary succession in West Gulf Coastal Plain forests where early- and late-successional species coexist (in other words, initial floristics composition; Egler 1954). The fast-growing, shade-intolerant pines are the early-successional group that initially achieves dominance following intermediate to severe canopy disturbances (Runkle and Yetter 1987, Trammell and others 2017, Weber and others 2014). This pattern is evident in this study where pine makes up four of five neighborhood types and is dominant in three. As cohorts approach the stem exclusion stage, the dominant pines begin to relegate many of the hardwoods to subordinate positions. The oak and the sweetgum maintain similar height growth rates and compete in the

Table 4—Number of red oak and white oak subject trees within each neighborhood type

	Number of subject trees		
Neighborhood type	Red oak group	White oak group	All oak
Pine	12	6	18
Pine-sweetgum	16	18	34
Pine-oak	32	24	56
Mixed hardwood-pine	18	17	35
Oak	7	6	13
Total	85	71	156

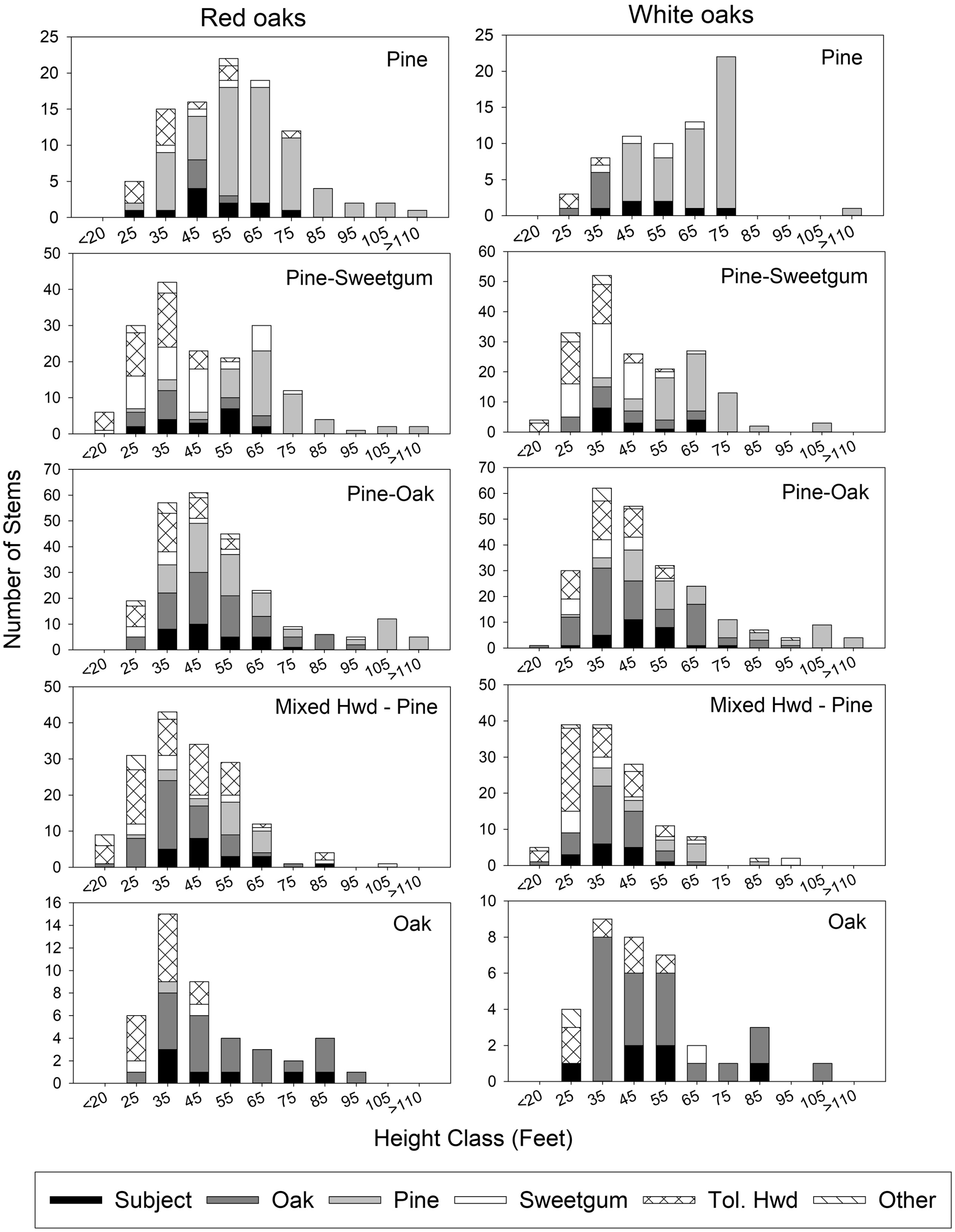

Figure 1—Number of stems in each height size class of subject trees relative to neighbors within each neighborhood type. Subject refers to subject oak trees and Tol. Hwd refers to the tolerant hardwood species group.

Table 5—*p*-values from the generalized linear models testing the effects of competition index, gap size, and neighborhood type on live crown ratio of red oaks, white oaks, and all oaks combined

Species group	Competition index	Gap size	Neighborhood type
Red oaks	0.528	0.020	0.266
White oaks	0.144	0.639	0.050
All oaks	0.138	0.124	0.012

lower canopy layers until eventually the hardier crowns of oak outcompete sweetgum (Clatterbuck and Hodges 1988, Oliver and Larson 1996). The most shade-tolerant hardwood species in Coastal Plain forests (blackgum, red maple, American beech [*Fagus grandifolia*], and American holly) are also the slowest growing, yet are capable of surviving beneath multiple canopy strata. However, oaks appear to be faring well in harvest gaps. Oaks are a major component in two of five neighborhood types and make up a considerable portion of the mixed-hardwood type. As these gap cohorts mature, many of the oaks will eventually attain upper canopy positions as the dominant pines senesce and begin to drop out of the overstory (Clatterbuck and Hodges 1988, Lloyd and Waldrop 1993, Weber and others 2014).

Oak subjects in pine neighborhoods had significantly lower live crown ratios than in pine-sweetgum, pine-oak, and oak neighborhoods. This may be attributed to the differences in crown characteristics that allow oaks and pines to coexist. The crowns of shade-intolerant pines allow for more light to penetrate through the upper canopy to the competing oaks (Canham and others 1994). Given that crown ratio is related to tree vigor (Dyer and Burkhart 1987), the greater live crown ratios in pine-sweetgum, pine-oak, and oak neighborhoods compared to pine neighborhoods from this study suggest that oak vigor is greatest in mixed-species neighborhoods rather than pure pine neighborhoods. Oak competitiveness may be increased with an increasing conspecific component, as evident in this study where the rates of increased live crown ratios relative to pure pine neighborhoods were greatest in oak neighborhoods, followed by pine-oak and pine-sweetgum, respectively. In addition, crown ratios in oak neighborhoods were significantly greater than in mixed hardwood-pine.

Live crown ratios of red oak subjects were greatest in small gaps when compared to medium and large gaps. This is likely due to the smaller openings favoring release of lower canopy oaks, rather than increasing light levels that favor establishment of pine. Larger group openings tend to reset successional trajectories and favor shade-intolerant species, while smaller openings are more likely to accelerate succession and favor shade-tolerant species (Prévost and Raymond 2012, Rantis and Johnson 1998, Trammell and others 2017). Harcombe and others (2002) found larger canopy disturbances promoted shade-intolerant species recruitment into the upper canopy and enriched the understory in shade-tolerant species. Shade-intolerant sapling density has also been noticed to increase with gap size (Perry and Waldrop 1995, Weber and others 2014) which could impose greater competition on oak stems. This study site in particular has seen this effect, where results of another investigation of this site show significant increases in pine and sweetgum density and basal area with increasing gap size. As opposed to white oaks, where no significant effects of gap size on live crown ratio were detected, red oak live crown ratio was largest in small gaps, suggesting red oaks benefited from the creation of smaller harvest openings. The percentage of upper canopy red oak subjects across the stand was greater when compared to the percentage of upper canopy white oaks in this study, further signifying greater competitiveness of red oaks versus white oaks at this stage of stand development.

In the Southern United States, making decisions at a neighborhood scale based on successional status of available species may aid in achieving desired stand conditions (Canham and others 2006, Coates and others 2003). Some studies have shown species of different shade tolerances have different effects on target trees (Zhao and others 2006); therefore, management that reduces direct competition from target species will have greater effects on achieving desired stand composition (Murphy and others 1993). Based on this study, managers in this region should consider timber stand improvement earlier in gap-cohort development if faster recruitment of oaks into larger size classes is desired (Murphy and Ehrenreich 1965). These entries should target neighboring dominant pine and competing sweetgum to allocate growing space to released oaks (Blair and Enghardt 1976). This may also benefit future oak mast production and increase oak basal area (Perry and Thill 2003, Rose and others 2012). Targeting larger pines could also provide timber-based revenue to the landowner, although this would require that the volume selected to cut meets the requirements for a timber sale; otherwise, this may not be a feasible option.

CONCLUSIONS

This study found a high diversity of neighborhood types within these earlier-successional group openings, supporting the initial relay floristics model, which states stands in the earlier stages of secondary-succession tend to accommodate early- and late-successional species. In addition, oak competitiveness may be increased with an increasing conspecific component within their neighborhoods given the higher live crown ratios of oak subjects in mixed-species neighborhoods compared to lower live crown ratios of oak subjects in pine-dominated neighborhoods. Subject trees in the red oak group were generally more competitive when compared to those in larger gaps, possibly due to lower light conditions initially suppressing pine dominance after gap creation, giving red oaks a competitive advantage. Managing southern mixedwoods may depend on making decisions at the neighborhood scale to achieve desired stand conditions. Nonetheless, this study provided an early framework for future experiments to examine longer term oak competitiveness in harvest gaps. For instance, additional studies could be conducted to better explain the effects of gap size and neighborhood competition on oak competitiveness. Future research may also include sampling oaks across a wider range of size classes to gain a better sense of oak's true competitiveness at the neighborhood scale.

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OAK REGENERATION SUCCESS IN OPERATIONAL SHELTERWOOD CUTS: YEAR TWO RESULTS

Andrew B. Self, John L. Willis, and Andrew W. Ezell

Abstract—The efficiency of shelterwood cutting in providing natural regeneration of bottomland oaks (*Quercus* spp.) is well documented. Typically, assuming environmental conditions are satisfactory, research projects yield adequate regeneration levels for targeted oak species. However, skepticism is often encountered when promoting the method for commercial operations in landowner management practices. Much of this hesitancy results from observing insufficient levels of oak regeneration after application of poor management technique. This study assesses viability of the system when established under operational constraints. A post-regeneration-cut bottomland hardwood stand was selected near Starkville, MS, to evaluate second-year oak regeneration response. This partial harvest study area was embedded inside a larger commercial harvesting operation. No special provisions for research were employed. Initial stand age was 86 years, the overstory was dominated by oak species, initial stand basal area (BA) was 115 square feet per acre, and residual post-harvest BA was 48 square feet per acre. Midstory injection was performed 1 year prior to regeneration cutting in an attempt to limit resprout potential of shade-tolerant species. Little research evaluating regeneration response at ground location in relation to crown location has been performed in bottomland hardwood systems. Consequently, three ground locations were selected based upon crown radius for evaluating regeneration response. These locations were half of crown radius, straddling dripline, and 25 feet outside dripline. Year two regeneration results for eight oak species are presented.

INTRODUCTION

A common challenge encountered when attempting to obtain adequate advanced oak (*Quercus* spp.) regeneration in closed canopy bottomland hardwood forests is that of obtaining sufficient levels of light for seedlings (Abrams 1992, Peairs and others 2004). Combinations of overstory and midstory vegetation often limit available light in these stands to levels below 10 percent (Jenkins and Chambers 1989, Lockhart and others 2000). These low light levels on the forest floor are often below the compensation point required for photosynthesis in oaks (Hanson and others 1987) and successful oak regeneration is often limited. Consequently, some form of overstory and/or midstory removal is the first step in increasing light levels to those required by oak seedlings for germination, survival, and growth. Partial harvesting in the form of shelterwood cutting is often prescribed as a viable regeneration system for obtaining satisfactory results in natural regeneration efforts with oaks (Bellocq and others 2005, Hodges and others 2005, Johnson and others 2009).

Regeneration success in bottomlands using the combination of midstory control and partial harvesting is well documented (Barry and Nix 1993, Guttery 2006, Janzen and Hodges 1987, Peairs and others 2004). Research efforts in bottomland hardwood systems have suggested that an optimal basal area (BA) target would be close to 50 square feet per acre when implementing partial harvesting to maximize regenerated seedling densities. Gardiner and Hodges (1998) observed oak seedlings require an available light level exceeding 25 percent for seedling survival in a shade cloth study. The authors also found seedling height and root-collar growth to be maximized at 53 percent sunlight. Peairs and others (2004) and Cunningham and others (2011) offered field corroboration of these results by observing that a residual BA of 50 square feet per acre combined with midstory control yielded the greatest oak seedling density in partial harvesting operations. These and similar findings have resulted in the common recommendation for a prescription combining partial harvesting and midstory control for natural regeneration in bottomland hardwood efforts. However, due to regeneration failures observed sometimes in operational settings, many land managers are reluctant to attempt the process.

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An additional, relatively unstudied, aspect of acorn production and the subsequent regeneration response in bottomland hardwoods centers around seed location and dispersal from parent tree crowns. Little investigation regarding oak regeneration as a function of position in relation to parent tree canopy has occurred. Acorn production occurs in younger portions of outer branches and twigs (Johnson and others 2009). In addition, greatest acorn production typically occurs on branches exposed to sunlight (Post 1998, Sharp and Sprague 1967), and in lower and mid-crown positions (Lewis 1992). Accordingly, greater acorn fall, and subsequent seedling production, is thought to occur near the dripline edge. The intent of this research was to evaluate regeneration establishment during operational shelterwood harvesting in bottomland hardwoods and to evaluate regeneration density by ground location in relation to parent tree crown.

MATERIALS AND METHODS

Site Description

A bottomland hardwood stand on the John W. Starr Memorial Forest near Starkville, MS, was selected for regeneration using the shelterwood system. Species composition, major topography, flooding regime, and soil series were similar across the area used in this study. Soil series was Mathiston silt loam and soil analysis indicated an average pH of 5.3. Estimated site index values (Baker and Broadfoot 1979) totaled 113 feet for cherrybark oak (*Q. pagoda*), 103 feet for Shumard oak (*Q. shumardii*), water oak (*Q. nigra*), and willow oak (*Q. phellos*), and 95 feet for swamp chestnut oak (*Q. michauxii*). Study plots were embedded inside a larger 200-acre commercial harvest sale area. Initial stand age was 86 years, the overstory was dominated by oak species, and initial stand BA was 115 square feet per acre.

Treatments

The intent of this study was to evaluate effectiveness of the shelterwood system in obtaining adequate oak regeneration under operational constraints; no special provisions for research were employed. All overstory and midstory stem manipulation was performed by non-research personnel and the intention to use the area for future research was not conveyed to logging contractors. Leave timber was marked by Mississippi State University Forest Operations personnel with the goal of retaining healthy, good form oaks at a residual BA of 50 square feet per acre. Harvesting was performed by an operational logging crew and occurred September through October 2015. Post partial harvest inventory estimated an average residual BA of 48 square feet per acre. Primary residual overstory species included cherrybark oak, water oak, willow oak, swamp chestnut oak, white oak (*Q. alba*), and sweetgum (*Liquidambar styraciflua*). Shumard oak and overcup oak (*Q. lyrata*) constituted a small component of residual stand BA. Midstory control was performed during October 2014 using the "hack and squirt" method with a 20 percent aqueous solution of a 52.6 percent imazapyr product. Midstory stems greater than 1 inch in diameter at breast height (d.b.h.) were targeted, resulting in the near elimination of midstory stems. Very few living midstory stems were present at initiation of this project. These included approximately 10 stems per acre of shade-tolerant species including red maple (*Acer rubrum*), American hornbeam (*Carpinus caroliniana*), and elm (*Ulmus* spp.). Due to previous overstory and midstory canopy closure, as well as logging disturbance, very little ground cover vegetation, including advanced oak regeneration, was present.

Study Design

Four stems of seven oak species were selected based on proximity to other trees, crown health and fullness, crown size, and distribution across the site. Oak species selected for evaluation were Shumard, water, willow, and cherrybark oak from the red oak functional group and white, overcup, and swamp chestnut oak from the white oak functional group.

The crown edge of individual trees selected was required to be a minimum of 100 feet from the crown edge of any tree of the same species. This stipulation was designed to eliminate skewing of regeneration estimates resulting from greater than normal acorn drop due to influx from multiple crowns. In addition, crowns were evaluated for health and fullness, with tree inclusion only occurring if the crown was determined to satisfactorily meet both qualifications. In addition, crown size was considered and if crown radius was not suitable for appropriate placement of regeneration subplots in at least three directions, the tree was deemed insufficient and was not used in this study.

Three lines of three, 9-foot-radius (0.006-acre) regeneration subplots were established based on relationship with live tree crown (fig. 1). Subplots were placed along lines positioned to fall directly underneath the crown where appropriate. Subplots were placed along lines at three locations based upon ground location in relation to mother tree crown radius. These locations were A (subplot center placed at half of crown radius from trunk), B (straddling crown dripline), and C (25 feet outside of crown dripline).

Oak Regeneration Measurements

Initial oak regeneration estimates were recorded during September 2015 and indicated an oak seedling density of eight seedlings per acre (SPA). Second year regeneration data were collected October 2018. Only seedlings of the species corresponding to the overhead mother tree were recorded in each subplot.

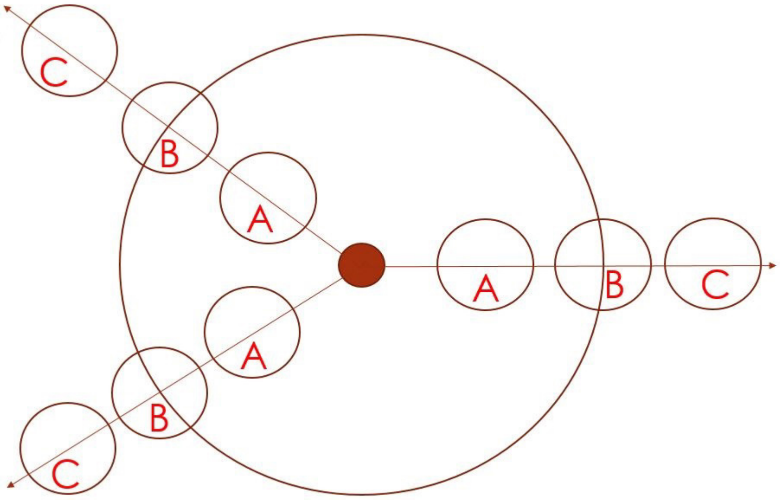

Figure 1—Relationship between regeneration subplots and tree crown.

Oak seedlings falling inside subplot boundaries were classified into height categories and recorded. Height classifications were less than 1 foot, 1 to 3 feet, and greater than 3 feet. Stocking calculations were performed using the stocking point system developed by Belli and others (1999). This stocking point system estimates the probability of one "free to grow" seedling 3 years after harvest. Using this system, a point total of 34 yields a 95 percent probability of at least one "free-to-grow" seedling/sapling at the end of the third growing season.

Data Analysis

Regeneration of oak species was pooled by red or white oak functional group to obtain seedling density by subplot ground location. Low seedling density in white oak species limited useful information when separated into the three subplot locations at the individual species level. Consequently, individual species calculations assessed species regeneration as a whole without separation into subplot locations. Regeneration height was used to calculate stocking point values and probability estimations using methodology established by Belli and others (1999).

RESULTS AND DISCUSSION

Second-year red oak regeneration was observed in greater abundance compared to white oak regeneration at the corresponding subplot location (table 1). An unseasonable April 2016 freeze occurred at the study area. It is possible that freezing temperatures during this period damaged white oak flowers which in turn lowered mast production and subsequent acorn germination during the 2016 growing season. Other literature has noted reduced or failed white oak seed crops in years when late spring freezes occurred (Cecich and Sullivan

Table 1—Seedlings per acre, stocking, and probability of regeneration success by oak functional group and regeneration subplot location

Functional group	Subplot location	Seedlings	Stocking points	Probability
		number per acre		*percent*
Red oak	A	2,145	44	95+
	B	2,361	59	95+
	C	1,434	43	95+
White oak	A	1,201	29	92
	B	863	24	88
	C	220	7	46

A = subplot center placed at half of crown radius from trunk, B = subplot center straddles crown dripline, C = subplot center located 25 feet outside of crown dripline.

Seedlings per acre and stocking points are averaged for that specific functional group/location combination.

Stocking point values calculated using method developed by Belli and others (1999).

Probability is likelihood of one "free-to-grow" tree at 3 years.

1999, Sharp and Sprague 1967). In addition, mammal species are known to preferentially select white oak acorns over those of red oaks due to lower tannin contents (Kirkpatrick and Pekins 2002, Robbins and others 1987, Short 1976). Decreased white oak seedling production is a logical assumption in cases of heavy white oak predation. The presence of white-tailed deer (*Odocoileus virginianus*) across the study area was apparent in the form of both tracks and browsing evidence. It is possible that lower white oak regeneration compared to that of red oaks was a result of one of these factors, or a combination thereof.

Observed SPA for red oak regeneration at A and B subplot locations was similar with greater SPA compared to C subplot locations; however, stocking point calculations at the B location were substantially higher compared to the other two locations (table 1). Regardless, stocking probabilities for all three red oak subplot locations exceeded 95 percent and thus indicated that regeneration levels were sufficient for future overstory recruitment in this particular study.

White oak regeneration followed a different trend with greatest SPA at A subplot locations, followed by nearly a third less regeneration at B subplot locations, and only 220 SPA at C locations (table 1). Stocking points followed a similar pattern, yet were at a level considered satisfactory in A and B subplot locations (92 percent and 88 percent, respectively), but fell to a level (7 points) where future regeneration was questionable in C subplot locations (46 percent probability).

While low seedling density of white oaks precluded splitting regeneration data for individual species comparisons into the three tested locations, an interesting observation arose when considering regeneration as a whole by species. Stocking point calculations indicated all seven species had been regenerated to at least a 50 percent probability of one “free-to-grow” seedling 3 years after partial overstory harvesting (table 2). When regeneration was evaluated by individual species, with the exception of swamp chestnut oak (50 percent probability), all individual species exhibited levels of regeneration considered acceptable (at least 71 percent probability) for considering the operation a success (table 2). This finding indicates that while white oak regeneration may be more clumped, regeneration of six of the seven species evaluated in this study would be considered sufficient for stand establishment on an individual species basis alone. Consequently, considering the likelihood of this regeneration being coupled with overlapping regeneration from adjacent stems of alternate oak species, realistic expectations of regeneration success are drastically increased.

CONCLUSIONS

This study was designed to evaluate oak regeneration response utilizing operational shelterwood cutting and to determine where regeneration established underneath oak crowns. Regeneration of both red and white oak species was more than adequate for establishment of a future oak-dominated forest. Red oak regeneration was deemed successful both underneath and outside of parent tree crown radius while white oak regeneration was considered successful only at positions underneath and straddling crown dripline. However, considering bottomland hardwood stands typically comprise a mixture of species and an influx of additional seedlings from adjacent trees is expected, natural regeneration using partial harvesting was successful and provided a sufficient level of advanced oak regeneration for the future in this study.

Table 2—Seedlings per acre, stocking, and probability of regeneration success by individual species

Functional group	Species	Seedlings	Stocking points	Probability
		number per acre		*percent*
Red oak	Shumard oak	863	14	71
	Water oak	2,031	64	95+
	Willow oak	1,269	36	95+
	Cherrybark oak	1,777	38	95+
White oak	White oak	385	26	90
	Overcup oak	141	14	71
	Swamp chestnut oak	114	8	50

Seedlings per acre and stocking points are averaged from subplot data at all subplot locations for that species.

Stocking point values calculated using method developed by Belli and others (1999).

Probability is likelihood of one “free-to-grow” tree at 3 years.

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RETENTION TREE SURVIVAL TRENDS IN BURNED AND UNBURNED AREAS MANAGED USING THE IRREGULAR SHELTERWOOD METHOD

David C. Clabo and Wayne K. Clatterbuck

Abstract—Survival of individual stems selected as retention trees in irregular shelterwoods is important as these stems are expected to remain for 20 percent or longer of the subsequent rotation. In mountainous terrain where windstorms may occur regularly and prescribed fire may be utilized to improve regeneration composition, survival of retention trees becomes less certain. An upland, mixed hardwood stand in Morgan County, Tennessee, received an irregular shelterwood harvest and a burn or no-burn treatment between 2014 and 2016. Retention tree assessments were made 3.5 years post-harvest and 2.5 years post-burn to allow for delayed individual stem mortality to occur. Results indicated greater mortality of retention trees in the burn treatment, but no differences in slope positions across treatments. Windthrow mortality ranged from 4.0 to 7.6 percent across all slope positions in the two treatments. Red oak species (*Quercus* spp., Section *Lobatae*) and conifer species had a higher probability of mortality than the yellow-poplar (*Liriodendron tulipifera*) reference group. Managers should select desirable retention trees that avoid possible tree mortality and damage from logging and prescribed burns when implementing irregular shelterwoods in aging hardwood stands.

INTRODUCTION

The irregular shelterwood, or shelterwood with reserves, regeneration method is a two-age or uneven-aged regeneration method where individual or groups of trees are left on site (Ashton and Kelty 2018). Typically, an average basal area from 10 to 40 square feet per acre is left in retention trees, and these trees are expected to remain for at least 20 percent of the subsequent rotation or longer (Johnson and others 1998, Nyland 2007). This method is used to retain trees on site that have the potential to increase in value, produce seed, create variable vegetation structure for wildlife, enhance structural diversity, and provide intermediate shade conditions for regenerating stems (Johnson and others 2009, Nyland 2007). Aesthetics may also be improved over clearcutting on highly visible sites such as mountainous terrain. Windthrow is a concern with this regeneration method, especially in mountainous terrain where slopes and ridges are exposed regularly to high winds.

Prescribed fire has been documented as a viable treatment in uncut stands and oak (*Quercus* spp.) shelterwoods to promote oak regeneration and establishment when oak seedlings and saplings are present (Barnes and Van Lear 1998, Brose and others 1999, Van Lear and Brose 2002). Information on overstory tree survival and condition following such burns is limited. Stands that have not been burned in many years, or stands that have an abundance of woody fuels following a shelterwood harvest are more likely to burn more intensely and have adverse effects on overstory trees that are intended to remain for an extended period of time as retention trees. Minimal information is available on retention tree survival on sites in the Cumberland Plateau or Cumberland Mountains physiographic regions following irregular shelterwood harvests where prescribed burning may or may not be utilized.

OBJECTIVES

The objectives of this study were to (1) monitor survival and mortality of reserve trees following an irregular shelterwood harvest in areas with and without prescribed burning, (2) compare retention tree survival across three slope positions in burned and unburned areas, and (3) assess reserve tree survival probability differences by species group and diameter class in burned and unburned areas.

METHODS

Study Site

The study site was located on a 76-acre property owned by the University of Tennessee, Forest Resources Research and Education Center in Morgan County, Tennessee (36.053955° N, -84.435428° W). This site was located on western and northwestern flanks as well as ridgetop positions of Little Brushy Mountain,

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which is near the southern terminus of the Cumberland Mountains Physiographic Province (Smalley 1984). Elevations ranged from 1,280 to 1,840 feet. Parent materials consisted of shale and siltstone, while soil series included the Gilpin-Boulin-Petros complex with varying percent slopes (USDA NRCS 2017, Wilson and others 1956). These soils were rocky silt loams, loams, and clay loams, and depth to bedrock ranged from 25 to 43 inches. Site indexes for shortleaf pine (*Pinus echinata*) and black oak (*Quercus velutina*) were 60 feet at base age 50 years and 90 feet (base age 50 years) for yellow-poplar (*Liriodendron tulipifera*) (Beck 1962, Martin 1966, Olson 1959, USDA NRCS 2017). The mean annual temperature was 55.9° F, and the region averaged 54 inches of precipitation annually with autumn as the driest season (NOAA 2017). The site had remained relatively undisturbed since the university conducted a stand improvement harvest in 1949 on a portion of the stand, except for cyclical southern pine beetle (*Dendroctonus frontalis*) outbreaks, which reduced the shortleaf and Virginia pine (*P. virginiana*) components across the stand. The most recent bark beetle outbreak occurred from 1999 through 2002 across the State (Cassidy 2004).

Vegetation on the site prior to harvest operations consisted mostly of mixed species upland hardwoods. Common overstory species included black oak, white oak (*Q. alba*), scarlet oak (*Q. coccinea*), chestnut oak (*Q. montana*), mockernut hickory (*Carya tomentosa*), yellow-poplar, and red maple (*Acer rubrum*). Common midstory and understory species included sourwood (*Oxydendrum arboreum*), sassafras (*Sassafras albidum*), blackgum (*Nyssa sylvatica*), serviceberry (*Amelanchier arborea*), eastern white pine (*P. strobus*), and mountain laurel (*Kalmia latifolia*). The site averaged 7,108 board feet per acre sawtimber (Doyle log rule form class 78). A commercial harvest began in October 2014 and was completed in April 2015.

Plot Layout and Measurements

Retention trees were marked during summer 2014 prior to the beginning of harvest operations. Oak and hickory species as well as shortleaf pine were preferred retention trees (with less desirable species such as sourwood and sassafras marked when those species were not present) so that approximately 15-20 square feet per acre basal area would remain following the harvest. Individual stems with at least intermediate crown classes, healthy appearance (no sign of stem or crown damage as well as crown dieback), and diameters between 4 and 14 inches were targeted as retention trees. Harvest occurred in fall of 2015. The site averaged 1,550 board feet per acre (Doyle log rule form classes 78 and 80) and 67 square feet per acre of basal area following the harvest as many marked take trees were left by the logging crew (table 1). Access to some areas of the stand was limited by steep topography, and wet weather during the winter of 2014-2015 prevented work from occurring for days at a time. The logging crew had to be off the site by April 1, 2015 for planting. During summer 2015, 300 variable-radius plots (10-factor prism) were established at random throughout the study site. All trees were identified to species and measured for diameter at breast height (d.b.h.). In addition, slope position and elevation were recorded at each plot location. Three slope position classifications were devised to characterize plot elevations: lower slope (1,280 to 1,380 feet), middle slope (1,380 to 1,670 feet), and upper slope (1,670 to 1,840 feet) positions.

Table 1—Pre- and post-harvest basal area, sawtimber volume, and pulpwood weight averages per acre for the irregular shelterwood study located in Morgan County, Tennessee

Timing	Basal area	Sawtimber	Pulpwood
	per acre	*vol per acre*	*tons per acre*
Pre-harvest	97	7,100	22.6
Post-harvest	67	1,550	20.6

Burn treatments were completed over 3 days during March 2016. Fuel loadings were variable across the burn areas due to the partial logging operation, but were most represented by Anderson's (1982) fuel model 11 for light slash. Due to the steep topography of the site, burns were first ignited as backing fires from higher elevation positions and allowed to burn down slope before flanking fires were ignited. The burns had 100 percent coverage and 32.4 acres of the 76 total acres were burned. Weather conditions for each of the 3 burning days are presented in table 2.

Retention tree plots were re-located and assessed during fall 2018 approximately 3.5 years post-harvest and 2.5 years post-burn to allow for possible delayed mortality to occur. While personnel limitations and time restraints prevented all plots from being redone, 154 of the original 300 plots were randomly selected and re-measured, with approximately 50 plots located at each slope position. Seventy-four plots were located in the burn treatment and 80 were in the no burn treatment. All retention trees were measured and assessed for d.b.h., stem damage (living trees only), and probable cause of mortality was noted for stems that were recorded as alive during the pre-burn inventory. In burn treatment plots, bark blackening or scorch greater than 10 feet up the tree bole as well as evidence of crown and root scorch were used as indicators for heat-related mortality. Bole blackening or scorch was defined as black discoloration on fissures and ridges of bark as well as noticeable pitting, consumption, or removal of bark on the bole (Loomis 1973). For hardwood species such as oaks and hickories, scorch more than 10 feet high on the bole of stems with a d.b.h. between 5 and

Table 2—Weather variables by date for the burn treatment for the irregular shelterwood study located in Morgan County, Tennessee

Date	Time	Temperature	Relative humidity	Wind speed	Wind direction	KBDI
		degrees F	*percent*	*miles per hour*		
March 17, 2016	5:00-7:00 PM	65-70	14-18	6.9-8.1	W	<300
March 18, 2016	12:00-7:00 PM	64-70	18-23	0.0-8.1	Variable	<300
March 20, 2016	1:30-5:30 PM	71-76	22-29	5.8-11.5	SSE-SSW	<300

KBDI = Keetch-Byrum Drought Index.

16 inches is associated with a probability of mortality exceeding 50 percent (Loomis 1973). If a tree had both visible stem and/or root scorch and was windthrown, the cause of mortality was classified as both. Stems that were topkilled but had resprouted were tallied as alive. In no-burn treatment areas, stems with obvious signs of windthrow mortality (uprooted and/or broken stem) were noted as wind-related mortality. Stems in both treatment areas that were dead but did not have any obvious wind or heat related damage were classified as other for the mortality cause. Trees that were damaged but still alive were classified as damaged.

Statistical Analyses

Percentage of stem deaths by windthrow, fire, both, or other causes as well as stem damage (live trees) were reported by treatment (*n* = 1,029 stems assessed). Retention tree survival (both those marked as retention trees prior to harvest and those that were left by the logging crew) was analyzed using analysis of variance (ANOVA) as a two-way factorial treatment design. Treatment (burn or no burn) and slope position (low, middle, or high) were fixed factors, while plot was considered a random factor. Fisher's protected least significant difference test was used for all pairwise comparisons of least-squares means to detect survival differences in treatments and slope positions. The binomial distribution was used for all survival analyses. ANOVA analyses were conducted in SAS© 9.4 using the Proc Mixed procedure (Littell and others 2006).

Multiple logistic regression was used to assess residual tree mortality probability by species group, diameter class, and treatment using Proc Logistic and the logit link function in SAS© 9.4. All statistical tests were conducted at an α = 0.05 significance level. Species groups for the regression analysis included blackgum, conifers (eastern white pine, and eastern hemlock (*Tsuga canadensis*)), yellow-poplar, white oaks (white and chestnut oak), red oaks (northern red oak (*Q. rubra*), black oak, and scarlet oak), red maple, and other hardwoods (sourwood, hickory spp., sugar maple (*Acer saccharum*), sweetgum (*Liquidambar styraciflua*), American beech (*Fagus grandifolia*), sassafras, and black birch (*Betula lenta*)).

RESULTS

The number of stems 2 inches or greater pre-burn averaged 239 trees per acre while 2.5 years post-burn the site averaged 161 trees per acre. Basal area per acre pre-burn averaged 67.5 square feet per acre and was reduced to 51.4 square feet per acre 2.5 years post burn. The burn reduced the number of trees per acre in the 2-inch and greater diameter class by 32.7 percent and basal area per acre was reduced by 23.8 percent. Nearly 30 percent of the trees that were assessed in the burn treatment areas were killed by heat-related causes, and 5.6 percent of stems had damage (table 3). Wind-related mortality was the leading cause of death in the no-burn treatment, while fewer stems had damage than the burn treatment. The red oak and the other hardwood species groups had the most wind-related mortality across all

Table 3—Number and percent of dead stems by mortality causal factor and treatment 3.5 years post-harvest and 2.5 years post-burn for the irregular shelterwood study located in Morgan County, Tennessee

		Mortality factor				
Treatment	Total trees, pretreatment	Heat related	Wind	Other	Heat and wind	Damage
			% of stems			*% of stems*
Burn	478	143 (29.9)	19 (4.0)	4 (0.8)	9 (1.8)	27 (5.6)
Unburned	551	15 (2.7)[a]	42 (7.6)	17 (3.1)	2 (0.03)[a]	17 (3.1)
All	1029	158 (14.5)	61 (5.6)	21 (1.9)	11 (1.0)	44 (4.0)

[a] Fire escaped containment lines briefly during the March 18, 2016 burn.

treatments, while blackgum, yellow-poplar, and conifer species group all had relatively minor wind-related mortality (table 4).

Treatment and slope position did not interact to affect residual stem survival (p = 0.94). Residual stems in the unburned treatment had significantly greater survival rates than those located in the burn treatment (85.3 ± 3.9 SE percent and 64.9 ± 3.8 percent, respectively, p = 0.004). No statistical differences in retention tree survival were observed for slope position (p = 0.14). Retention tree survival averaged 79.4 ± 2.8 percent, 78.6 ± 2.9 percent, and 66.4 ± 3.9 percent for lower, middle, and upper slope positions, respectively. Average survival rates ranged from 90.3 ± 2.0 percent on lower slope positions of the no burn treatment, to 55.3 ± 4.4 percent on upper slope positions of the burn treatment (fig. 1).

Table 4—Percent windthrow by species across both treatments for the irregular shelterwood study located in Morgan County, Tennessee

Species	Windthrow
	percent
Blackgum	2.9
Conifers	0.0
Other hardwoods	6.9
Red oaks	11.2
Red maple	5.8
White oaks	5.1
Yellow-poplar	2.9

The logistic regression analysis revealed that species group and treatment were both significant factors in the odds of mortality (table 5). The main effects model analysis revealed that red oaks (p = 0.02) and conifer species (p = 0.01), as well as the stems in the burn treatment (p < 0.0001), had a significantly greater probability of mortality than the reference species, yellow-poplar (table 6).

When the maximum likelihood estimates were converted to odds ratios, the odds of mortality for the conifer and red oak groups were 2.1 and 1.7 times greater, respectively, than the odds for the reference group yellow-poplar. The odds of mortality for stems in the burn treatment were 1.9 times greater than the odds for stems in the no-burn treatment.

DISCUSSION AND MANAGEMENT IMPLICATIONS

Retention tree mortality rates were increased by a single prescribed burn in this study. Stem density and basal area were reduced by the burn post-harvest. Burn treatment retention trees were less likely to experience wind-related mortality than no-burn treatment stems, but small and declining stems in the burn treatment were most likely killed by heat-related effects before windthrow mortality could occur. Vascular cambium and fine root damage are primary modes of decline in hardwoods and the degree of damage is affected by fire intensity (Regelbrugge and Smith 1994). Individual hardwood tree mortality in burn areas can be explained by a complex of variables including peak burn temperature, flame residence time, tree vigor, and bark thickness (Hare 1961, Yaussy and Waldrop

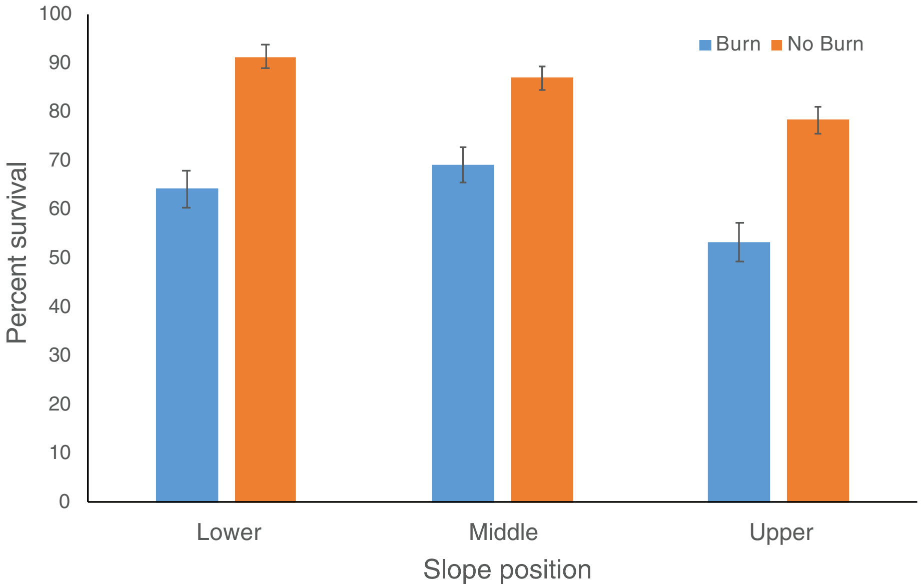

Figure 1—Residual tree average survival rate and standard error for the treatment by slope position interaction for the irregular shelterwood study located in Morgan County, Tennessee (p = 0.94).

Table 5—Type III fixed effects results for the logistic regression analysis for the irregular shelterwood study located in Morgan County, Tennessee

Effect	DF	Wald chi-Square	Pr>ChiSq
Species	6	21.3515	0.0016
d.b.h.	1	0.3667	0.5448
Treatment	1	60.3787	<0.0001

d.b.h. = diameter at breast height.

Table 6—Maximum likelihood estimates for the irregular shelterwood study located in Morgan County, Tennessee

Parameter		DF	Estimate	Standard error	Wald chi-Square	Pr>ChiSq
Intercept		1	-1.2006	0.2166	30.7215	<0.0001
Species	Blackgum	1	-0.4545	0.4105	1.2259	0.2682
Species	Conifers	1	0.7458	0.3061	5.9377	0.0148
Species	Other hardwoods	1	0.1161	0.2951	0.1548	0.6940
Species	Red maple	1	0.2927	0.1681	3.0324	0.0816
Species	Red oaks	1	0.5169	0.2135	5.8593	0.0155
Species	White oaks	1	-0.3051	0.1912	2.5458	0.1106
d.b.h.		1	-0.0093	0.0154	0.3667	0.5448
Treatment	Burn or no	1	0.6214	0.0800	60.3797	<0.0001

d.b.h. = diameter at breast height.

2010). Some stems in both treatments were affected by logging damage and most likely by the development of secondary agents of decline such as *Phytophthora* and *Armillaria* though these factors were not addressed in this study (Yaussy and Waldrop 2010).

Slope position did not significantly affect retention tree survival. Increased windthrow is often a concern at upper slope positions and ridge lines with two-age or irregular shelterwood stands in mountainous terrain (Stringer 2006). This site had approximately 560 feet in elevation change from lower slope positions to higher slope positions, but was partially protected from prevailing weather systems by another section of Little Brushy Mountain. Past research has demonstrated that prevailing winds that blow perpendicular to hill crests cause wind speeds to increase from lower slope positions to higher slope positions (Ruel 1995). This along with similar prescribed fire ignition patterns and weather conditions across the site may provide some explanation as to why similar retention tree survival rates occurred across slope positions in this study. The lack of significance in the treatment x slope position interaction term suggests that the effects of prescribed fire in irregular shelterwood stands are independent of slope position. This finding may encourage use of prescribed fire as a management tool to alter regenerating species composition in irregular shelterwood stands in similar terrain.

Red oak was one of the species groups identified as having a greater probability of mortality than yellow-poplar. This result has been noted with other studies in upland hardwood stands that had previously had fire excluded for many years (Regelbrugge and Smith 1994, Yaussy and Waldrop 2010). Decline of mature red oak stems may have been one of the main factors resulting in their greater probability of mortality. Red oaks such as scarlet and black oak tend not to live as long on average as white oaks and some other upland hardwood associates such as yellow-poplar (Stringer 2006). Red oaks also develop decay fungi regularly, especially scarlet oak and black oak (the two most common mature red oak species on this site) (Berry 1969). The other conifer species group also had a higher probability of mortality than the reference group (yellow-poplar). Eastern white pine and eastern hemlock are very susceptible to fire, especially smaller diameter stems, due to thin bark that provides minimal heat insulation. Older and larger stems are moderately susceptible to fire due to thicker bark compared to younger stems (Godman and Lancaster 1990, Wendel and Smith 1990).

Windthrow has been identified as a concern for retention trees in irregular shelterwood harvests. Local climate, tree age, species, and vigor all affect windthrow rates in these stands (Nyland 2007). Exposed slopes and landscape positions magnify windthrow concerns (Stringer 2006). Windthrow rates for mature, overstory stems vary by species, and shade-tolerant species tend to be more wind firm than shade-intolerant species (Canham and others 2001). Greater likelihood of windthrow was observed for upper slope and ridge landscape positions in a two-age deferment harvest study in Kentucky (Stringer 2006). The Kentucky study documented a similar to slightly greater windthrow rate range (7 to 10 percent) than this study. A similar shelterwood study in the Ouachita Mountains of Arkansas where favored retention trees were white oaks, hickories, and red oaks found a lower windthrow mortality rate (0.3 percent) than this study (Starkey and Guldin 2004). Based on results from this study and Stringer (2006), upland hardwood stands located in the Cumberland Plateau and Cumberland Mountains regions that receive the first cut of an irregular shelterwood are at more risk for mortality than undisturbed stands where the average annual mortality rate for average-sized, mature stems has been reported as 0.5 percent per year (Lorimer 1989).

The irregular shelterwood regeneration method can be implemented to maintain desirable residual stems on site which may fulfill multiple management objectives (Johnson and others 1998, Johnson and others 2009, Nyland 2007). Species, tree age, size, health, and topographic position should be considered collectively in the selection of retention trees for an irregular shelterwood in aging hardwood stands, especially with logging and burning operations. Red oak species, eastern white pine, eastern hemlock, and species with thin bark should be avoided as retention trees unless composition and structure prescriptions necessitate them. Favorable retention trees should include more fire-tolerant and longer-lived species such as white oaks (Dey and Hartman 2005). During logging, directional felling and concentrating tops away from retention trees may decrease heat-related mortality if prescribed burning is utilized (Wade and others 2000). Tree mortality and damage can be minimized with careful assessment and selection of retention trees when logging and prescribed burns are conducted in irregular shelterwood applications.

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7. Intermediate Management and Stand Development

Moderator:

Tom Dean

COMPARISON OF INDIVIDUAL-TREE COMPETITION METRICS IN AN UNEVEN-AGED, BALDCYPRESS AND BLACK WILLOW FLOODPLAIN FOREST

Alicia L. McAlhaney, Richard F. Keim, and Scott T. Allen

Abstract—Forest competition is typically assessed at the stand scale, but metrics that account for individual-tree competition may be more useful for understanding controls over growth in disturbed stands with heterogeneous structure. We evaluated whether local competition measures and crown dimension measures in an uneven-aged floodplain forest were capable of accounting for the effect of competition on baldcypress (*Taxodium distichum*) and black willow (*Salix nigra*). Contrary to our hypothesized inverse relationships, various metrics of local competition and individual crown dimension variables were poorly correlated with each other for dominant and codominant trees of the two species. The variability between species and overall poor relationships were likely attributable to physiological and morphological differences, complex stand structure, and the relatively low levels of competition experienced by dominant and codominant trees.

INTRODUCTION

Stand structure and composition affect the trajectory of forest development through inter-tree competition (Franklin and others 2002). Numerous measures have been used to quantify the effects of competition at both the stand and individual-tree levels, but none have proven useful in all situations. Nonetheless, individual-tree competition measures remain important when interpreting patterns in growth. This can be especially true when stands are highly heterogeneous, such as forested wetlands where flooding may alter tree establishment patterns and thereby limit the occupancy of available aboveground growing space (Allen and others 2015).

There is a need to determine which measure best represents competition for such applications. Distance-dependent measures have been most commonly used to evaluate local competition effect on trees (Tome and Burkhart 1989). These measures (such as local basal area, local trees per hectare, and local stand density index) have been used to predict growth, but none have been consistently useful for quantifying competition effects on tree structure (Daniels and others 1986). Another type of competition measure involves quantifying the number of neighboring trees that influence the crown of a subject tree through shading. The effects of neighboring trees are dependent on distance (crowding) and shade influence (Canham and others 2004).

Competition is also manifested in tree size and shape (Curtis 1970, Krajicek and others 1961). Local competition reduces resource availability (especially light availability), and thus can influence both crown shape and size (Pacala and others 1996, Thorpe and others 2010). Some competition measures take advantage of this influence of density on crown size, using the restriction of crown dimensions of subject trees to infer and quantify local competition. For example, Meadows and others (2001) introduced a classification system for characterizing crown shape and quality in uneven-aged bottomland hardwoods of the Southeastern United States, which Dimov and others (2008) have shown to be a useful predictor of tree growth in competitive environments. Regardless of crown class (for example, dominant or codominant), increased stand density decreases crown dimensions, hence the association can provide insight on competitive effects (Holdaway 1986). Tree height, crown length, and live crown ratio can also be used to evaluate competition effects and dominance of a tree.

We evaluated various metrics of both local stand density and individual-tree crown characteristics (1) to assess the validity and interchangeability of each metric and (2) to further our understanding of whether and how competition and crown structure covary for two important species in a floodplain forest, baldcypress (*Taxodium distichum*) and black willow (*Salix nigra*). We hypothesized, for both species, that there would be

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strong inverse relationships between local competition and crown dimension metrics.

MATERIALS AND METHODS

Study stands were adjacent to Bayou Sorrel, a distributary of the Atchafalaya River in south-central Louisiana. Species dominating the sites were baldcypress, black willow, green ash (*Fraxinus pennsylvanica*), Drummond's red maple (*Acer rubrum* var. *drummondii*), and water tupelo (*Nyssa aquatica*), with water-elm (*Planera aquatica*) and swamp-privet (*Forestiera acuminata*) common in the understory. Trees were selected from three stands varying in their degree of hydrological connectivity to flowing water (McAlhaney 2018), but we lumped all trees from all stands for this analysis because there was no indication that site affected relationships. All stands were uneven-aged, with a history of frequent disturbance from flooding and sediment deposition on a rapidly accreting floodplain (Hupp and others 2008).

A total of 37 baldcypress and 39 black willow trees from dominant and codominant crown classes were sampled. These trees were chosen for minimum visible signs of damage and were competitively independent of other sampled trees. Ages of trees, determined by coring, were 54–145 years old (324 years old for two sampled trees) for baldcypress and 38–58 years old for black willow. The condition of trees was variable. Baldcypress crowns were conical but becoming flat topped (a common characteristic of maturity). Black willow crowns were irregular, many with signs of damage and epicormic sprouting, and trees were approaching age of senescence. Average diameters were 49 cm (range 35–64 cm) for baldcypress and 60 cm (19–92 cm) for black willow. The average height for both species was 24 m (range 20–27 m for baldcypress and 17–28 m for black willow).

Several measurements were made of the dimensions of each sample tree and local competition. Total height and height to crown base were measured using a TruPulse 200x laser rangefinder to the nearest 1 m. Crown length and live crown ratio were calculated from these measurements. A numerical crown classification rating system for floodplain forests developed by Meadows and others (2001) quantified the crown of each sample tree, using visual estimates of the amount of sunlight the crown received from above (MTop; scale: 1-10), the amount of sunlight the crown received from the sides (MSide; scale: 1-10), crown balance (MBal; scale: 1-4), and crown size (MSize; scale: 1-4).

We also devised and evaluated a new competition metric derived from Biging and Dobbertin (1992) that counted the number of trees occupying an inverted cone extending from the crown base of the sample tree. For each subject tree, we tallied the number of other tree crowns occupying that cone as a measurement of competition. These cone-of-influence (COI) metrics were calculated using 30°, 35°, 40°, and 45° angles from the crown base of each subject tree. To ascertain whether each neighbor was in each cone, its distance from the sample tree and its height were measured (to the nearest meter), allowing calculation of whether it intersected each inverted cone.

Local stand density was evaluated using variable-radius, point samples using basal area factors (BAF) of 20 and 10 basal-area-factor (BAF; ft^2 ac^{-1} $tree^{-1}$, converted to equivalent metric units of 4.59 and 2.29 m^2 ha^{-1} $tree^{-1}$) using angle prisms with sample trees at point center. All trees were tallied, which allowed calculation of local basal area (local BA20 and BA10), trees per hectare (local TPH20 and TPH10), and Reineke's (1933) stand density index (local SDI20 and SDI10). Simple relationships between competition measures were then determined by correlation analyses, using Spearman rank correlation coefficients to improve robustness of fit in the context of highly variable local stands including outliers containing large numbers of small trees.

RESULTS

Local stand density was relatively low, with most trees inhabiting areas with local density near or below 660 SDI20 (S.I. units), the density at which self-thinning begins. Although the ranges of local stand density data for baldcypress and black willow suggest that baldcypress inhabited locations of lower local densities, the majority of the data (excluding outliers) suggest that trees from both species occupied locations of similar stand density (table 1).

Table 1—Mean (range) of local competition indices for baldcypress and black willow

	Competition measure					
Species	BA20	TPH20	SDI20	BA10	TPH10	SDI10
Baldcypress	25(5-60)	1198(8-17017)	541(58-1296)	23(9-41)	1121(54-4585)	507(146-943)
Black willow	28(5-83)	3094(26-52902)	699(100-3325)	27(5-66)	2977(104-43811)	689(97-2689)

BA = basal area (m^2 ha^{-1}), TPH = trees per hectare, SDI = stand density index (S.I. units).

Competition measures calculated based on prism basal area factors of 20 and 10 (U.S. units).

Relationships between current levels of local tree competition and size and shape of the dominant or codominant crowns varied by species (table 2). Crown size (length) response to competition for baldcypress was stronger than for black willow, but crown shape (from Meadows crown scores) was most related to competition for black willow. The most consistent relationship was that black willow crowns were less symmetrical in the presence of competition, mostly regardless of metric used (table 2).

The relationships between COI and sample tree dimensions were generally weak except that the number of trees occupying narrow cones (i.e., low COI) was correlated with smaller crowns, especially in black willow (table 3). As the cone angle increased, implying a larger area and thus larger number of trees potentially competing with the sample tree, there were weaker relationships. The mean number of tallied trees by angle was low: 1 – COI30, 1.5 – COI35, 3.5 – COI40, and 5 – COI45, limiting the precision of this metric. Even at the widest angle of 45°, there were no trees within the COI45 of four sample trees, although there were 27 trees in COI45 of one sample tree. There were 20 trees in COI40 of two sample trees. There were fewer than 13 trees in the 30–45° cones of 73 of the 78 sample trees.

Most crown dimensions only weakly correlated with each other, with the exception of weakly positive correlations between the amount of overhead sunlight received (MTop) and crown sizes or tree total height (table 4). However, the range for MTop was 9 or 10 for every tree because the study was designed to focus on more dominant trees, with only three trees having MTop score of 9; therefore, the marginally statistically significant relationships involving this variable were not especially meaningful. In black willow, more balanced crowns also tended to be longer.

Only black willow had many significant relationships between local competition measures and number of trees in the COI (table 5). The number of trees occupying the large COIs were positively correlated with other stand-density metrics for black willow, but in baldcypress there was only a single, unexpectedly negative, relationship with TPH10. Both total heights and

Table 2—Correlations (Spearman's *ρ*) between local competition measures and individual tree dimension metrics of baldcypress and black willow

Species	Competition measure					
Crown dimension measure	BA20	TPH20	SDI20	BA10	TPH10	SDI10
Baldcypress						
MTop	-0.15	0.01	-0.07	-0.10	0.13	-0.01
MSide	0.08	0.03	0.09	-0.06	0.30*	0.14
MBal	0.13	0.07	0.08	-0.04	-0.07	-0.07
MSize	-0.09	-0.02	-0.05	-0.07	0.00	-0.04
MTotal	0.07	0.06	0.09	-0.09	0.27	0.11
Height (m)	-0.09	0.07	0.00	-0.01	0.05	-0.03
Crown length (m)	-0.32*	-0.20	-0.27	-0.38**	-0.24	-0.39**
Live crown ratio	-0.15	-0.07	-0.11	-0.32*	-0.19	-0.30*
Black willow						
MTop	0.06	0.09	0.11	0.25	0.25	0.28*
MSide	-0.24	0.00	-0.17	-0.26	-0.01	-0.14
MBal	-0.35**	-0.29*	-0.34**	-0.37**	-0.30*	-0.39**
MSize	-0.29*	-0.13	-0.26	-0.27	-0.06	-0.21
MTotal	-0.40**	-0.15	-0.33**	-0.43**	-0.14	-0.33**
Height (m)	0.11	-0.18	0.01	0.13	-0.14	0.00
Crown length (m)	0.02	0.04	0.06	0.14	0.03	0.10
Live crown ratio	-0.13	0.10	0.01	-0.01	0.13	0.09

BA = basal area (m^2 ha^{-1}), TPH = trees per hectare, SDI = stand density index (S.I. units).

Competition measures calculated based on basal area factors of 20 and 10 (U.S. units).

Meadows and others (2001) crown scores: MTop, top light; MSide, side light; MBal, balance; MSize, size; MTotal, total score.

Asterisks indicate $p < 0.10$, double asterisks indicate $p < 0.05$.

Table 3—Correlations (Spearman's ρ) between local competition measures (trees in the cone of influence) and individual tree dimension metrics of baldcypress and black willow

Species	Competition measure			
Crown dimension measure	COI30	COI35	COI40	COI45
Baldcypress				
MTop	-0.17	-0.07	0.00	0.03
MSide	0.07	0.03	-0.04	-0.28*
MBal	-0.04	0.14	0.23	0.17
MSize	-0.17	-0.06	-0.02	0.01
MTotal	0.01	0.07	0.02	-0.20
Height (m)	-0.05	-0.05	-0.15	-0.04
Crown length (m)	-0.26	-0.10	-0.03	0.20
Live crown ratio	-0.39**	-0.22	-0.06	0.18
Black willow				
MTop	-0.34**	-0.20	-0.09	0.00
MSide	-0.14	-0.20	-0.11	-0.21
MBal	-0.01	0.07	-0.12	-0.12
MSize	0.18	0.20	0.13	-0.04
MTotal	-0.05	-0.04	-0.10	-0.23
Height (m)	-0.05	-0.08	-0.09	-0.05
Crown length (m)	-0.45**	-0.45**	-0.36**	-0.19
Live crown ratio	-0.37**	-0.37**	-0.30*	-0.18

COI = cone-of-influence metrics.

Meadows and others (2001) crown scores: MTop, top light; MSide, side light; MBal, balance; MSize, size; MTotal, total score.

Asterisks indicate $p < 0.10$, double asterisks indicate $p < 0.05$.

Table 4—Correlations (Spearman's ρ) between Meadows crown scores and crown dimension measures of baldcypress and black willow

Species	Crown dimension measure				
Crown dimension measure	MTop	MSide	MBal	MSize	MTotal
Baldcypress					
Height (m)	-0.05	-0.14	-0.16	-0.11	-0.15
Crown length (m)	0.25	-0.08	0.04	0.14	-0.01
Live crown ratio	0.31*	-0.12	0.02	-0.02	-0.11
Black willow					
Height (m)	0.30*	-0.20	0.23	0.27	0.06
Crown length (m)	0.27*	-0.05	0.34**	0.09	0.13
Live crown ratio	0.01	0.03	0.17	-0.04	0.08

Meadows and others (2001) crown scores: MTop, top light; MSide, side light; MBal, balance; MSize, size; MTotal, total score.

Asterisks indicate $p < 0.10$, double asterisks indicate $p < 0.05$.

Table 5—Correlations (Spearman's ρ) between local competition measures and cone-of-influence competition metrics of baldcypress and black willow

Species	Competition measure					
COI angle	BA20	TPH20	SDI20	BA10	TPH10	SDI10
Baldcypress						
COI30	0.09	---0.05	0.00	0.18	0.07	0.17
COI35	0.00	-0.11	-0.10	0.00	-0.12	-0.05
COI40	0.07	-0.08	-0.04	0.09	-0.18	0.00
COI45	-0.06	-0.17	-0.16	0.01	-0.38**	-0.18
Black willow						
COI30	0.14	0.06	0.11	0.04	-0.04	-0.08
COI35	0.07	0.01	0.04	-0.04	-0.08	-0.16
COI40	0.22	0.21	0.25	0.19	0.16	0.14
COI45	0.36**	0.38**	0.42**	0.36**	0.28*	0.30*

COI = cone-of-influence metrics.

BA = basal area (m^2 ha^{-1}), TPH = trees per hectare, SDI = stand density index (S.I. units).

Competition measures calculated based on basal area factors of 20 and 10 (U.S. units).

Asterisks indicate $p < 0.10$, double asterisks indicate $p < 0.05$.

crown lengths were similar for baldcypress (24 m and 13 m, respectively) and black willow (23 m and 14 m, respectively), so there was no reason to expect different relationships among the variables by species.

DISCUSSION

Contrary to expectation, the local competition metrics correlated poorly with the individual crown dimension variables, which may originate in physiological and morphological differences. The lack of correlation between local stand density and common crown dimensions (height, crown length, live crown ratio) for black willow was unexpected, because black willow is shade intolerant, and because there was correlation for the more shade-tolerant baldcypress. However, there were generally less-symmetrical crowns in black willow facing greater competition. Although not evaluated in this study, differences in growth physiology and the resulting crown shape response may be the cause for variability in relationship strengths of competitive effect on sample trees. For example, hardwoods such as black willow have the ability to develop highly asymmetric crowns to reduce competition influence (Lorimer 1983) by phototropic growth, and indeed the crowns of our sample black willow trees were generally irregular in shape.

The competition indices may have been poorly correlated with crown characteristics because the local stand densities in this study did not create enough competition effect. The stand density for sampled trees was mostly at or below the threshold of competition at which self-thinning begins for baldcypress (SDI ≈ 660, Keim and others 2010). Although similar stand density measures for black willow have never been studied, this study suggests black willow crown size is relatively insensitive to these levels of competition.

The weak relationships between both local competition and crown dimensions and both Meadows crown scores and COI measures suggest these measures were insufficient for both species. However, these weak relationships potentially originated because the samples consisted of only dominant and codominant trees. Similarly, the low data range of trees within the cone of influence in this study may contribute to the lack of predictive utility in competition effect. Also, much of the stand density near the sampled trees originated from smaller species such as Drummond's red maple and swamp-privet. Stand structure was irregular and multi-layered, which also potentially contributed to inconsistencies between species and among competition metrics.

CONCLUSIONS

We tested relationships between many metrics of stand density, competition, and crown morphology in an uneven-aged, forested wetland, and found few of these metrics demonstrated consistent suitability for explaining or predicting dimensions of dominant and codominant trees. Contrary to expectation, the competition metrics were weakly significant predictors of crown dimensions for both species. The nature of this stand—frequently disturbed and generally of low density—may have contributed to the relative lack of sensitivity of trees to neighbors. Also, because the sample was only of dominant and codominant trees, the results may be insufficient for inferences across the entire range of competition intensity.

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APPROACHES TO MODEL MID-ROTATION TREATMENT EFFECTS IN LOBLOLLY PINE PLANTATIONS IN THE SOUTHEASTERN UNITED STATES

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Abstract—Loblolly pine (*Pinus taeda* L.) plantations are extensive in the Southeastern United States and represent a significant component of the forest products market in this region. For optimal stand-level management decisions, the growth response to any combination of mid-rotation silvicultural treatments like fertilization, thinning, or competing vegetation management needs to be accurately predicted over the long term. We present a review of the most common mid-rotation silvicultural treatments applied in loblolly pine plantations and provide a conceptual framework about their effects. Three theoretical expected types of responses are illustrated as a guide for better and more comprehensive modeling approach selection. Preliminary exploratory data analysis of remeasured plots from a mid-rotation treatment study established by the Plantation Management Research Cooperative at the University of Georgia indicates that basal area growth after thinning follow a Type I response and treatments such as thinning + fertilization or thinning + fertilization + vegetation control can follow either Type I or Type II responses. Finally, some thoughts are provided on how to improve the prediction accuracy of growth-and-yield models considering mid-rotation treatments.

INTRODUCTION

Throughout the Southern United States, pine plantations have made a significant expansion. Particularly, loblolly pine (*Pinus taeda* L.) plantations represent an essential sector of the forest products market in this region. At the same time, improvements in silvicultural practices and intensive management have shown a remarkable gain in productivity (Fox and others 2004). Mid-rotation silvicultural practices have shown important improvements in growth (Snowdon 2002). The most common silvicultural practices at mid-rotation are thinning, fertilization, and vegetation control. However, for optimal stand-level management decisions, the growth response after a specific silvicultural treatment, or combination of treatments, needs to be accurately predicted over the long term. Reliable estimates are critical for landowners to make informed management decisions or to evaluate investment opportunities.

Existing loblolly pine growth-and-yield equation systems have been extended with multiplicative or additive sub-models, also called “modifiers,” at the stand level to represent the changes in growth due to individual silvicultural practices (Amateis 2000, Gyawali and Burkhart 2015, Pienaar 1997). Evidence of interactions between silvicultural treatments has been reported (Sword Sayer and others 2004), but little research exists that explicitly considers the interaction effect on the growth-and-yield equations system. Even fewer considerations have been given to the potential type of response that would be observed after a mid-rotation treatment is applied.

Consider the case of modeling the yield of a stand that received two or more mid-rotation silvicultural treatments. The simple addition of independently fitted modifiers (or the sequence of multiplications according to the case) does not guarantee an accurate prediction of the stand yield. A more elaborate procedure is needed in such a way that the resulting interactions of treatments are considered in growth-and-yield equation systems. Conventional statistical procedures could be used to estimate the effect of the interactions but require long-term field experimental data. To address this issue, the Plantation Management Research Cooperative (PMRC) at the University of Georgia has established and repeatedly measured several controlled loblolly pine mid-rotation silvicultural treatment (MRT) experiments across the Southeastern United States. Despite these efforts, not all the potential combinations of type and intensity of silvicultural treatments are available in controlled

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experiments. Additional information is required to improve the accuracy of the predictions, especially if they will be applied to sites different from those where the controlled experiments were established.

Alternatively, non-empirical growth models have been proven to perform successfully in explaining the stand-level growth responses to silvicultural treatments in loblolly pine and other species. These non-empirical models are known as process-based models. Simulation outputs of process-based models can be integrated as *a priori* knowledge with experimental data to improve the precision of growth predictions. Process-based models use well-established physiological models and only require environmental information, which is easily gathered and is available for the Southeastern United States. Prior research has shown that process-based models can model the productivity effects of mid-rotation treatments in loblolly pine plantations (Bryars and others 2013, Subedi and Fox 2016).

This paper reviews the most common mid-rotation silvicultural treatments applied in loblolly pine plantations and presents a conceptual framework about response types as a guide for model development. Also, preliminary results from a PMRC study are used to illustrate the expected nature of the responses in loblolly pine. Finally, some thoughts are provided on how to improve the accuracy in growth-and-yield predictions when several combinations of mid-rotation silvicultural treatments are present.

SILVICULTURAL TREATMENTS

Fertilization

Silvicultural practices serve to increase productivity in loblolly pine plantations. For example, mid-rotation fertilization with nitrogen (N; 150 to 200 pounds per acre) and phosphorous (P; 25 to 50 pounds per acre) on a majority of soils types throughout the Southeastern United States produces a large and consistent growth response in the volume of approximately 25 percent (Fox and others 2007). N and P fertilization with responses of approximately 55 cubic feet per acre per year have been shown to enhance the profitability of loblolly pine plantations (Fox and others 2007). Fertilization treatments increase nutrient availability at the tree level, and as a consequence, an increased leaf area index is expected, resulting in improved growth (Albaugh and others 2017).

Competition Control

At early ages, herbaceous and hardwood competition can adversely affect gains in growth (Jokela and others 2010). Early control of competing woody and herbaceous vegetation increases wood volume by 23 to 121 percent when evaluated at the age of 15 years (Miller and others 2003). At the tree level, competition reduces nutrient availability and increases competition for water, which influences radiation use efficiency.

Thinning

Thinning is another important silvicultural practice in loblolly pine plantations. There is evidence that thinning not only changes the structure of the stand (diameter distributions, and changes in spatial competition) but also alters the post-thinning height growth of dominant and codominant trees (Sharma and others 2006) and improves the stem quality of the residual stand. Thinning, in particular, has received considerable attention from researchers. Some studies of thinning effects have evaluated empirical approaches at the tree (Albaugh and others 2017, Soderbergh and Ledermann 2003) or stand level (Franklin and others 2009). Thinning is a way to modify the process of site resource allocation. In general, the primary objective of this treatment is to concentrate light, water, and nutrients on fewer and better trees that have the potential to survive over the entire rotation, ending up in a higher-value product.

MODELING MID-ROTATION TREATMENTS

The extra growth gained at the stand level (or plot level) is always referenced or measured with respect to the growth in the untreated stand (called the control plot or untreated plot) with similar site and stand structural attributes, including site index (SI), trees per acre (TPA), and basal area (BA). The treatments can be a single silvicultural practice or a combination of practices, and the expected response, which may also depend on several other stand characteristics such as age, could have a longer-term effect or a more temporary effect.

Long-term experimentation is the correct approach to infer about the growth drivers and is the only way to evaluate the magnitude of the response given specific treatments. However, these kinds of experiments are costly and time consuming to install and measure, and it is impossible to observe the response in all possible combinations of experimental factors across the Southern United States. Researchers conventionally have used experimental data to update growth-and-yield equations to be able to infer the expected response in a new location. This could involve either explicitly modeling the treatment effect into the growth-and-yield equations or modeling a response sub-model independently and using it as a modifier of the untreated growth-and-yield equations.

The explicit modeling of treatments has been done by incorporating silvicultural treatments into the growth-and-yield models as indicator variables (Fang and others 2001). This approach has two limitations: (1) it is difficult to separate the effects of different treatments at the stand level because each silvicultural treatment produces an enhanced growth response of different magnitude and duration, and (2) the positive responses in growth due to the implementation of a silvicultural treatment is attributed both to the improved treatment and a secondary effect of changes to stand stocking and/or structure that result from the improved treatment (Miller and Tarrant 1983).

The alternative approach consists of estimating a modifier equation. This method is used to adjust the typical or base pattern of growth of a plantation that has not received a given silvicultural treatment (also called the control case). Some researchers have found that the effect of the silvicultural treatment can be modeled using an additive modifier (Amateis 2000). In this case, the modifier is added to the base growth model. For example, the response of dominant height and basal area growth models for slash pine (*Pinus elliottii* Engelm.) in the Southern United States in response to bedding and herbicide treatment could be explained with additive modifiers (Pienaar and Rheney 1995). The volume responses to woody and herbaceous competition control at age 15 years in loblolly pine plantations were also found to be additive (Miller and others 2003).

Multiplicative modifiers have proven useful for growth-and-yield equations that consider thinning practices (Bailey and others 1985). For instance, a modifier can be incorporated into a procedure to evaluate the growth of a thinned plantation compared to a non-thinned plantation of the same age, SI, and TPA remaining in the thinned plantation immediately after thinning (Pienaar 1997). Today, this procedure, also known as the Index of Suppression, continues to be used in growth-and-yield models with thinning management practices. However, there are no recent studies that have validated this procedure for loblolly pine under more intensive management regimes.

Finally, updated growth-and-yield models are essential to project the long-term stand-level effects of silvicultural treatments, which help to support forest management decisions. This becomes even more important when one considers that field trials are challenging to replicate and cannot be installed due to their expensive and time-consuming nature (Weiskittel and others 2011).

Response-Type Models

A prior understanding of the potential types of stand growth response is important to guide the modeling strategy by defining appropriate modifier functional forms. Two response types to silvicultural treatments applied at the establishment or during early ages have been reported as Type I and Type II (Snowdon 2002). Here we define three possible types of basal area responses when silvicultural treatments are applied at mid-rotation (fig. 1). Type I responses are characterized by a temporary increase in growth rate after treatment compared with the untreated scenario or control, and an extra peak in growth is obtained. Thereafter, the treated stand growth gradually approaches back to the control. The yields of the treated and untreated stands follow a parallel trajectory (fig. 1A). This type of response is likely observed with practices that do not permanently change the site conditions, for example, additions of N fertilizer or weed control at mid-rotation.

Response Type II typically occurs when the treatment has a substantial and sustained effect on site properties. The resulting growth over time shows a parallel trajectory with the control growth after treatment. Consequently, a divergent trend in yield is observed when compared with the untreated stand condition (fig. 1B). Mid-rotation silvicultural practices that produce long-term changes in productivity are associated with Type II responses, such as an improvement in nutrient supply with phosphorous on soils with P deficiencies, irrigation, repeated N fertilization, or hardwood competition release.

Response Type III is characterized by a temporary increase in growth rate after treatment, but one that is not sustained over time. The initial gain in growth is followed by a decline in growth. Ultimately, yields are the same as the untreated scenario (fig. 1C). This type of response is likely observed when the treatments are applied on sites that are fully stocked and the intra-specific competition is increased due to the treatment.

Response Types I, II, and III could be combined with a thinning modifier. That is, if the silvicultural treatment is applied at the moment of thinning, then the theoretical response type may be observed on the growth curve for the remaining trees after thinning.

Case study—The Plantation Management Research Cooperative's Mid-Rotation Treatment study has 62 installations throughout the Southern United States established in non-thinned and thinned plantations. Five 0.75-acre treatment plots were established in each installation and trees in the 0.5-acre interior area were remeasured every 2 years since treatment was applied. One plot did not receive any treatment of thinning and four plots were assigned the following treatments: thinning only, thinning + fertilization (200N + 25P + additional nutrients based on foliar test), thinning + vegetation control, and thinning + fertilization + vegetation control.

Let us only consider the measurements from the non-thinned stands. For the sake of the example, we calculated the response as the difference in basal area between the treated plot and the control at each measurement age. We used the untreated plot as a control to compute the responses of the thinned plots. Therefore, we expected to see negative values for the response (fig. 2). A negative magnitude in

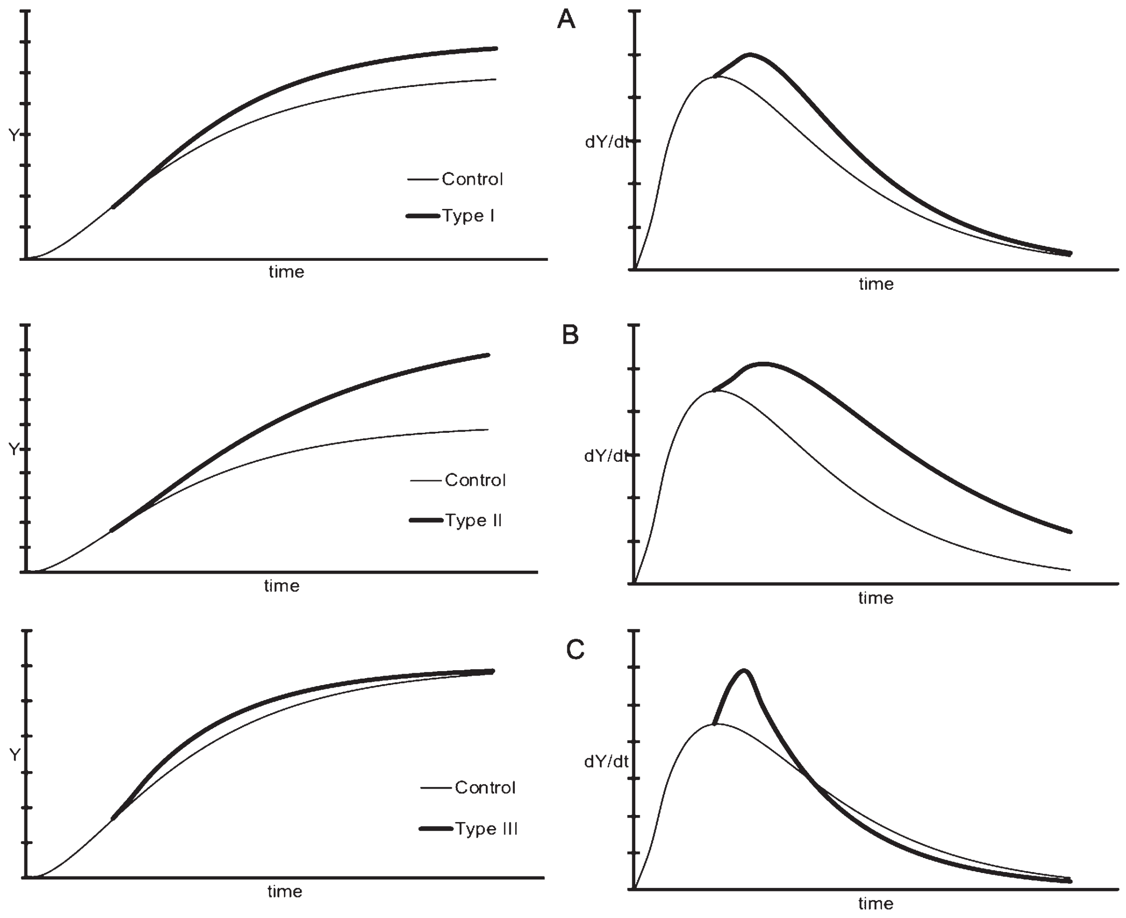

Figure 1—A theoretical pattern of responses to mid-rotation silvicultural treatments in yield and growth for the basal area of a loblolly pine plantation. (A) Type I response, (B) Type II response, and (C) Type III response.

response meant that the treatment reduced the stand characteristic that we were analyzing. This happened with stand-level basal area in the thinning treatment. Interestingly, in the three physiographic regions, the observed pattern over time resulted in a constant response, which implied that the thinned stands were following a Type I response.

The control plot for Thinning + Fertilization and Thinning + Fertilization + Vegetation Control was the Thinning only plot. We observed that some plots did not respond to combinations of treatments (fig. 3). Stands that are close to their productive potential have been shown to not respond to treatments (Zhao and others 2016). Plots with an increasing response over time indicate a Type II response. Here we only present the absolute response observed in the measured plots, but statistical modeling will be later developed, and the interactions between treatments will be tested with additional remeasurements.

Defining the expected response type is important for determining the modifier equation form. Depending on site and stand characteristics, it is likely that the interaction between treatments will produce a change in the response type. The next step in our research consists of testing a flexible modifier allowing it to account for the effects of physiographic region, thinning intensity, amount of vegetation competition at the thinning age. The modifier should also be able to represent either a Type I or Type II growth response.

Process-based Models

Some authors argue that process-based models per se are still limited concerning management and decision support because of their data and parameterization requirements (Franklin and others 2009, Mason and Dzierzon 2006). However, the process-based model 3-PG (Physiological Principles to Predict Growth) developed by Landsberg and Waring (1997) has proven to work very well in predicting long-term thinning responses in Scots pine (*Pinus sylvestris* L.) in Finland (Landsberg and others 2005); BGC-models (biogeochemical-mechanistic models) have been used with Norway spruce (*Picea abies* (L.) H. K.), and European beech (*Fagus sylvatica* L.) in central Europe (Petritsch and others 2007), and TRIPLEX (a hybrid monthly time-step model of forest growth, carbon, and

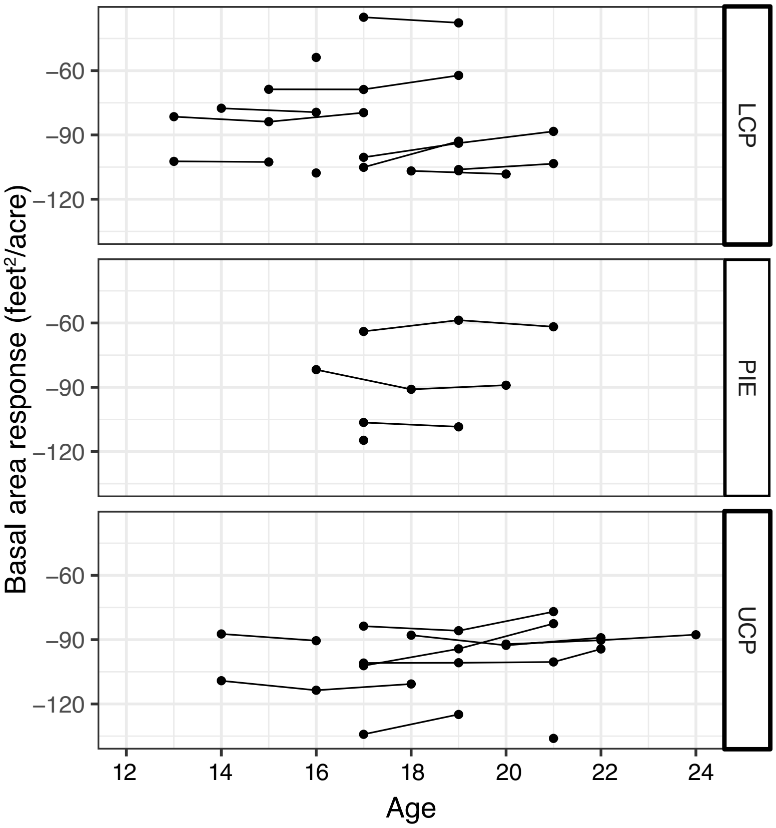

Figure 2—Basal area response to thinning over age for 25 installation plots of the PMRC MRT study grouped by physiographic region. LCP: Lower Coastal Plain, PIE: Piedmont, and UCP: Upper Coastal Plain. The response at each measurement was defined as the difference in basal area between the thinned plot and the unthinned control plot. The remeasurements of each plot are represented with dots connected by lines.

nitrogen dynamic) has been used for Jack pine (*Pinus banksiana* Lamb.) in Canada (Wang and others 2011).

The process-based model 3-PG (Landsberg and Waring 1997) is one of the simplest models readily available. The 3-PG model requires monthly climatic information and site soil characteristics to simulate stand growth. Outputs from this model include stem, foliage, and root biomass, stand volume, leaf area index, basal area, and mean diameters at each monthly step. The structural parameters needed to obtain predictions of biomass and volume in untreated stands throughout the Southeastern United States has been studied by Bryars and others (2013).

While 3-PG can be used to simulate thinning treatments (Landsberg and others 2005), it is not as versatile, in general, as the conventional growth-and-yield model equation systems. However, 3-PG could provide insight about the expected effect when several silvicultural treatments are combined. That is, once a calibrated 3-PG model is obtained for a particular site, it could be used to study the relative growth change under different silvicultural treatment intensities and timings. A reliable process-based model is valuable, especially to generate information about the expected effect of silvicultural treatments on sites where there are no existing trials, or to inform empirical models with prior information on interaction effects when few trial replications are available.

CONCLUSIONS

Since the silvicultural practices of vegetation competition control, fertilization, and thinning are known to have an impact on the future growth and yield of loblolly pine stands, it is important to understand how to incorporate these responses and their interactions into growth-and-yield models. The current loblolly pine models developed by the PMRC, as well as others in the literature, always consider the stand-level growth-and-yield models for the untreated conditions and use modifiers to adjust the projected growth as a response to individual silvicultural treatments. We illustrate hypothetical possible response types when mid-rotation treatments are present. Preliminary results from a PMRC MRT study show that the growth response of loblolly pine plots with mid-rotation treatments like Thinning + Fertilization or Thinning + Fertilization + Vegetation Control can be

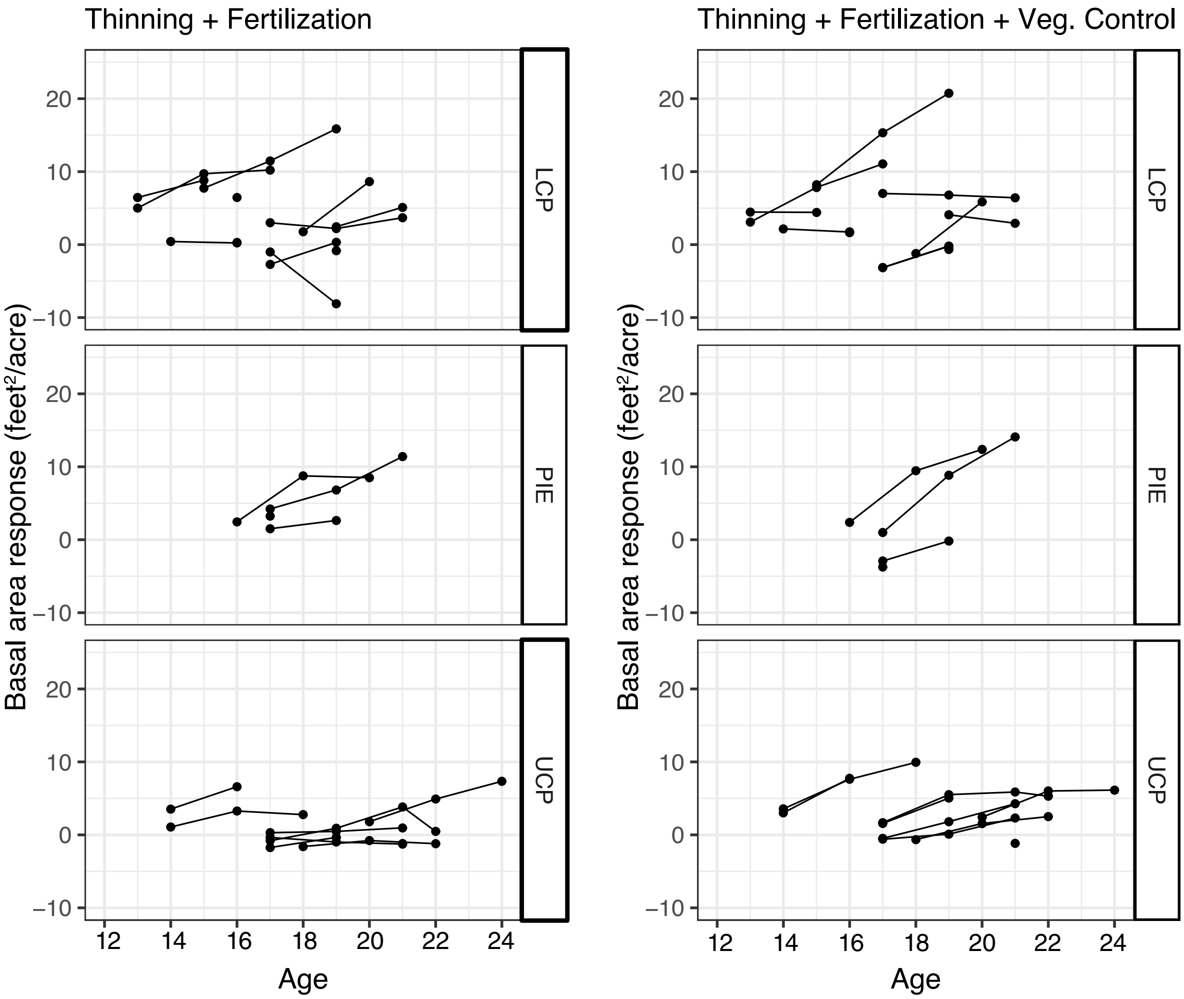

Figure 3—Basal area response to combinations of treatments over age: Thinning plus fertilization (left) and Thinning plus fertilization plus vegetation control (right). Installation plots of the PMRC MRT study grouped by physiographic region. LCP: Lower Coastal Plain, PIE: Piedmont, and UCP: Upper Coastal Plain. The response at each measurement was defined as the difference in basal area between the plots with combined treatments and the respective Thinning only control plot.

either Type I or Type II. Plots with Thinning only follow a Type I growth pattern exclusively. Process-based knowledge promises to be a useful source of information that can be incorporated as a piece of prior information in empirical models. Further research will evaluate the prediction accuracy of models combining experimental data and process-based information.

ACKNOWLEDGMENTS

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ASSESSING THE ESTABLISHMENT, GROWTH, AND SURVIVAL OF WEST GULF COAST SOUTHERN PINES IN EAST TEXAS

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Hans M. Williams, and Yuhui Weng**

Abstract—West Gulf Coast provenance loblolly *(Pinus taeda* L.), longleaf (*P. palustris* Mill.), shortleaf (*P. echinata* Mill.), and slash pines (*P. elliottii* Engelm.) were planted in east Texas to compare initial growth and survival across various soil types. Containerized seedlings were planted in December 2015 on three sites in Shelby, Houston, and Cherokee counties using a randomized complete block design. Seedlings were measured initially January-February 2016 and again January-February of 2017, 2018, and 2019. Three years after planting, survival was greatest (76.4 percent) on the study site with fine sandy loam textured soils that were well drained to somewhat poorly drained and was lowest (26.4 percent) at the study site with high Texas leafcutter ant (*Atta texana*) activity. Tree heights and diameters were greater for loblolly and slash pine than shortleaf and longleaf pine.

INTRODUCTION

Pine plantations are an important economic resource in east Texas. Pines are grown for timber production across diverse landscapes and soil types by private landowners and large timber management organizations. Because these plantations can take up to 35 years to maximize financial returns, it is important for landowners to invest in the species that will best meet desired objectives. Each of the four commonly planted southern yellow pine species in this region (loblolly pine (*Pinus taeda* L.), longleaf pine *(P. palustris* Mill.), shortleaf pine (*P. echinat*a Mill.), and slash pine (*P. elliottii* Engelm.)) requires specific site conditions to achieve maximum timber growth rates. Capitalizing on these differences in yield may provide the landowner with improved profit. Because of their resistance to fusiform rust and drought injury, West Gulf Coast provenance southern pines are gaining interest as viable options in this sub-region, and comparisons between these species may provide landowners with a better understanding of which will maximize wood production on their site in the early years of rotation. Similar studies have been conducted on southern pine growth comparisons but were further east and predated tree improvement programs (Coile and Schumacher 1953).

MATERIALS AND METHODS

Site Locations and Descriptions

The study took place on three sites in Houston, Cherokee, and Shelby counties located within the east Texas Upper Gulf Coastal Plain. All study sites were located in recently clearcut areas that were adjacent to loblolly pine plantations but varied greatly in dominant soil type and drainage classifications (table 1). The Houston County site was located 11.3 km east of Crockett, TX (31°18’45.7”N 95°18’05.1”). Study plots were predominantly on fine-loamy, fine silty loam, and loamy soils. Soil drainage was classified as somewhat poorly drained to well drained with slopes ranging from 1 to 5 percent. A mix of herbicides including 1.4 L of Chopper, 3.7 L of Accord, and 0.1 L of Oust was applied at 30 L per hectare by ground application in fall of 2015. The Cherokee County tract was located 9.6 km west of Rusk, TX (31°46’32.3”N 95°13’46.2”W) on fine-loamy to loamy textured soils with drainage classifications of well drained to somewhat excessively well drained. The study plots were on a small ridge where commercial plantings of loblolly pine had repeatedly failed due to poor survival. This site was mowed prior to planting. The Shelby County site was located 6.4 km southeast of Tenaha, TX (31°54’48.8”N 94°12’43.9”W). The soil textures were

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very fine sandy loam, and fine loamy sand with drainage ranging from moderately well drained to well drained. Study plots were laid out on the property edge on either side of a logging road. A mix of herbicides including 1.4 L of Chopper, 3.7 L of Accord, and 0.1 L of Oust was also applied at 30 L per hectare by ground application in fall 2015.

Experimental Design

Plots were arranged in a randomized complete block design with three replicates per site for each of the four species. Research plots were 36.5 m by 36.5 m, with trees planted at a 2.4-m by 2.7-m spacing (1,500 trees per hectare). In Houston and Shelby counties, all blocks were directly adjacent to the others, but plots were more dispersed in Cherokee County in non-stocked openings within a 14-year-old loblolly pine commercial planting already on site.

Planting

Trees were planted in December 2015. Loblolly, slash, and shortleaf pines were machine planted as containerized seedlings, but longleaf pine containerized seedlings were hand planted to reduce the deep planting of a machine planter. All seedlings were planted in furrows created by the machine planter. Seedlings were provided by International Forest Company and all were of West Gulf Coast provenance (table 2).

Data Collection

To eliminate edge effects, the outer rows of each plot were reserved as buffer rows where no data were collected. Groundline diameter (GLD) was measured on each seedling where the main stem of the seedling intercepted the soil and was recorded to the nearest millimeter. Seedling height was measured to the nearest 0.5 cm from the intercept of the main stem with the soil

Table 1—Soil series characteristics found at sites in Cherokee, Houston, and Shelby counties in east Texas

Site Soil series	Soil texture	Drainage class	Slope
			%
Cherokee County			
Bowie	fine sandy loam	well drained	3-8
Darco	loamy fine sand	somewhat excessively drained	1-3
Lilbert	loamy fine sand	well drained	3-8
Houston County			
Fuller	fine sandy loam	somewhat poorly drained	1-3
Lovelady	loamy sand	well drained	1-5
Pophers	silt loam	somewhat poorly drained	0-1
Shelby County			
Eastwood	very fine sandy loam	well drained	5-15
Latex	fine sandy loam	moderately well drained	1-3
Metcalf-Sawtown	complex	somewhat poorly drained	0-2

Source: USDA NRCS (2016).

Table 2—Genetic information and origin of pines planted at Houston, Shelby, and Cherokee counties, December 2015

Pine species	Genetics	Origin
Loblolly	Improved, second generation, superior growth and form	Cherokee County, Texas
Longleaf	Natural stand mix	Newton County, Texas
Shortleaf	Improved, orchard mix	Southern Arkansas
Slash	Improved, second generation, superior growth, form, and rust resistance	Northern Louisiana

to the top of the terminal bud. GLD, height, and survival data were recorded each January-February from 2016 to 2019.

Data Analysis

A mixed model analysis of variance was used to test the effects of site and species on seedling height and diameter using the model:

$$Y_{ijkl} = \mu + \text{Site}_i + \text{Species}_j + \text{Block}_{k(i)} + \text{Site}_i{*}\text{Species}_j + \varepsilon_{ijkl} \qquad (1)$$

where site and species were considered fixed variables and block was considered a random variable.

Binary survival data were analyzed using a logistic model to calculate the odds ratio estimates and probability of survival for each species at each site for each individual year. The effect of site, species, and block on survivability were analyzed using the model:

$$Y_{ijkl} = \mu + \text{Site}_i + \text{Species}_j + \text{Block}_{k(i)} + \text{Site}_i{*}\text{Species}_j + \varepsilon_{ijkl} \qquad (2)$$

Assumptions of normality were checked by plotting residual values of heights and diameters by species for all three measurement years. For both models a significance threshold of $\alpha=0.05$ was used.

RESULTS

Establishment

One month after planting, mean initial heights and diameters varied significantly at the species level ($p < 0.0001$). Loblolly and slash pine mean heights were greater than shortleaf pine heights, which was also greater than longleaf pine. Mean basal diameters were significantly different at the species ($p < 0.0001$) and site ($p = 0.0090$) levels. Cherokee site diameters were greater than both Shelby and Houston site diameters. Longleaf diameters were greater than loblolly and slash pine diameters, and slash diameters were greater than shortleaf diameters. Four months after planting (April 2016), survival was not significantly different among species ($p = 0.9688$) or sites ($p = 0.0720$).

Year 1

Heights among the four southern pines varied with site, as suggested by a significant site*species interaction ($p = 0.0298$). Differences in mean height among sites were only significant for loblolly pine ($p = 0.0325$). Loblolly pines at the Shelby site were significantly taller than those at the Cherokee site. Survival was significantly different at the site ($p = 0.0010$) and species ($p = 0.0015$) levels. Tree survival at both the Houston and Shelby sites was greater than at the Cherokee site. Loblolly, shortleaf, and slash pine survival rates were greater than longleaf pine across all study sites.

Year 2

Similar to first-year height, mean height at year 2 varied with site and pine species, as suggested by the significant species*site interaction ($p = 0.0022$). Loblolly pines differed significantly ($p = 0.0281$) in height among sites with greater mean heights at the Shelby and Houston sites than at the Cherokee site. Slash pine also differed significantly ($p = 0.0354$) among sites and similarly performed better at the Shelby site than at the Cherokee site.

Species differences in second-year diameter also varied with site ($p = 0.0004$ for the interaction between site*species). Loblolly pine diameters differed significantly ($p = 0.0286$) among sites. Loblolly pine trees at the Shelby site had the largest diameters, followed by trees at the Houston and Cherokee sites.

Two years after planting, survival rates varied significantly at the site ($p = 0.0015$) and species ($p = 0.0002$) levels. The survival rates at the Houston and Shelby sites were greater than survival rates at the Cherokee site. Loblolly, shortleaf, and slash pine survival rates were greater than longleaf survival rate across all sites.

Year 3

Pine species mean height varied with site (site*species interaction for mean height $p = 0.0028$) (fig. 1). Mean height differed across sites for loblolly ($p = 0.0167$) and slash pine ($p = 0.0243$); these species had similar trends with pines on the Shelby site being tallest and those in the Cherokee site the shortest.

Mean diameter results were similar to those of tree height (fig. 2). Loblolly ($p = 0.0160$) and slash pine ($p = 0.0190$) diameters differed among the sites, with trees from Shelby and Houston sites being significantly larger in diameter than trees from the Cherokee site.

The interaction between site and species for third-year survival was significant ($p = 0.0140$) (fig. 3). Survival in Houston and Shelby sites was greater ($p < 0.05$) than survival at the Cherokee site for all pine species.

DISCUSSION

Growth

Greater growth in loblolly pine could have been due to their improved genetics (McCrady and Jokela 1998), and the observed faster growth rates of loblolly pine compared to the other southern pines (Gibson and others 1986, Smith and Schmidtling 1970). Soils in

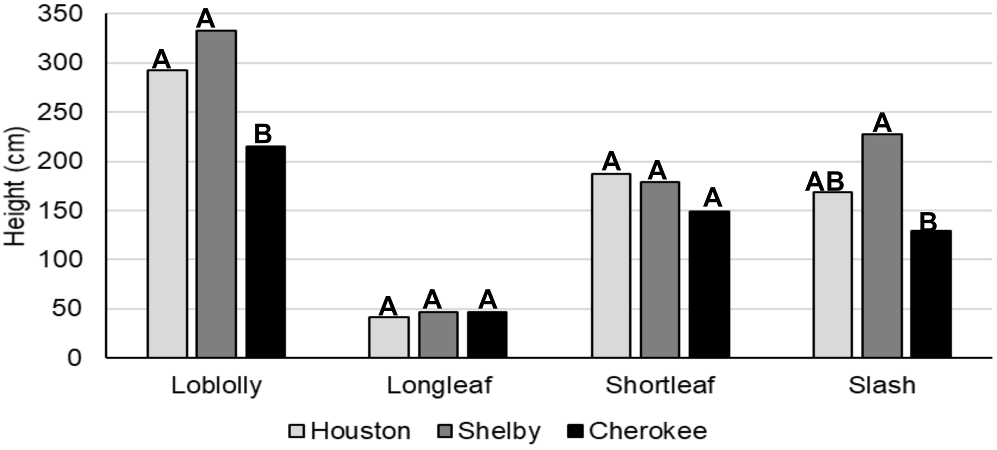

Figure 1—Mean height 3 years after planting of loblolly, longleaf, shortleaf, and slash pines at each study site. Tukey analysis conducted within species, columns headed by different letters are significantly different at $p < 0.05$.

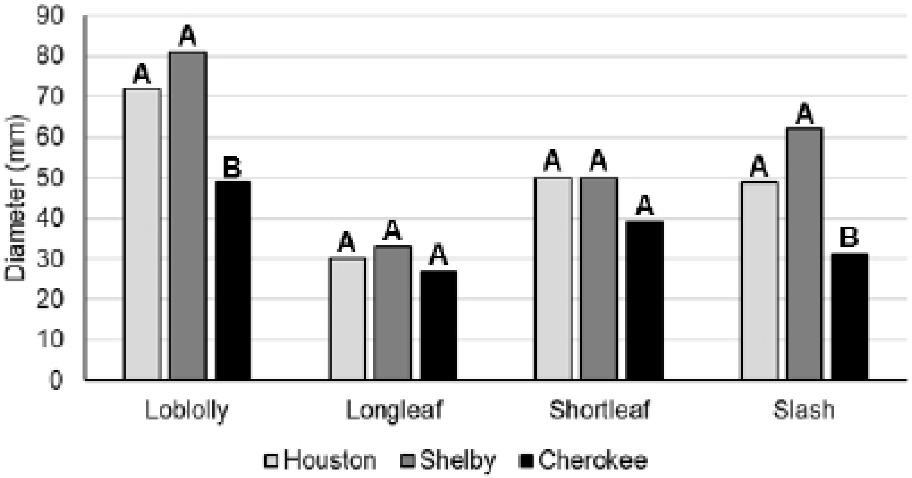

Figure 2—Mean diameter 3 years after planting of loblolly, longleaf, shortleaf, and slash pines at each study site. Tukey analysis conducted within species, columns headed by different letters are significantly different at $p < 0.05$.

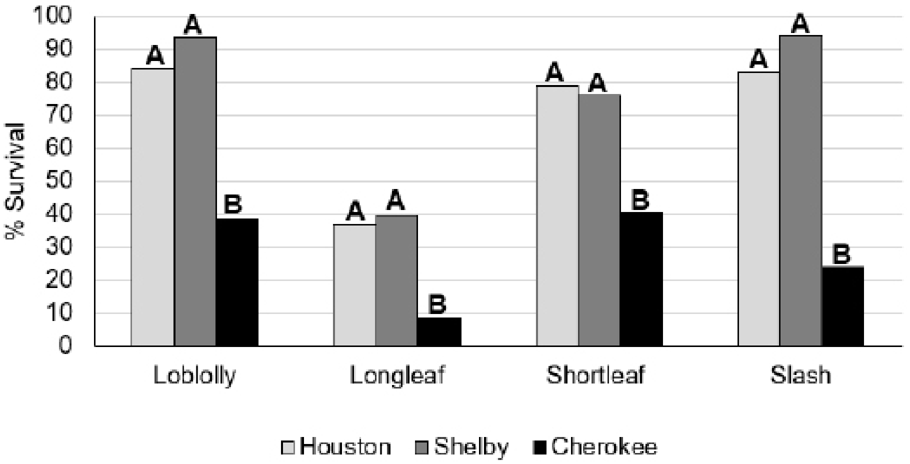

Figure 3—Percent survival of loblolly, longleaf, shortleaf, and slash pines at each study site 3 years after planting. Tukey analyses conducted within species, columns headed by different letters are significantly different at $p < 0.05$.

Houston and Shelby counties were representative of soils (moist, loamy textured, with adequate drainage) where loblolly pine typically outperforms the other southern pines (Baker and Langdon 1990, Haywood and others 1990, McKee and Shoulders 1970, Shoulders 1976, Tiarks and Shoulders 1982). In similar comparison studies, loblolly pine produced a much higher yield than other southern pines on soils with adequate nutrient and moisture availability (Haines and Gooding 1981, Haywood and others 1990, Faust and others 1999, Jokela and others 2000, Kramer 1943).

Slash pine was genetically superior to shortleaf pine in terms of growth, form, and rust resistance; however, east Texas is farther west than the native range of slash pine and receives less average annual rainfall which could potentially reduce its performance. When planted in poorly drained and nutrient deficient soils, which made up a small area of the Houston County site, slash pine began to outperform loblolly pine (Fisher 1983, Shoulders 1976, Shoulders and Parham 1983). However, slash pine does not put on substantial growth on soils with a nutrient availability that satisfies the higher relative demands of loblolly pine (Jokela and others 2000) and is quickly outcompeted. Shortleaf seedling genetics and naturally slower growth rate (Guldin 1986, Lawson 1990) than loblolly and slash pine resulted in lower yearly growth rates.

The majority of longleaf seedlings produced almost no aboveground stem biomass 3 years after planting. The length of the grass stage in longleaf pine was affected by competition of herbaceous plants (Barnett 1989, Boyer 1993, Brockway and Outcalt 1998, Nelson and others 1985, Ramsey and others 2003, Scott and Burger 2014). Those few longleaf that grew out of the grass stage within the first 3 years had the potential to meet the productivity of the other southern pine species in future growing seasons (Croker 1990, Landers and others 1995).

Survival

The higher-than-expected survival rates of loblolly, shortleaf, and slash pines may have been a result of higher than average rainfall received in east Texas between 2016 and 2019 (total rainfall 2016 = 1440 mm, total rainfall 2017 = 1235 mm, total rainfall 2018 = 1490 mm, total average annual rainfall in east Texas = 1185 mm). The greatest causes of mortality among loblolly, shortleaf, and slash pine were damage to seedlings by feral hog activity. Similar to other studies, feral hogs uprooting pine seedlings leaves roots without suitable soil contact and exposed to high temperatures and sunlight, preventing them from recovering (Pessin 1939). Feral hog damage to seedlings was the main cause of mortality in Shelby County and Houston County. During the first and second years of growth, feral hog activity at these sites was high, and uprooting of seedlings caused them to be exposed to wind, low moisture, and hot temperatures. Another factor affecting seedling mortality immediately after planting was inundated conditions of several plots for several weeks after establishment.

Much of the longleaf mortality in the first year may have been due to inadequate planting conditions (planting temperatures of 26 °C were higher than recommended (Lantz and others 1996)). Terminal buds and root collars of the longleaf pine seedlings remained underwater in inundated plots for several weeks, preventing the absorption of sunlight and oxygen for root allocation. Several containerized seedlings also floated out of planting holes, exposing the roots to winds and direct sunlight. Sediment washed over top of the terminal buds once waters subsided, and buried the root collars of longleaf pine, resulting in high mortality within the first 4 months (Hainds 2003, Larson 2002).

During summer months and months with low precipitation, soils in Cherokee County did not provide adequate soil moisture. Defoliation by Texas leafcutter ants (*Atta texana*) were the leading cause of mortality for all species at Cherokee County. Leafcutter ant damage was observed as early as 1 month after planting and continued through the third year. Survival on plots affected by leafcutter ants ranged from a high of 20 percent to a low of 1 percent. Cherokee County longleaf pine plots were also subject to feral hog damage and deer herbivory over the course of the study. Herbivory mortality was caused by the removal of the terminal bud and root collar and the exposure of root systems (Pessin 1939). Herbaceous plant competition for nutrient and water resources may have also impacted the survival and lower growth rates of pines (Metcalfe 1985).

CONCLUSIONS

Growth of the four species in this study varied greatly, potentially driven by differing nutrient demands, response to moisture stress, and site-based environmental factors. The highest yield of all four species after the third growing season was observed on the moist, sandy loam, high-nutrient-available soils in Shelby County. The least amount of aboveground growth was on the well-drained, deep sands in Cherokee County. Seedling survival was greatest in Shelby and Houston counties, which could have been due to the lack of environmental factors affecting survival (Texas leafcutter ants and feral hog damage) in Cherokee County. Lower survival rates of longleaf pine could potentially be attributed to the lack of herbaceous weed control and planting error.

For landowners who wish to obtain the highest growth, we recommend loblolly pine be planted on sites where soil nutrient availability and soil moisture are adequate to support its faster growth rates. Loblolly has high adaptability and can outcompete the other pine species when soil water and nutrients are readily available. Slash pine is recommended as the species of choice on poorly drained soils where nutrients become limiting to loblolly pine. Shortleaf pine should be considered on soils that are excessively drained, where nutrients are very limiting, or on sites where prescribed fire may be frequently applied. Longleaf pine should be considered on sites that are most prone to drought, as its ability to retain high needle moisture and surface area during extended periods of low precipitation allows it to outcompete loblolly and slash pines on extremely dry soils (Sayer and others 2005). Prescribed fire, active forest management, and herbaceous competition control should also be implemented to increase longleaf pine success. If properly managed, longleaf pine growth is comparable to the other southern pines after growing out of the grass stage. (Schmidtling 1987, Outcalt 1993).

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FIRST THROUGH FOURTH GROWING SEASON RESPONSES OF PLANTED LOBLOLLY PINE TO THINNING IN THE WESTERN GULF REGION

Jason Grogan, Yuhui Weng, and Dean Coble

Abstract—Thinning is commonly used in managing loblolly pine (*Pinus taeda* L.) plantations in the Western Gulf Region. While long-term loblolly pine growth responses to thinning have been well documented, understanding of the response in the first couple of years after thinning is limited. Data were collected for a loblolly pine thinning study from 16 sites across east Texas and western Louisiana over the first four growing seasons following thinning. Three thinning intensities, with residual stockings of 150, 225, and 300 trees per acre after thinning, and an un-thinned control were implemented across a range of sites with varying edaphic conditions. Thinning was performed at a stand age of approximately 12 years by removing every fifth row and then thinning from below poor quality trees from remaining rows. Thinning responses were expressed in relative terms by calculating the difference between a treatment mean and the control mean and expressing it as a percentage of the control mean. Results showed that (1) growth responses in diameter at breast height (d.b.h.) were positive at all thinning intensities, and the responses were stronger for the heavier thinning intensities and increased with year after thinning; (2) growth responses in total height were negligible, especially for heavier thinning intensities; and (3) tree size affected thinning responses both in d.b.h. and height growth, depending on the year post-thinning. Small trees (d.b.h. class of 6 inches) had the largest responses in d.b.h. growth but the responses of the medium (d.b.h. class of 8 inches) and large trees (d.b.h. class of 10 inches) increased with year until year 3. Responses in height growth of small trees were positive at year 1, in particular for heavier thinning, but became negligible after three growing seasons, while medium and large trees showed an opposite pattern, with the responses being small and negative initially but becoming positive, although small, at year 4. These results provide important information regarding early response of loblolly pine plantations to thinning in the Western Gulf Region.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) plantations form a significant proportion of forest land in the Western Gulf Region and are especially important on intensively managed timberlands. In Louisiana in 2013, the growing stock of loblolly pine forests was nearly 9 billion cubic feet (Oswalt 2016). In east Texas, forest lands occupy about 12.1 million acres, of which, 2.9 million acres (24 percent) are classified as pine plantations, with most being composed of loblolly pine (Miles 2013). Due to the economic importance and large annual harvest and reforestation area, extensive studies have examined improving plantation productivity via practicing various silvicultural treatments, including thinning (Fox and others 2007). Typically, loblolly pine plantations in the Western Gulf are first thinned at approximately age 12 (average range of 10 to 15 years), commonly using a combination of geometric and low/improvement thinning (for example, removing every fifth row for access and then removing undesirable trees in the remaining rows).

Loblolly pine, a shade-intolerant tree species, produces best diameter growth under full sun. By opening the canopy, thinning improves light, nutrient, and water availability to residual trees through the removal of less desirable competing trees. Long-term effects of thinning on loblolly pine plantations are well documented. Research indicates that effects of thinning on tree growth varies with thinning method (Baldwin and others 1989), site productivity, geographic region, and other factors (Amateis 2000). For example, thinning has a positive influence on diameter-at-breast-height (d.b.h.) growth. Thinning's impact on total height (THT) growth is small and even negative immediately after application but may became positive thereafter (Ginn and others 1991, Tasissa and Burkhart 1997). Other than intensity of thinning and elapsed time since thinning, other factors such as type of thinning, stand age at time of thinning and site environmental conditions may alter the response.

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The application of these findings to pine plantations in the Western Gulf Region should be used with caution since these studies (1) focused on the Southeastern United States, with few samples in plantations in the Western Gulf Region and (2) utilized a low thinning method, rather than a geometric/low combination regularly used by forest industry. Most reported studies have focused on long-term responses despite the fact that short-term responses are more relevant to common forest management practices. Forest industry standard practices rarely delay second thinning or regeneration harvests for more than 5-7 years after first thinning, thus short-term, rather than long-term, response may be most relevant to current operational forest managers. Understanding of early responses to thinning for loblolly pine, while important for pine plantation management, still is limited. To this end, the East Texas Pine Plantation Research Project initiated a thinning study on 16 sites in 2014. Data from the first 2 years after thinning of nine sites were reported (Grogan and others 2018). An update of Grogan and others (2018), including data from additional sites (16 sites in total) and results for 4 years after thinning, is presented here.

MATERIALS AND METHODS

Sixteen research sites were established between 2014 and 2016, including 11 on regenerated forest sites (cutover and site prepared) and 5 on old field sites (fig. 1). Distributed across east Texas and western Louisiana, sites were selected so that various site qualities were sampled. Initial stand stocking ranged from 550 to 605 trees per acre, which is typical for young pine plantations in this region. Stand averages at time of plot installation were 13.7 years of age (range: 12 to 15), site index of 72 feet at base age 25 years (range: 59 to 87 feet), 7.6 inches d.b.h. (range 4.0 to 13.6 inches), and total height (THT) of 47.9 feet (range: 12.0 to 69.0 feet).

Four 0.5-acre square plots were established at each site with each plot having comparable site index, basal area, and number of trees to minimize variation. One of four thinning treatment categories was randomly assigned to each plot: no thin (control); thin to 150 residual trees per acre (T150, heavily thinned), thin to 225 (T225, moderately thinned), or thin to 300 (T300, lightly thinned). Thinnings followed current operational practices, using a combination of geometric and low thinning techniques by removing every fifth row for access and then removing undesirable trees in the remaining rows to meet the thinning target density.

The individual tree d.b.h. (inches) and THT (feet) were recorded before and annually after thinning. A preliminary analysis showed no difference among plots within a plantation for both traits before thinning. Trees were further assigned into three d.b.h. classes based on pre-thinning d.b.h. values: DC6 (d.b.h. ≤ 6.9 inches), DC8 (7.0 ≤ d.b.h. ≤ 8.9 inches), and DC10 (d.b.h. ≥ 9 inches). Data were examined for errors and outliers removed. An analysis of variance was carried out to test thinning response using the following mixed model:

$$y_{ijklm} = \mu + P_i + S_{j(i)} + T_k + D_l + ST_{j(i)k} + SD_{j(i)k} + TD_{kl} + \varepsilon_{ijklm} \qquad (1)$$

where

y_{ijklm} is the d.b.h. or THT value of the m^{th} tree belonging to the l^{th} d.b.h. class and growing at the k^{th} thinning treatment plot of the j^{th} site and i^{th} plantation type,
P_i is the i^{th} plantation type effect,
$S_{j(i)}$ is the j^{th} site (within the i^{th} plantation type) effect,
T_k is the k^{th} thinning treatment effect,
D_l is the effect of the l^{th} d.b.h. class,
$ST_{j(i)k}$, $SD_{j(i)k}$, and TD_{kl} were interactions between site and thinning, between site and d.b.h. class, and between thinning and d.b.h. class, respectively, and
ε_{ijklm} is a random error with a mean of 0 and a variance σ^2.

Plantation type (cutover versus old field), thinning treatment, d.b.h. class, and their interactions were treated as fixed while site (within a plantation type) and its related interactions, $ST_{j(i)k}$ and $SD_{j(i)k}$, were treated as random so that results can be applied to the region. Other possible interactions were dropped as their effects were not significant. Note that a significant response refers to $\alpha = 0.05$ unless otherwise stated. Where significant treatment effects were observed, treatment least-square means were calculated. Thinning response (relative difference, RD) was calculated as the difference between the treatment and the control means, and then expressed as the percentage of the control:

$$RD = \frac{\text{Mean of a treatment} - \text{Mean of Control}}{\text{Mean of Control}} \times 100 \qquad (2)$$

A positive RD suggests a positive response and an increase in growth from thinning relative to the un-thinned control.

RESULTS

Responses in Diameter Growth

Site effects were not significant, explaining less than 1 percent of the total variation for d.b.h. growth for each year after thinning (YAT) other than the second year, of which 10.9 percent of the variation was accounted for by site. Effects of site and thinning treatment interactions were small, explaining less than 4 percent of the total variation each YAT. Site and d.b.h. class interaction was important for 1 and 2 YAT, accounting for 17.9 percent and 11.5 percent of the variation, respectively, but became less important at 3 and 4 YAT.

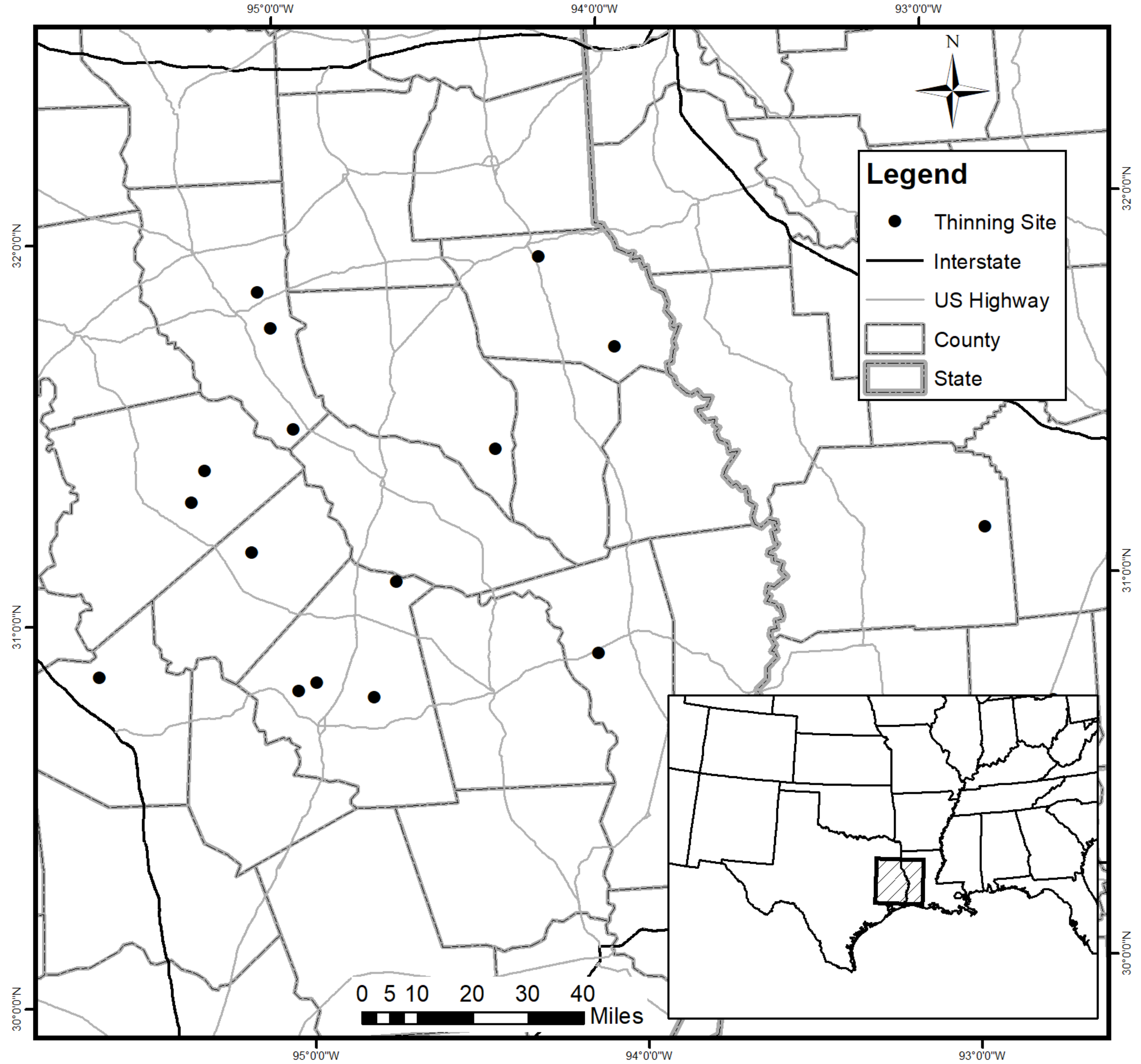

Figure 1—Locations of sites of the East Texas Pine Plantation Research Project loblolly pine thinning study.

Thinning enhanced d.b.h. growth significantly (table 1), more so in the more heavily thinned plots (fig. 2). The RD for each thinning treatment increased each of the first three YAT, yet 3 and 4 YAT were similar (fig. 2). For example, the T150 resulted a RD of 13 percent 1 YAT and increased to over 18 percent at 3 and 4 YAT. Multiple comparisons using the Tukey test showed (1) thinning treatments resulted in significant larger d.b.h. than the Control other than for T300. T300 had significant larger d.b.h. than the control at 1 YAT, but differences became insignificant 2 YAT; (2) d.b.h. differences among three thinning treatments varied with year, differences were significant only between T150 and T300 at 1 YAT but became significant between T150 and T225 2 YAT and among all treatments 3 YAT. At the fourth YAT, however, the thinning effects reduced, remaining significant only between T150 and T300.

Effect of plantation type on d.b.h. growth was significant. While trees on old fields grew faster than those on cutover sites on average, greater thinning responses on cutover sites than on old field sites were observed (fig. 3). This was particularly true for heavier thinning and at 3 and 4 YAT. Plantation type interaction with thinning treatment was not significant.

Diameter class influenced thinning response significantly (fig. 4). Under all intensities, smaller trees had greater, positive relative responses at each YAT. The RDs were comparable across 4 years for DC6, but increased from 1 to 3 YAT and then stabilized for those of DC8

Table 1—Average diameter at breast height by thinning treatment and year post-thinning

Thinning treatment	Year 1	Year 2	Year 3	Year 4
T150	9.15 a	9.68 a	10.00 a	10.62 a
T225	8.77 ab	9.20 b	9.37 b	10.01 ab
T300	8.24 b	8.62 bc	8.79 c	9.34 bc
Control	8.12 c	8.43 c	8.41 c	8.98 c

T150, T225, and T300: 150, 225 and 300 residual trees per acre after thinning; unthinned plots used as control.

Means within a column not followed by a common letter differ at α = 0.05 level.

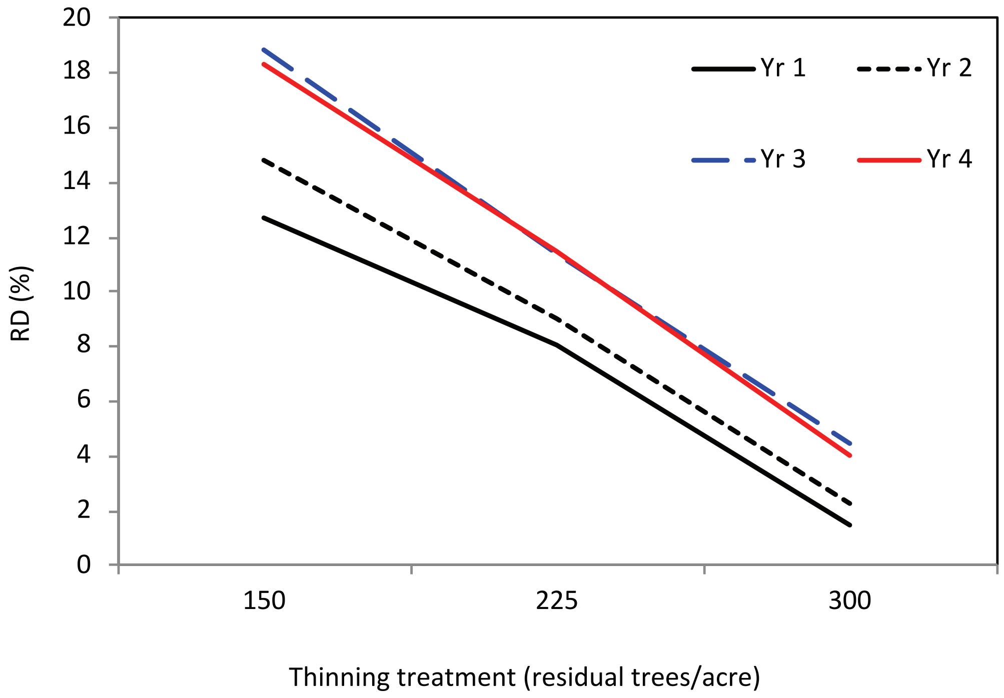

Figure 2—Relative differences (RD in percent) in d.b.h. growth for the thinning treatments compared to unthinned control one (Yr 1), two (Yr 2), three (Yr 3), and four (Yr 4) growing seasons after thinning.

and DC10. The only exceptions were the combination of T300 and DC10, with RD being negligible or even negative for the first 3 YAT, then becoming positive at 4 YAT. Thinning treatment and d.b.h. class interaction was significant for the first and second YAT, but not significant for the third and fourth YAT.

Responses in Height Growth

Effects of plantation type and thinning treatment on THT growth were statistically non-significant (data not shown). During the first 4 years post-thinning, T150 and T225 had positive RDs, while T300 showed negligible or negative responses. Diameter class, influenced THT growth significantly, depending on the year post-thinning (fig. 5). Trees of DC6 responded positively to thinning and showed a declining response with year post-thinning. DC8 and DC10 response was negative, similar among thinning treatments, and improved gradually with year.

DISCUSSION

Effects of thinning on d.b.h. growth were evident after one growing season post-thinning (table 1), supporting the previous findings of loblolly pine thinning studies in the Western Gulf Region (Coble and Grogan 2016) and other Southern United States regions (Pukkala and others 1998, Tasissa and Burkhart 1997). Some other studies reported different results; Ginn and others (1991) and Peterson and others (1997) found that when loblolly pine stands are thinned, time elapsed before the effects were evident (d.b.h. was not significantly greater in thinned stands until 4 years after thinning). However,

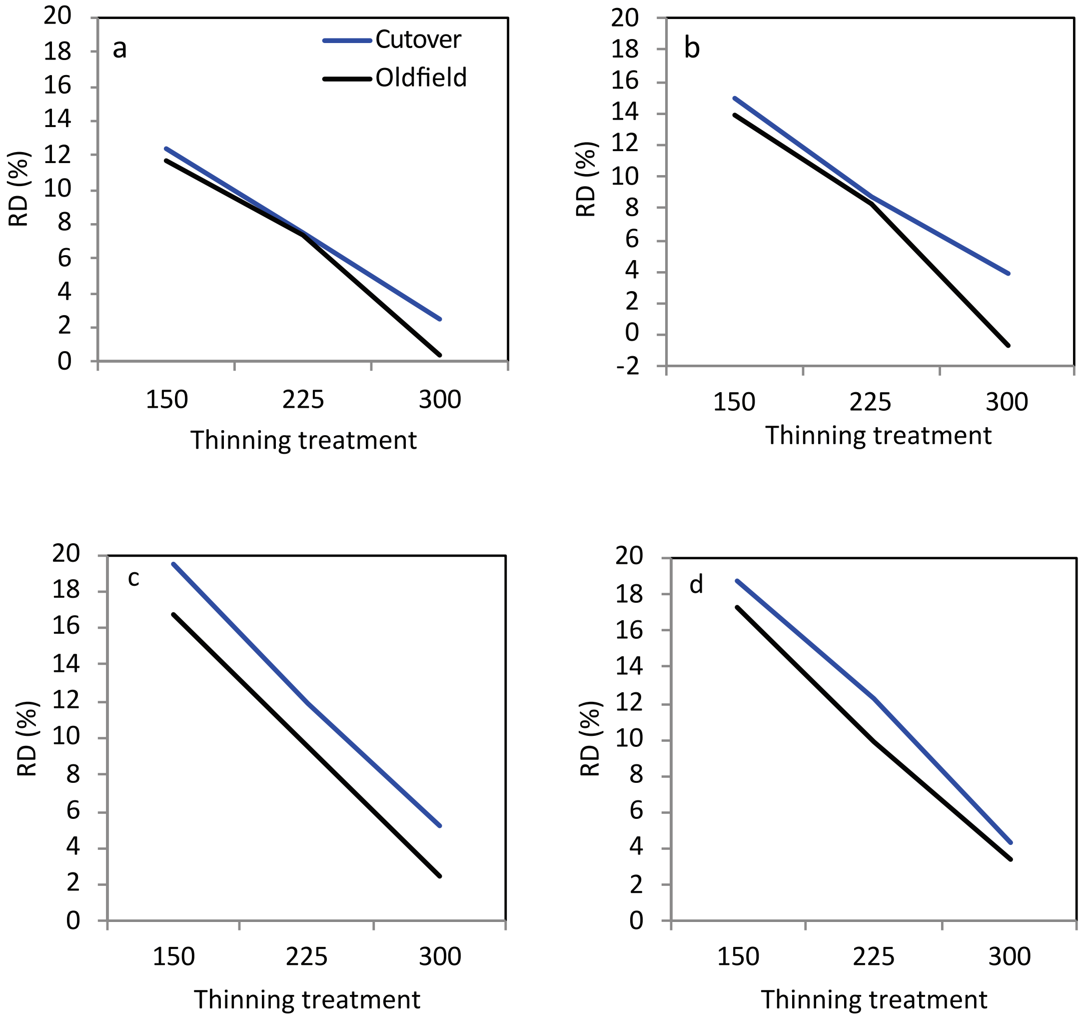

Figure 3—Effects of plantation type on d.b.h. growth responses to thinning (a) 1, (b) 2, (c) 3, and (d) 4 years after thinning. Relative difference (RD) is percent difference from the control.

some other studies reported similar results to this study. Greater d.b.h. growth following thinning for the heavier thinnings (fig. 2; table 1) and temporal patterns of increased response over time were observed in other loblolly pine studies (Moschler and others 1989, Pienaar and Rheney 1995, Tasissa and Burkhart 1997). Clearly, thinning improves availability in light, nutrient and/or water, resulting in an increase in d.b.h. growth over time until site resources again become limited (crown closure) at which time thinning effects decline.

Response of various size (d.b.h.) trees to thinning is of great interest to forest managers and growth-and-yield modelers (Burkhart and Tome 2012). Over the 4-year post thinning period, small trees (DC6) consistently responded more rapidly and strongly than the medium-sized (DC8) and large trees (DC10) (fig. 4), suggesting small trees may utilize free growing space more efficiently and create more photosynthate for growth, at least for the first 4 years post-thinning. Responses of larger trees (DC8 and DC10) were positive and were improved with year after thinning (fig. 4). The exception was T300, of which the responses of trees of DC8 and DC10 were negligible or even negative at the first and second years post-thinning, although became positive thereafter. Overall, trees responded positively in d.b.h. growth despite their size, clearly small trees benefit immediately and more after thinning than large trees. How the growth of individual trees of different sizes within a stand respond to thinning has rarely been studied on loblolly pine, but other species show contradictory results (Eriksson 1987, Hynynen 1995), with some being consistent with results reported here (Makinen and Isomaki 2004).

While radial growth is markedly responsive to thinning, height growth is statistically unaffected (Ginn and others 1991). Various theories have been proposed to explain the contrasting outcome between height growth and radial growth from thinning. After a thinning, a remaining tree first must improve its carbohydrate balance through increases in crown diameter and leaf

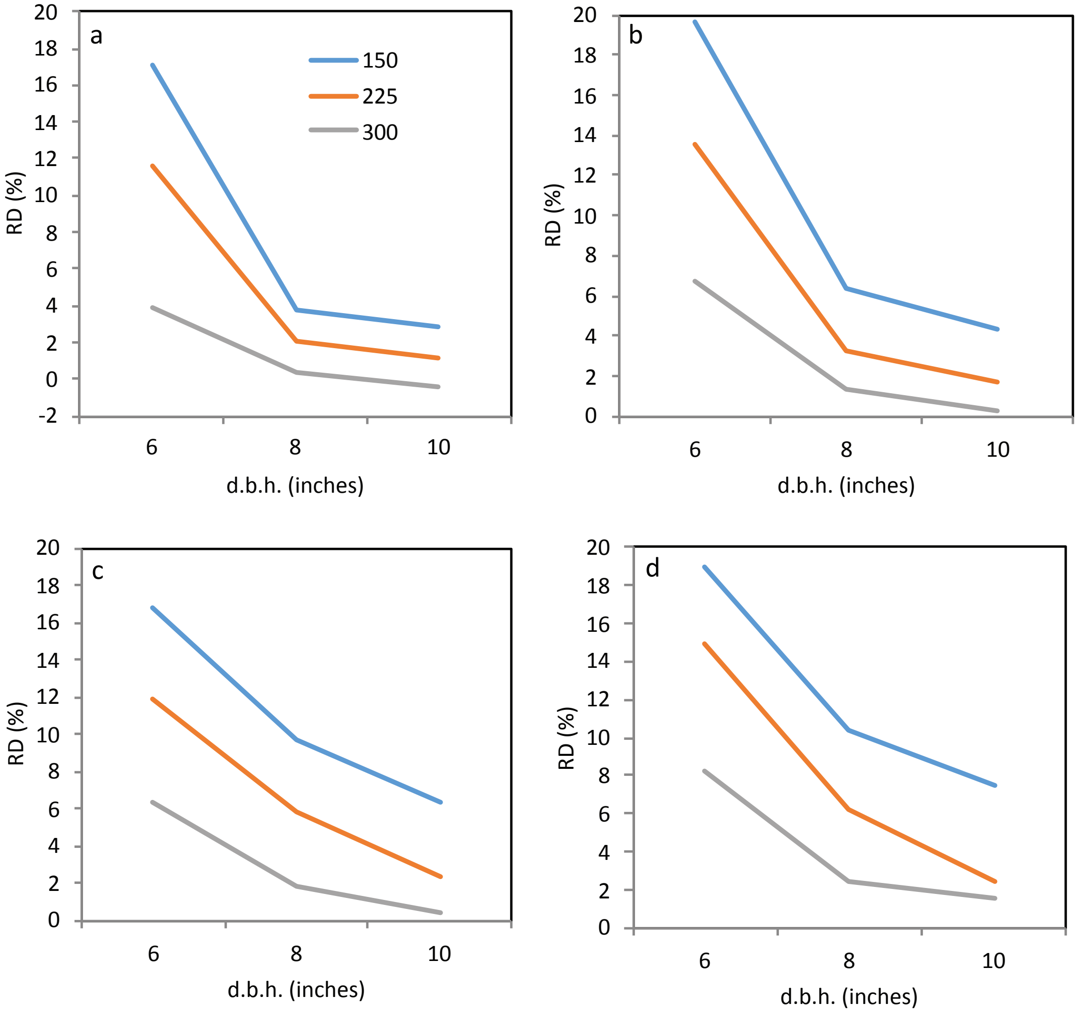

Figure 4—Initial tree d.b.h. effect on d.b.h. growth response to thinning (a) 1, (b) 2, (c) 3, and (d) 4 years after thinning. Relative difference (RD) is percent difference from the control.

area before it increases its volume growth, which often is at the expense of height growth, resulting in decreases in height growth during the first 2 years after thinning (Haywood 1994). Thinning response may also reflect a tradeoff between growing space improvement and thinning shock of a stand after thinning (Harrington and Reukema 1983). These results support both inferences generally, showing negligible increase or decrease in THT growth in all tested thinning intensities over the 4 years post-thinning. In the long term, trees on thinned plots may become comparable in height, or even taller, than those on unthinned counterparts (Brooks and Baily 1992). Despite weak responses overall, THT growth response varied with tree size, depending on the year post-thinning (fig. 5). The small-sized trees had an immediate positive response which subsided with year, while responses of large trees were negative initially but increased slowly with year. After four growing seasons, the RDs in height growth were mostly negative for trees of DC6 and DC8 but were all positive for trees of DC10. Although suppressed trees could react more rapidly and strongly (in relative terms) to thinning initially than large trees, the decline in their growth is accordingly more sudden and faster.

CONCLUSIONS

This study followed operational thinning protocol (i.e., method and stand age at thinning) typical for the region and sampled diversified environments across the region, and therefore the scientific implications derived from this study should reflect thinning responses of operationally thinned plantations in the region. Our results indicated that loblolly pine positively responded in d.b.h. growth immediately after thinning and this response became more evident with increasing year until 3 YAT. Trees responded more strongly to heavier thinning in d.b.h. growth. Thinning effects on height growth were basically negligible, regardless of thinning intensity. Results also showed that initial tree size could substantially affect tree growth response to thinning. The study will be monitored and measured in the future, and additional conclusions may be made when more data become available.

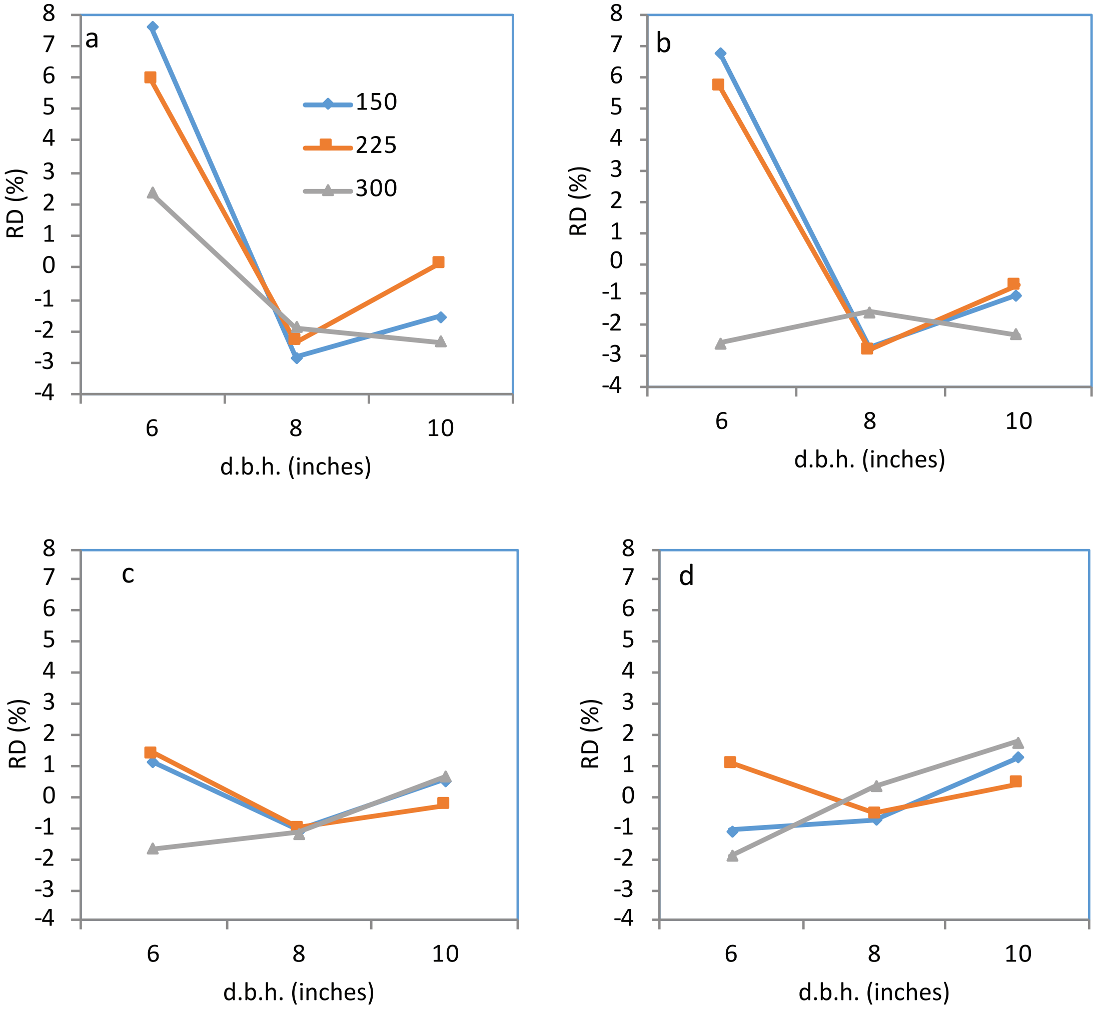

Figure 5—Initial tree d.b.h. effect on total height growth response to thinning (a) 1, (b) 2, (c) 3, and (d) 4 years after thinning. Relative difference (RD) is percent difference from the control.

ACKNOWLEDGMENTS

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FERTILIZATION AND THINNING EFFECTS ON PLANTATION LOBLOLLY PINE TAPER AND WOOD QUALITY

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Harold E. Burkhart, Jerre L. Creighton, Otávio C. Campoe, David R. Carter,
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Abstract—Loblolly pine (*Pinus taeda* L.) plantation forestry continues to incorporate silvicultural advances that increase individual tree growth. These faster-growing trees may have different stem characteristics than their slower-growing predecessors, with unknown effects on wood quality. We examined fertilizer and thinning effects on individual tree taper and wood properties of loblolly pine in the Piedmont of Virginia, United States. Treatments included two levels of thinning (500 (unthinned) and 200 trees per acre residual density) and two levels of fertilization after thinning (none and 200 pounds of nitrogen + 25 pounds of phosphorus per acre) applied at age 15. Nine years after treatment application, age 24, trees (*n* = 24) were measured and destructively sampled. Wood disk samples were collected and evaluated for oven-dry specific gravity. Thinning significantly increased diameter at breast height (d.b.h.), with no significant change in total height. Log taper from 4.5 feet to 24 feet and wood specific gravity were not affected by treatment. Wood specific gravity at breast height ranged from 0.52 to 0.56. Overall, fertilizer and thinning increased the diameter of the first log without changing wood quality. Height to live crown significantly increased 9 feet at 500 trees per acre residual density compared to the 200 trees per acre, resulting in the potential for greater log length with live-branch-free mature wood growth, especially on the second log.

INTRODUCTION

Advances in silvicultural practices in Southeastern United States loblolly pine (*Pinus taeda* L.) plantations have more than doubled productivity since the 1960s (Fox and others 2007). Part of that realized productivity increase is due to mid-rotation fertilization and thinning, which are now common silviculture treatments. It is important to understand the effects of fertilization and thinning on wood quality to avoid an unexpected reduction in quality of any additional high-value wood produced (Antony and others 2015, Love-Meyers and others 2009). Quality shifts could occur as changes in wood specific gravity, knot location, and log shape.

Specific gravity, the ratio of the density of a substance to the density of water, is a common metric for evaluating wood quality due to its high correlation with pulp yield, and strength of wood products (Panshin and de Zeeuw 1980). Tasissa and Burkhart (1998) found up to a 50 percent reduction in basal area through thinning did not alter ring specific gravity. A decrease in specific gravity is expected after mid-rotation fertilization at high rates, such as ~300 pounds of nitrogen (N) per acre, due to increased early wood to late wood ratio (Albaugh and others 2004) or a reduction in latewood specific gravity (Antony and others 2009, Borders and others 2004). Mid-rotation fertilization at lower levels, for example, 100-200 pounds N per acre, however, can result in increased radial growth without decreasing specific gravity (Antony and others 2009). Small changes in ring specific gravity are rarely detectable at the whole-disk level (Antony and others 2015, Rodriguez and Tomazello-Filho 2019).

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The most financially valuable part of the tree is the butt log or first log. Lumber grade is affected by stem form and knot size frequency and location, which is a function of branch location in standing timber (Clark and others 1994). Height to live crown (HTLC) is easily measured in the field and gives a general idea of live-branch knot location on the stem before harvest. Fertilization has little to no effect on HTLC (Yu and others 2003). On the other hand, increased stand density has a strong negative influence on branch diameter of the first log (Ballard and Long 1988). If thinning occurs before the crown recedes, the trees will retain their lower branches (Peterson and others 1997). Clark and others (1994) found that stands with a higher initial planting density that were then heavily thinned yielded a higher percentage of stronger lumber due to less juvenile wood and smaller knots in the lower bole, when compared to stands planted at a wider spacing.

Stem taper is a measure of the degree of cylindricity of a stem (Larson 1963). Highly tapered stems produce lower lumber and pole yields by volume because of the diameter difference between the log-ends (Larson and others 2001). In general, greater stem taper results from fast-growing trees with longer live crowns than slower-growing trees with less live crown length (Larson and others 2001). With a balance of stand density and volume growth, however, loblolly pine on a high quality site with good height growth should show minimal taper in the first log pre- and post-thinning (Larson and others 2001). When comparing fertilized and unfertilized trees, Zhang and others (2002) reported that fertilization reduced outside- and inside-bark taper.

In this study, we evaluated mid-rotation fertilization and thinning effects on wood quality of stems in a 24-year-old loblolly pine plantation, 9 years post-treatment. We tested the hypothesis that fertilization and thinning do not affect growth, specific gravity, or taper.

METHODS

Study Design

Our study was part of a larger study (named Regionwide 19) testing the effects of fertilization and thinning on loblolly pine productivity, established in Appomattox-Buckingham State Forest near Appomattox, VA . The site was located in the Piedmont (37.426N, -78.66E) on a silt loam, with slopes between 2 and 7 percent, classified as Littlejoe and Spears Mountain soil series (USDA NRCS 2017). The site was planted at a density of 500 trees per acre in 1994. Treatments were established in spring of 2009 at age 15 as a split-plot design with four replicates. The thinning treatments were the split-plot and fertilization was the main plot. All plots received operational weed control in summer 2010.

A subset of plots from the larger trial was used in this study to examine the effects of fertilization and thinning on wood quality. We evaluated two levels of fertilization, (with 200 pounds of nitrogen + 25 pounds of phosphorus per acre and without) and two levels of residual stand density (unthinned at 500 and thinned to 200 trees per acre) in factorial combination, with two replicates. This subset design yielded four treatments: no fertilizer and unthinned 500 trees per acre (NF 500TPA), no fertilizer and thinned to 200 trees per acre (NF 200TPA), with fertilizer and unthinned 500 trees per acre (F 500TPA), with fertilizer and thinned to 200 trees per acre (F 200TPA).

Sample Collection

In spring 2018, at age 24, we destructively sampled three trees per plot (subsamples) and two plots per treatment for four treatments. In total, 24 trees were felled. Healthy trees were selected that were as close to plot average d.b.h. as possible (within 0.7 inches). After the tree was felled, total height and HTLC were measured. Two-inch-thick wood disks were cut from the main stem at 4.5 feet above the ground (breast height), and then at increments of 10 feet above breast height up to a 2-inch diameter top (14, 24, 34 feet, etc.). The wood disk samples were kiln dried for 1 week (at 221 °F) to approximately 10 percent moisture content. We measured over-bark dimensions, inside-bark dimensions, and dry weight. For the disks cut at breast height, the dimensions and dry weight were also taken with the bark removed. Dry disk volume (cubic inches) was measured by water immersion for the disk cut at breast height without bark.

Data Analysis

Specific gravity was calculated as oven-dry weight/ oven-dry volume/density of water for all over-bark disks and for disks without-bark at breast height (Williamson and Wiemann 2010). Individual tree volume was calculated using thinned (200 TPA) and unthinned (500 TPA) equations by Tasissa and others (1997). HTLC was evaluated using data from the larger study including four replicates over time. Log taper was quantified by taking the slope of the line between the inside-bark diameters of the height of log end points. Taper for two 10-foot log increments was calculated, 4.5-14 feet and 14-24 feet. Analysis of variance (ANOVA) was used to test for differences among treatments for specific gravity, d.b.h., total tree height, individual tree volume, HTLC by year, diameter inside-bark, and taper as linear slope of log end points. If $p < 0.05$, ANOVA was followed by a post-hoc Tukey HSD test. Main effects and interactions were examined using JMP® statistical software.

RESULTS AND DISCUSSION

Productivity

Diameter significantly increased from 9.4 to 10.9 inches with thinning ($p < 0.001$, fig. 1a). There were no significant fertilization effects on d.b.h. ($p = 0.632$). There

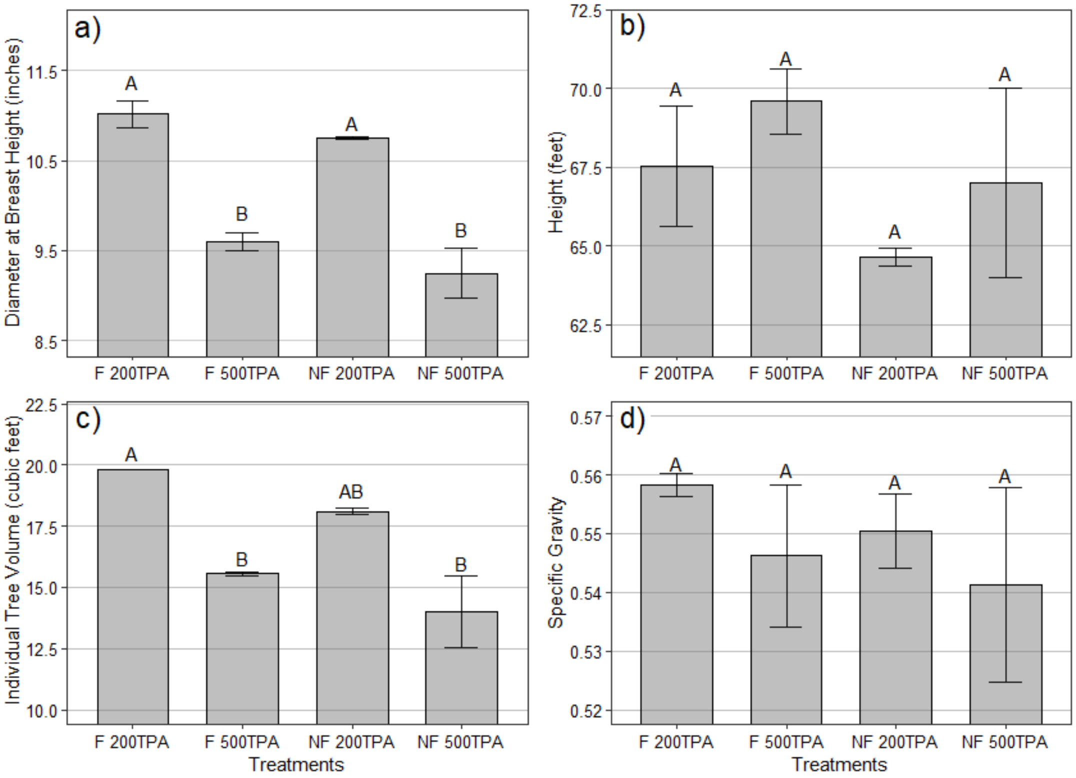

Figure 1—Fertilized 200 trees per acre (F 200TPA), fertilized 500 trees per acre (F 500TPA), unfertilized 200 trees per acre (NF 200TPA), and unfertilized 500 trees per acre (NF 500TPA) treatment means and standard errors for a) d.b.h. (inches), b) height (feet), c) individual tree volume (cubic feet), d) wood disk specific gravity without bark at breast height. Ordered letters show significant differences from Tukey HSD post-hoc test.

was no significant interaction between thinning and fertilization for d.b.h. ($p = 0.651$). Total height ranged from 64.0 to 70.6 feet, with no significant differences among treatments ($p = 0.416$, fig. 1b).

The F 200TPA treatment had significantly higher individual tree volume than the F 500TPA and NF 500 TPA treatments, by an average of 5 cubic feet per tree ($p = 0.017$, fig. 1c). Others have shown individual tree volume increased after thinning, due to increased resources available to the remaining trees (Albaugh and others 2017). Height is not generally affected by thinning or N fertilization, as such, the volume response to treatment predominately results from diameter increases (Albaugh and others 2017). Individual tree volume growth after a thinning comes as a tradeoff to stand volume growth.

Specific Gravity

Increased tree growth after thinning can change ring width and the ratio of earlywood:latewood. Wood specific gravity at breast height ranged from 0.52 to 0.56 with no significant differences among treatments ($p = 0.734$, fig. 1d). Moreover, we found that wood specific gravity was not affected by fertilization or thinning in the largest and most valuable section of the tree for timber production. In addition, there were no significant differences in over-bark specific gravity throughout the height of the trees ($p > 0.05$). An increase in specific gravity of just 0.02 can significantly increase dry pulp wood yield (Mitchell 1964). A larger sample size may have increased our sensitivity to detect differences in specific gravity at that scale (Williamson and Wiemann 2010). Ring specific gravity following fertilization decreases with increased volume growth; however, this effect may last for just 2 or 3 years post N fertilization (Love-Meyers and others 2009). At the whole-disk level, fertilization did not significantly affect specific gravity (Antony and others 2015, Rodriguez and Tomazello-Filho 2019), which our findings support (fig. 1d).

Height to Live Crown

Without thinning, HTLC significantly increased from age 18 to 24 ($p = 0.022$, fig. 2). At age 24, we found no significant HTLC differences ($p = 0.624$) or interactions ($p = 0.807$) with fertilization. Thinning to 200TPA likely allowed more light lower in the crown than the 500TPA treatments (Yu and others 2003). Additional light would have allowed the 200TPA to retain leaf area lower in the crown, which would support and retain lower branches. Nine years post-thinning, HTLC averaged 39.3 and 30.3 feet, in the 500TPA and 200TPA plots, respectively. This difference in HTLC over time results in a merchantable log free of live branches (~0-32 feet) in the 500TPA

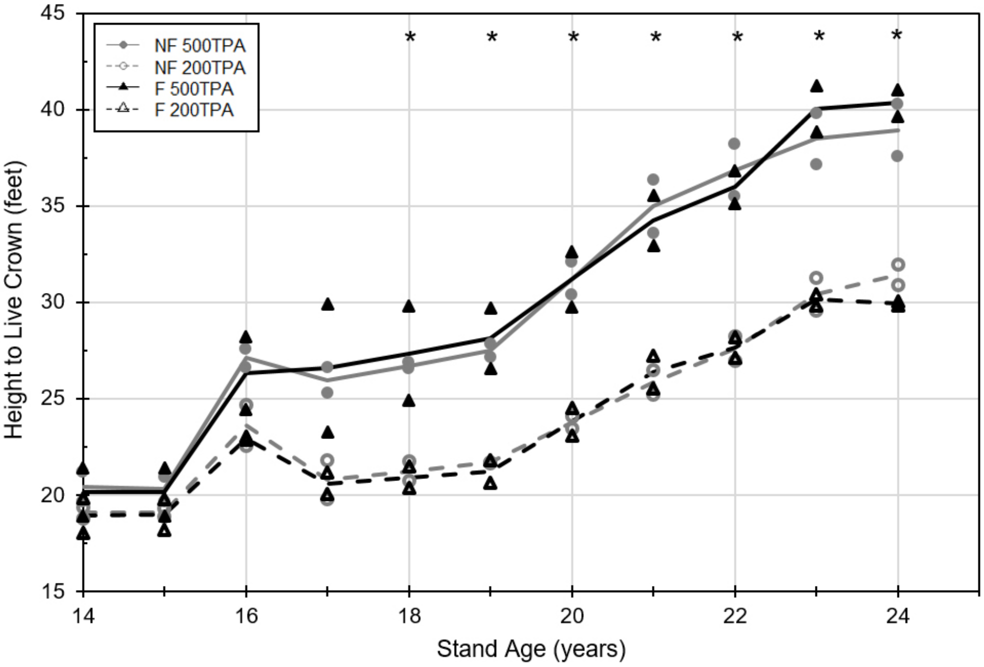

Figure 2—Height to live crown over time for fertilized 200 trees per acre (F 200TPA), fertilized 500 trees per acre (F 500TPA), unfertilized 200 trees per acre (NF 200TPA), and unfertilized 500 trees per acre (NF 500TPA) treatments. Points show mean per plot, where lines show treatment average. Includes data for 11 measurement trees per plot over time. Significant thinning effects by year are denoted by asterisk (*, $p < 0.05$). There were no significant fertilization effects or interactions.

treatment after age 21, whereas the 200TPA treatments still retain live branches below 32 feet and within potential high timber value log length.

Taper

We found significant increases in inside-bark diameter with thinning at 4.5, 14, 24, and 34 feet and with fertilization at 4.5, 34, and 44 feet ($p < 0.05$, fig. 3). There was no significant fertilizer by thinning interaction ($p > 0.05$). We found no significant treatment effect on the taper slope for the first (4.5-14 feet, $p = 0.458$) and second (14-24 feet, $p = 0.983$) logs (fig. 4a-b). These results show that thinning increases the inside-bark diameter of the stem (4.5-34 feet) without increasing the slope, or taper, of the log within the most valuable section.

CONCLUSIONS

In this study, we found that reducing stand density from 500 to 200 trees per acre increased inside-bark diameter of the first and second log without changing taper or wood specific gravity at the individual tree scale. These results would be positive for a mill operator to know that thinned stands from similar sites yield larger logs where the only potential quality difference would be live branches lower on the stem when compared to unthinned stands. For a timberland manager, whose primary economic incentive is to produce more value, these results provide information about the tradeoffs of individual tree value and stand volume in thinned and unthinned stands.

If the trends in diameter, height, volume, specific gravity, HTLC, and taper remain the same through the life of the stand, there are potential tradeoffs between producing rapidly growing wood and clear wood. Based on our results, this tradeoff is influenced by HTLC, in other words, lower live branches, and increases in volume growth with thinning. Currently, the selection of optimum silvicultural treatment, be it fertilization or thinning or a combination of both, is driven by the balance between volume production and individual stem size. Few mills pay a premium for high quality individual stems and consequently, the economics currently tilt the scale in favor of volume production.

In future work at the Appomattox, VA, site, we aim to collect similar data at the time of harvest, near year 30, to assess second thinning and fertilization effects on wood quality. With this study, we hope to inform future research evaluating fertilization and thinning effects on wood quality at second thinning and harvest at other Regionwide 19 sites that differ by location and soil type.

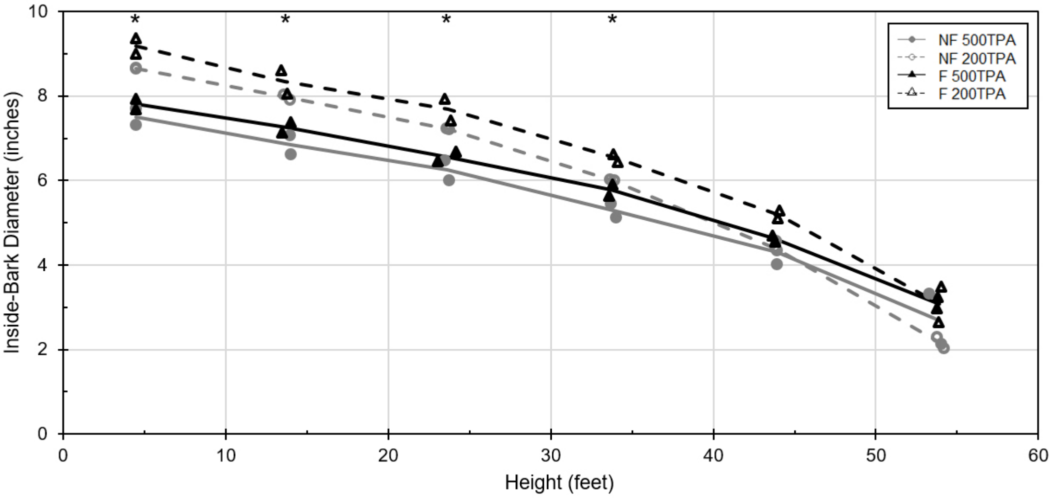

Figure 3—Diameter inside bark (inches) by height (taper) for fertilized 200 trees per acre (F 200TPA), fertilized 500 trees per acre (F 500TPA), unfertilized 200 trees per acre (NF 200TPA), and unfertilized 500 trees per acre (NF 500TPA) treatments. Points show mean per plot, where lines show treatment average. Data shown is from breast height to 54 feet, which is the tallest common diameter measured for all trees and does not include the total height of the tree. Significant thinning effects by year are denoted by asterisk (*, $p < 0.05$).

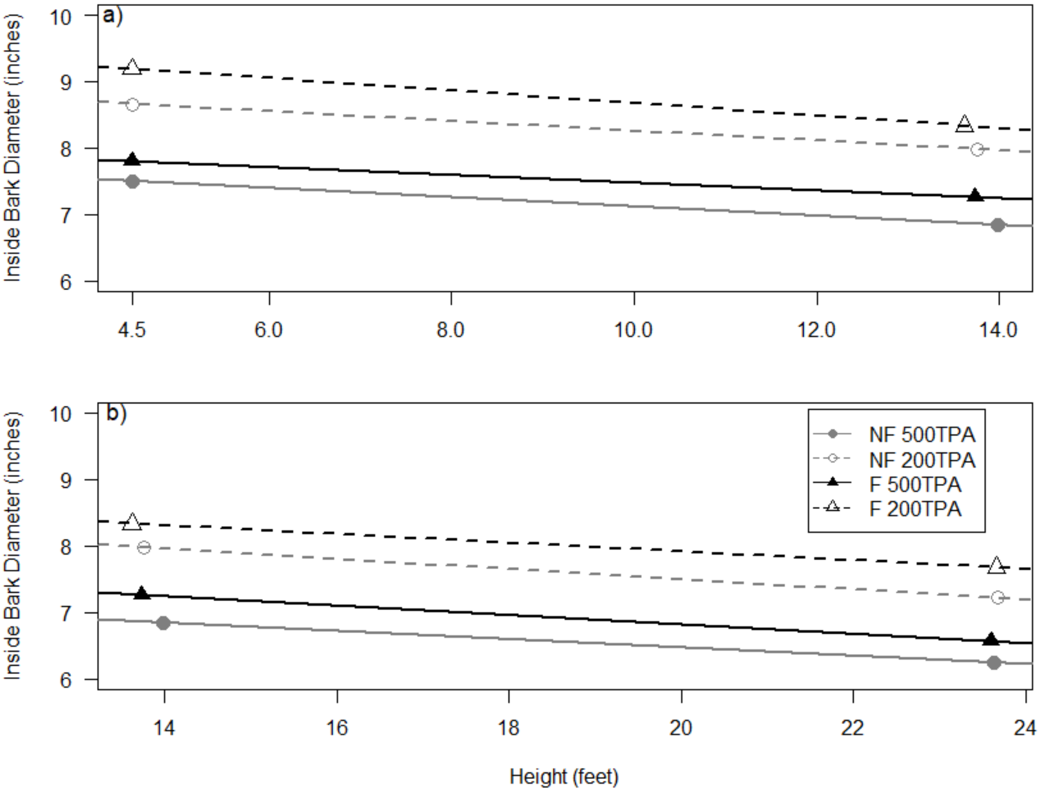

Figure 4—Linear relationship between the inside-bark diameter (inches) end points of the a) first log, 4.5–14 feet, and b) second log, 14–24 feet, for fertilized 200 trees per acre (F 200TPA), fertilized 500 trees per acre (F 500TPA), unfertilized 200 trees per acre (NF 200TPA), and unfertilized 500 trees per acre (NF 500TPA) treatments. There were no significant differences in the slope of the lines between treatments for the first and second log.

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ABOVEGROUND CARBON STOCK AND DISTRIBUTION IN MANAGED AND UNMANAGED MATURE, NATURAL-ORIGIN, PINE-HARDWOOD FOREST STANDS

Mohammad M. Bataineh

Abstract—Carbon storage and maintaining forest complexity have been important objectives in developing forest management strategies to address global climate change. Although maintaining complexity and carbon stores are inherently interrelated, the effect of management strategies on these objectives have generally been examined independently. Moreover, little is known about the effect of management on carbon stock and distribution in structurally and compositionally complex forests. This study examines the effect of selective, partial harvests on carbon stock and distribution in natural-origin, 80- to 120-year-old, pine (*Pinus* spp.)-hardwood stands of southeastern Arkansas. Carbon pool estimates were derived for all aboveground pools. Harvests resulted in slightly more uniform stand structure and reduced aboveground carbon stores by 8 tons per acre. Post-harvest large tree residuals maintained carbon stock at relatively high-levels with greater potential for live tree carbon increment. Carefully planned partial harvests in complex stands may allow for greater flexibility in balancing maintenance of carbon stock and fostering structural and compositional complexity.

INTRODUCTION

Area of natural-origin pine (*Pinus* spp.) forest in the Southeastern United States declined dramatically between 1950 and 2010 (Hartsell and Conner 2013). This decline was associated with an increase in pine plantation dominance over the landscape (Zhang and Polyakov 2010), as landowner's preference shifted toward short-rotation, high-yielding systems. Similar but less drastic declines were also reported for oak (*Quercus* spp.)-pine forest (Hartsell and Conner 2013), highlighting the increased homogenization of the southern landscape. In Arkansas, declines in natural-origin pine and oak-pine forest amounted to 2 million acres since 1978, while planted pine acreage increased by 3 million acres (USDA FIA 2019). Area changes in natural-origin pine were accompanied by increased structural uniformity. For example, 70 percent of the remaining natural-origin pine in Arkansas is currently under 40 years old and natural-origin stands greater than 80 years account for only 3 percent of the area (USDA FIA 2019).

In light of these trends, it is becoming more important to quantify and document the current conditions of mature, unmanaged, natural-origin pine, pine-hardwood, and upland hardwood stands. These stands represent a legacy of natural disturbance and stand dynamics and may serve as reference conditions (Bragg 2013, Bragg and Shelton 2011) and analogs in establishing, converting to, restoring, or maintaining structurally and compositionally complex forests that may have higher adaptive capacity than their counterparts. Although current management strategies to address global climate change stress enhancing carbon stores and fostering forest adaptive capacity through maintenance of structural and compositional complexity, there is clearly a trade-off between storing carbon on site using highly stocked stands and promoting stand-level complexity (D'Amato and others 2011). Moreover, little is known about the effect of management on carbon stock and distribution in structurally and compositionally complex forests, such as mature, natural-origin pine-hardwood forests of the Upper West Gulf Coastal Plain (UWGCP).

Although pine-hardwood stands of the UWGCP were described as transient in successional development in the absence of disturbance (Bragg and Shelton 2011, Hartsell and Conner 2013), these stands provide potential for the establishment and maintenance of mixed-species, multi-cohort/stratified stands that provide for enhanced carbon stores while simultaneously maintaining and enhancing complexity. The objective of this study was to examine the effect of selective, partial harvests on carbon stock and distribution in natural-origin, 80- to 120-year-old, mature pine-hardwood stands of southeastern Arkansas.

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MATERIALS AND METHODS

Study Area

The study area is within the UWGCP, which is described as rolling plains punctuated with fluvial terraces, bottomlands, and low cuestas. Forests dominate the landscape with loblolly pine (*Pinus taeda*), shortleaf pine (*P. echinata*), sweetgum (*Liquidambar styraciflua*), oak (*Quercus* spp.), gum (*Nyssa* spp.), and hickory (*Carya* spp.) as main species (Woods and others 2004). Elevation is 430 feet above sea level. The climate is characterized by warm summers and mild winters with mean annual precipitation of 53 inches, 70 percent of which falls in November through May, and an annual frost-free period of 236 days (Larance and others 1968). Mean annual temperature is 62.8 °F. Soils series of the study area include Savannah (siliceous, semiactive, thermic Typic Fragiudults), which are described as very deep, moderately well-drained, and slowly permeable on uplands and terraces; Wehadkee (mixed, active, nonacid, thermic Fluvaquentic Endoaquepts), which are very deep, poorly to very poorly drained along streams and on floodplains in bottomlands; Boswell (mixed, active, thermic Vertic Paleudalfs), which are very deep, moderately well-drained, and very slowly permeable fine sandy loams on uplands; Caddo (siliceous, active, thermic Typic Glossaqualfs), which are described as very deep, poorly drained, acidic soils, with little organic matter in upland locations; and Stough (siliceous, semiactive, thermic Fragiaquic Paleudults), which are poorly drained, acidic, of low fertility, coarse loams along stream terraces (Larance and others 1968).

Study Design and Treatments

Four mature (80-120 years old), natural-origin, pine-hardwood stands were selected in Cleveland County, Arkansas. The four stands had a similar disturbance history with a harvest in the late 19th century followed by no management intervention until the partial harvest treatments in 2013. Stand overstories were composed of a mixture of pine-hardwood with shortleaf pine, loblolly pine, southern red oak (*Q. falcata*), cherrybark oak (*Q. pagoda*), post oak (*Q. stellata*), and white oak (*Q. alba*) as main components. Dense hardwood dominated understories were present with an abundance of shrubs and vines. Stands were 4 to 9 miles apart.

In fall 2013, two stands were harvested (i.e., East and Northeast stands) and two were left unharvested (i.e., North and West stands). The harvest was a selective, partial cut that removed a quarter to a third of the standing overstory basal area. Removals included the midstory layer. The management objective was to increase the growth of residual overstory trees while also stimulating regeneration of pine and oak species. No pre-harvest data were available.

Measurements

In fall 2015, the four stands were selected for sampling. Within each stand, 10 permanent 0.2-acre plots were established to measure overstory trees (≥5 inches in diameter at breast height (d.b.h.)). Using the same plot centers, snags (standing dead trees with ≥5 inches d.b.h.) were measured within 10 0.5-acre plots extending beyond the perimeter of overstory tree plots (fig. 1). Three nested 0.02-acre subplots were used for sapling (<5 inches in d.b.h. and ≥4.5 feet in height) measurements. Three 6.8-foot-radius microplots were established for measurements of tree seedlings (1 foot < height < 4.5 feet). Ground vegetation was measured within each of three 10.7-square-foot quadrats centered at each microplot. Coarse (≥3 inches diameter at intersection) and fine (<3 inches diameter at intersection) downed woody material (DWM) were quantified using three line transects along the same azimuth used for establishing the three microplots. DWM transects were 52.7 feet in length and the whole length was used in sampling coarse DWM while a 22-foot transect section was used for fine DWM. None of the plots fell in riparian areas.

Within each permanent plot and subplot, all overstory trees and saplings were identified, tagged, and d.b.h. measured. Snag d.b.h. and total height were measured and snags were assigned one of five decay classes following Chojnacky and others (2004). Tree seedlings were harvested within each microplot and ground vegetation by growth habit were also clipped to estimate biomass. Samples were dried to a constant mass at 212 °F then weighed. DWM was counted or diameter measured along corresponding transect lengths then converted to biomass estimates using Brown's (1974) established methodology. DWM was assigned to one of five decay classes following Chojnacky and others (2004). Snags and DWM were identified to species when unique features were still present and lumped into either pine or hardwood groups when no identifiable species features were present. Specific gravity of DWM species were determined using Miles and Smith (2009).

Analytical Approach

The updated generalized national biomass equations were used to calculate biomass for overstory trees, saplings, and snags (Chojnacky and others 2014). Snags biomass were reduced based on decay status following Harmon and others (2011). Individual tree estimates were pooled for each sampling plot and biomass estimates were converted into carbon using a 0.5 ratio. Seedlings and ground vegetation biomass were determined using dry weights then converted to carbon estimates. Ground vegetation was pooled by growth habit within each quadrat. DWM weights were adjusted based on decay following Chojnacky and others (2004). DWM mass

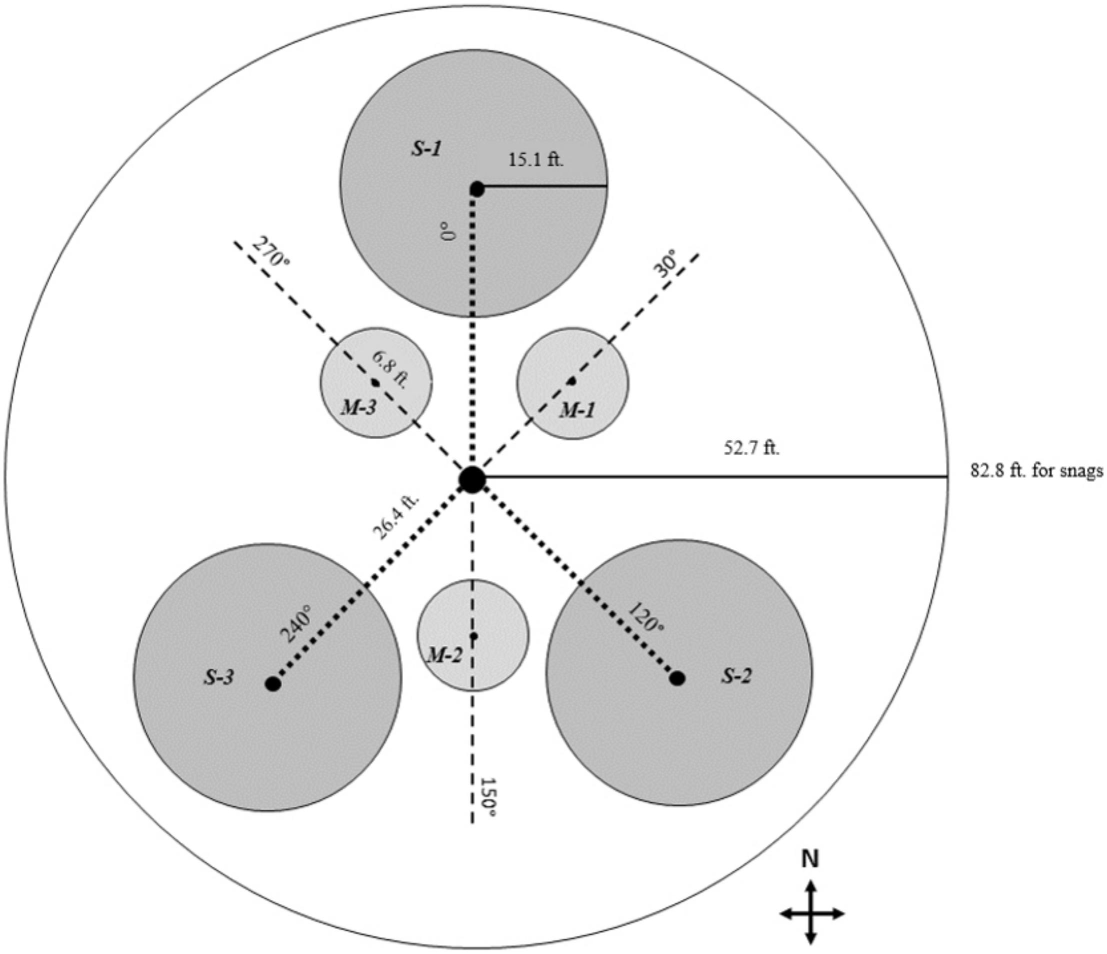

Figure 1—Sampling plot layout and size with sapling subplots (S) and seedlings and ground vegetation microplots (M).

was also converted to carbon estimates using a 0.5 ratio. All carbon estimates were converted to tons per acre estimates.

Standard stand descriptive summary statistics were calculated for tree density, basal area, quadratic mean diameter, stand density index, and site index. Site index was calculated using the curves developed by Zahner (1962) for loblolly pine in southern Arkansas as compiled by Carmean and others (1989). Overstory and sapling d.b.h. distributions were constructed and a two-parameter Weibull function was fit to each stand d.b.h. distribution to highlight differences in tree sizes among stands. The effect of the selective, partial harvests on carbon stock and distribution was tested using one-way analysis of variance (ANOVA) at an alpha level of 0.05. The analysis was conducted based on a completely randomized design. All analyses were conducted using R software version 3.0.2 (R Development Core Team 2013). No indication of patterns in residual plots were detected as evidence of violation of assumptions of normality and homogeneity of variance.

RESULTS AND DISCUSSION

As expected, harvest removals resulted in lower overstory density for managed stands (table 1). In general, the four sites were similar in their site index while their site productivity did not appear to have a confounding effect on growth potential. Overstory d.b.h. distributions were positively skewed for unmanaged stands while managed stands distributions were unimodal (fig. 2). The selective, partial harvest appeared to remove larger diameter trees while maintaining relatively high overstory basal area. Harvests appeared to maintain the pine-hardwood composition of the stands with the proportion of pine basal area remaining at 44 percent and 66 percent for East and Northeast stands, respectively (fig. 3). Harvests appeared to have removed a large portion of the saplings layer (fig. 3).

Unmanaged stands had 12 tons per acre higher aboveground carbon stores in combined overstory trees and saplings ($p < 0.01$, fig. 4). Live tree carbon estimates for unmanaged stands were on par with that reported for the Hyatt's Woods (~ 58 tons per acre; Bragg 2013).

Table 1—Post-harvest overstory attributes for four mature (80-120 years old), natural-origin, pine-hardwood stands in Cleveland County, Arkansas

Treatment					
Stand	Density	Basal area	QMD	SDI	SI
	trees per acre	*square feet per acre*	*inches*	*trees per acre*	*feet*
Managed					
East	51 (14)	92.6 (17.5)	18.6 (2.1)	133 (26)	103 (3)
Northeast	56 (18)	89.4 (29.7)	17.2 (1.2)	132 (43)	99 (6)
Unmanaged					
North	105 (32)	130.9 (33.8)	15.5 (2.2)	203 (52)	104 (7)
West	133 (44)	120.6 (41.8)	13.1 (2.4)	198 (64)	95 (10)

Mean values with standard deviation in parenthesis.

QMD = Quadratic mean diameter, SDI = Stand density index, SI = Site index.

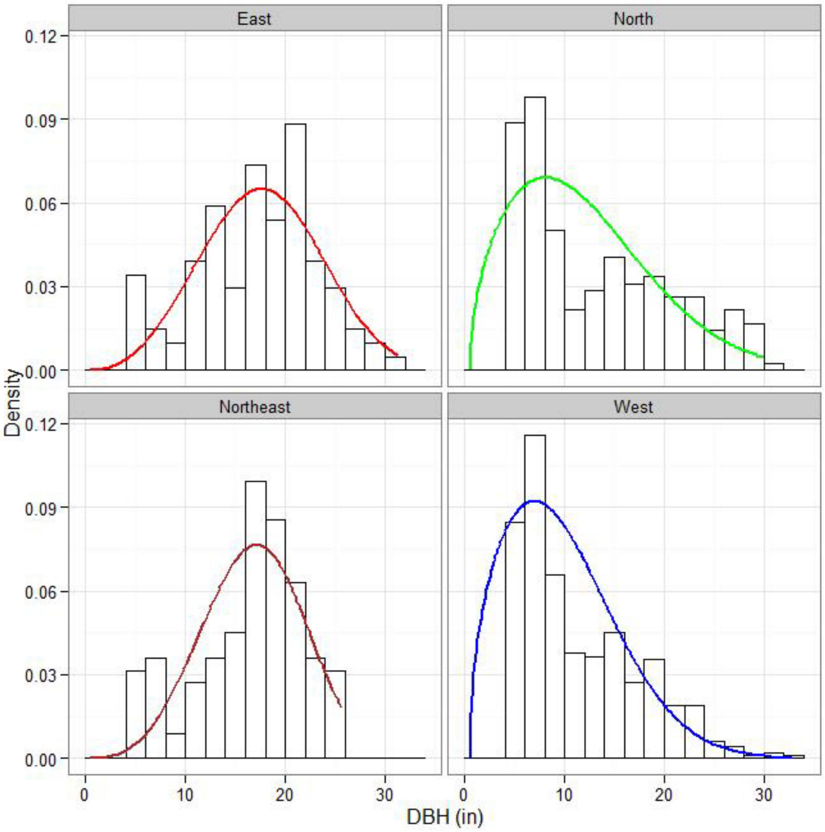

Figure 2—Overstory tree (d.b.h. ≥5 inches) d.b.h. distribution (trees per acre) with fitted two-parameter Weibull model for each of managed (East and Northeast) and unmanaged (North and West) mature (80-120 years old), natural-origin, pine-hardwood stands in Cleveland County, Arkansas.

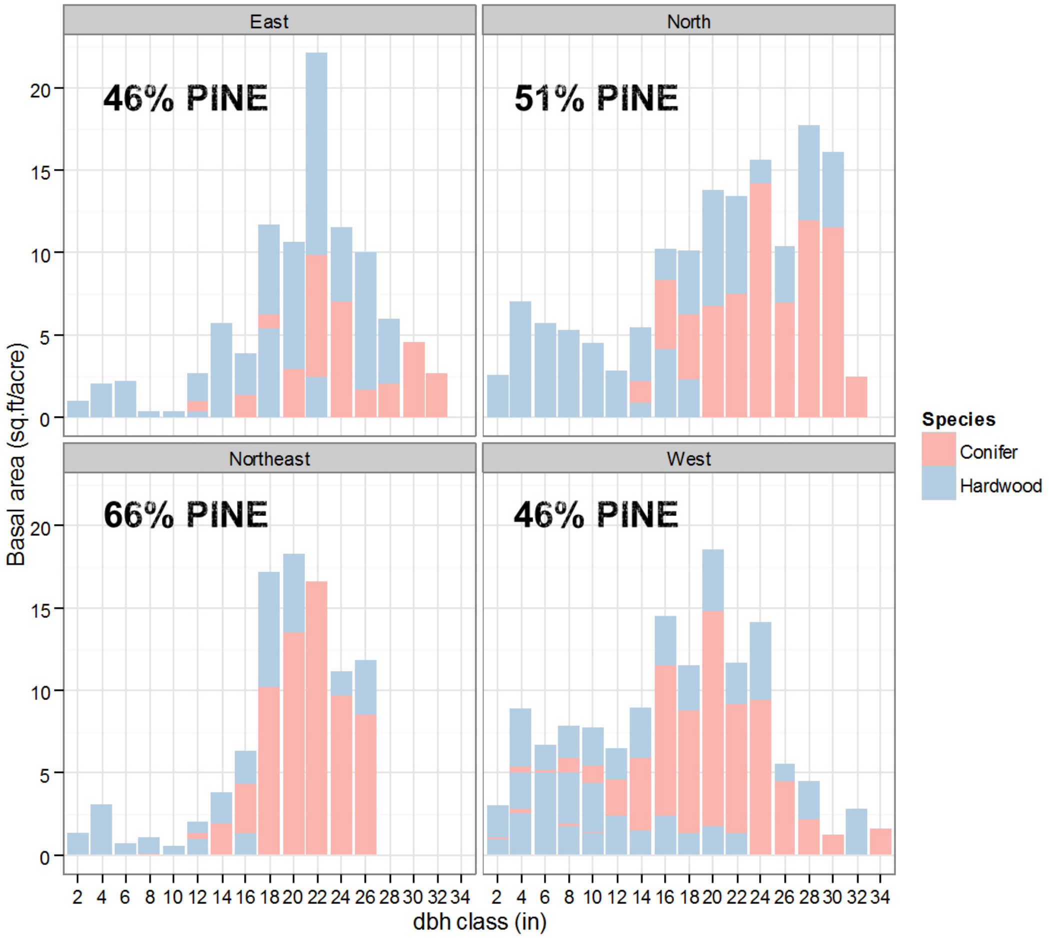

Figure 3—Combined sapling (<5 inches in d.b.h. and ≥4.5 feet in height) and overstory tree (d.b.h. ≥5 inches) d.b.h. distribution for each of managed (East and Northeast) and unmanaged (North and West) mature (80-120 years old), natural-origin, pine-hardwood stands in Cleveland County, Arkansas. Red color indicates conifer while blue indicates hardwood.

Ground vegetation and seedling carbon stores did not differ between managed and unmanaged stands (p = 0.4 and 0.2, respectively). DWM was 4 tons per acre higher in managed stands ($p < 0.01$, fig. 5). In general, greater within-stand variability in tree and sapling carbon stores were observed for unmanaged stands (fig. 4) while managed stands had greater within-stand variability in DWM carbon stores (fig. 5).

As stated previously, no pre-harvest data were available. However, the four examined stands shared a similar disturbance and management history and were in close proximity and of similar site quality. In other words, there was no reason or evidence to indicate that those stands had dramatically different initial structures and volumes. Therefore, harvest removals resulted in reduction in carbon stores of live trees and saplings by 12 tons per acre while increasing DWM carbon stores by 4 tons per acre (figs. 4 and 5), for a net effect of 8 tons per acre. These trends are consistent with declines in tree density following harvest and increase in DWM as a result of harvest slash (Fraver and others 2002). Given that stands were sampled within a 2-year period following harvest and that overstory basal area remained relatively high, it is not surprising that ground vegetation and seedling carbon stores did not differ from that in unmanaged stands.

CONCLUSIONS

As area of natural-origin pine forest-type in the Southeastern United States continues to decline and landscape homogeneity increases, it is imperative to document the current conditions of mature, unmanaged, natural-origin pine, pine-hardwood, and upland hardwood stands that represent a legacy of natural disturbance. A better understanding of the effect of harvesting in these compositionally and structurally complex stands will provide for management strategies that maintain carbon stores while simultaneously maintaining and/or enhancing forest complexity. A selective, partial harvest in natural-origin, mature, pine-hardwood stands in southeastern Arkansas resulted

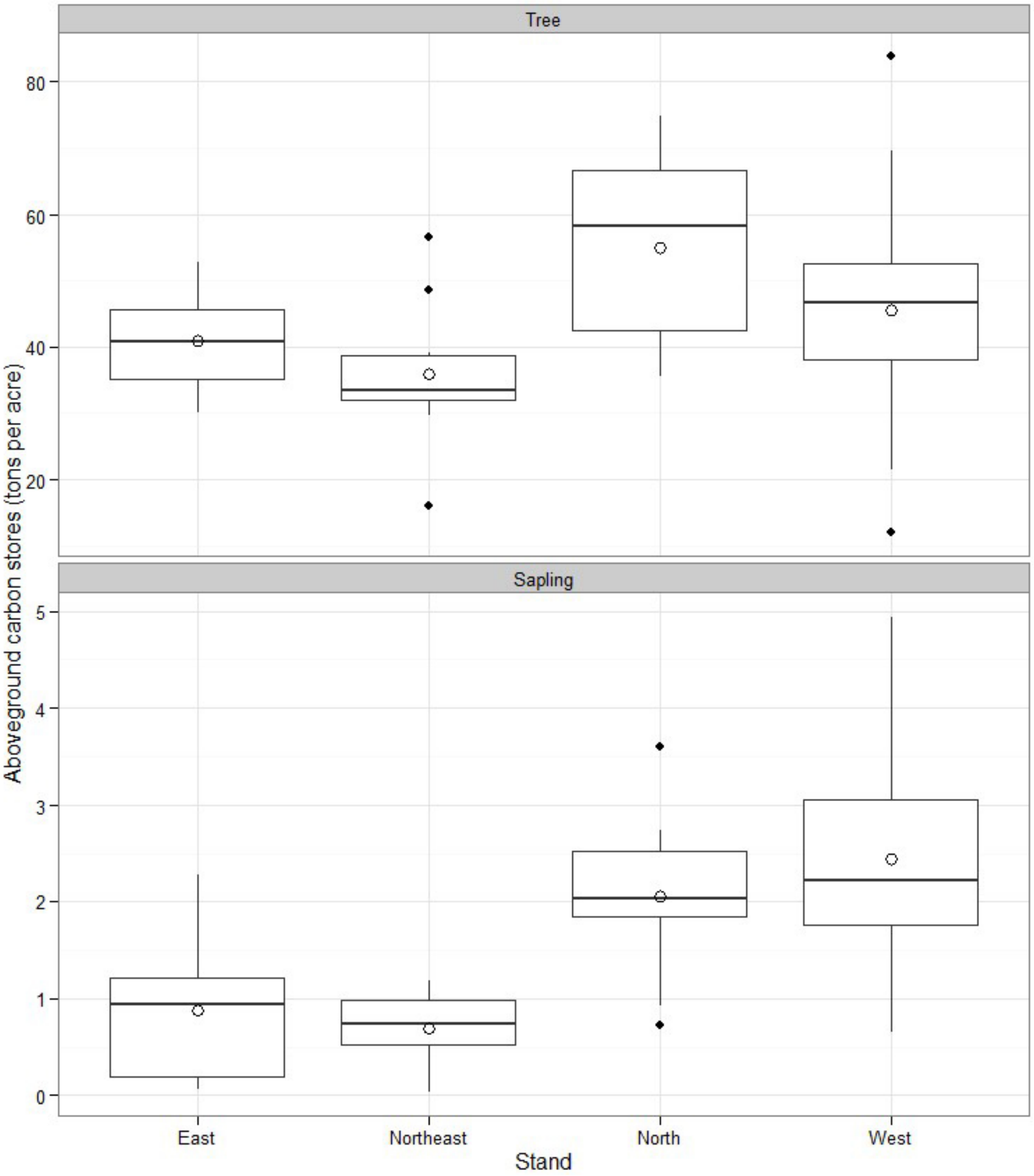

Figure 4—Box plot distribution of overstory tree (d.b.h. ≥5 inches; top) and sapling (<5 inches in d.b.h. and ≥4.5 feet in height; bottom) live, aboveground carbon stores for each managed (East and Northeast) and unmanaged (North and West) mature (80-120 years old), natural-origin, pine-hardwood stand in Cleveland County, Arkansas. Each box represents the 25th, median (50th; horizontal dash), and 75th percentiles. The error bars (whiskers) represent the 10th (below) and 90th (above) percentiles; open circles represent mean; and filled diamonds represent outliers.

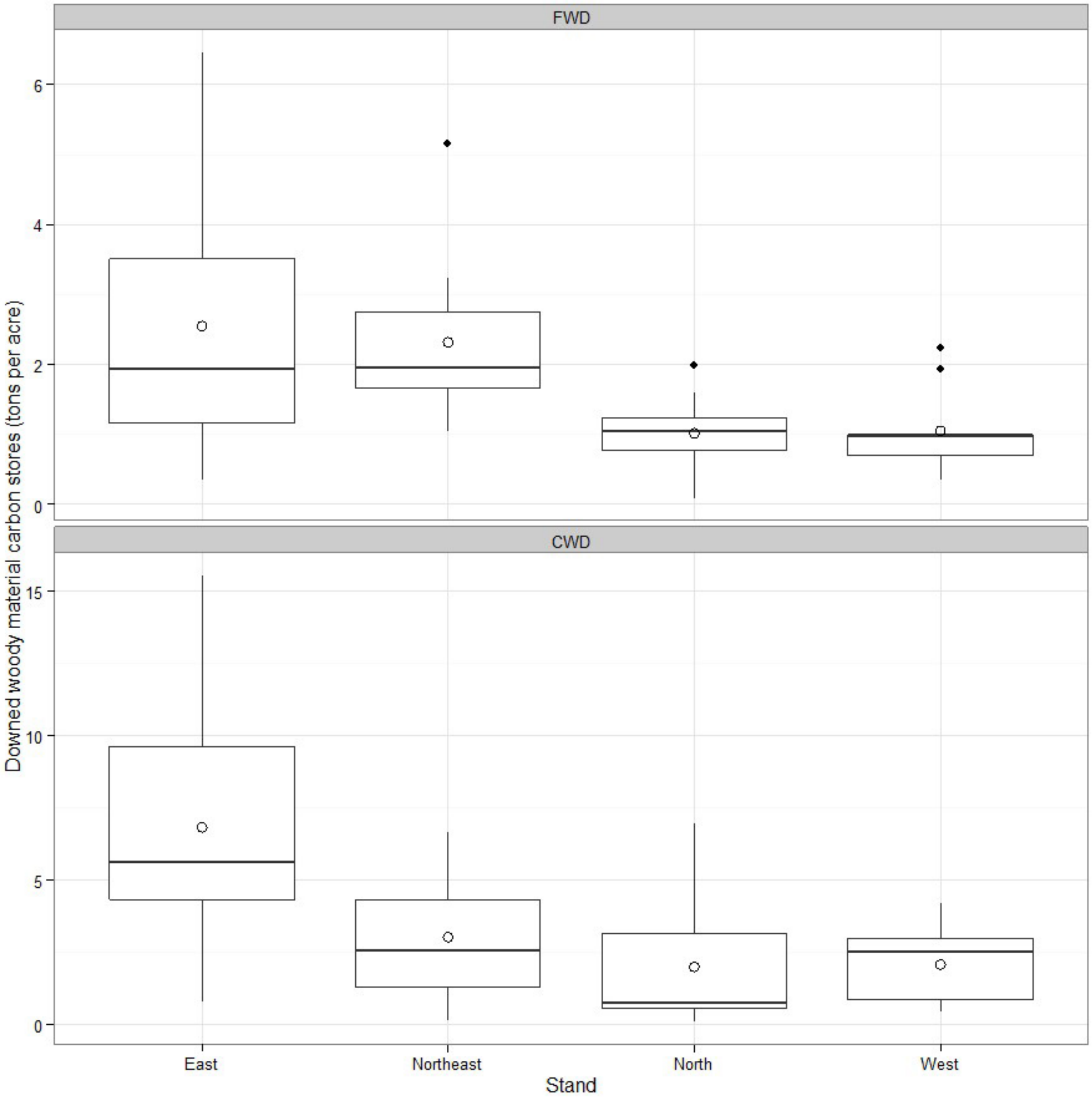

Figure 5—Box plot distribution of fine (<3 inches diameter at intersection; FWD; top) and coarse (≥3 inches diameter at intersection; CWD; bottom) downed woody material carbon stores for each managed (East and Northeast) and unmanaged (North and West) mature (80-120 years old), natural-origin, pine-hardwood stand in Cleveland County, Arkansas. Each box represents the 25th, median (50th; horizontal dash), and 75th percentiles. The error bars (whiskers) represent the 10th (below) and 90th (above) percentiles; open circles represent mean; and filled diamonds represent outliers.

in slightly more uniform stand structure and reduced aboveground carbon stores by 8 tons per acre. Post-harvest residuals of large trees maintained carbon stock at relatively high-levels with greater potential for live tree carbon increment. Carefully planned partial harvests in complex stands such as mature, natural-origin pine-hardwoods of the UWGCP may allow for greater flexibility in balancing maintenance of carbon stores while fostering structural and compositional complexity.

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RED MAPLE COMPOSITION IN AN OLD GROWTH FOREST 50 YEARS FOLLOWING DISTURBANCE

Michael K. Crosby, Rachel B. Butler, and B. Nicole Hodges

Abstract—Red maple (*Acer rubrum*) has become an increasingly important component in forests of the Eastern United States. In the absence of disturbance, this species proliferates in the understory and grows into the canopy. Growth and expansion of red maple was assessed in an old-growth forest in northern Georgia. Forty plots were established in the forest in 1960 following an ice storm, covering three forest communities (i.e., oak-pine (*Quercus* spp.-*Pinus* spp.), chestnut oak (*Q. montana*), and mixed forest). These plots were remeasured in 2015. Seedling frequency increased in the oak-pine and chestnut communities, red maple saplings comprised significant portions of saplings in the understory, and basal area increased throughout the forest. In an effort to assess seedling numbers in the forest, Geographically Weighted Regression was employed to allow for an assessment of variable changes throughout the forest. The best-fitting model had an adjusted R^2 value of 0.77 and included basal area and slope, indicating the importance of these variables on red maple seedling germination. This supports the 'super generalist' label of red maple, and its continued growth into the midstory could allow red maple to become a canopy dominant species following subsequent natural disturbances. Forest managers should be prepared to take necessary steps to control red maple in similar forests in the Southeastern United States.

INTRODUCTION

Red maple (*Acer rubrum*) has become an increasingly significant component of forests in the Southern United States previously dominated by oak species (*Quercus* spp.) (Abrams 1998, Fei and Steiner 2007, McDonald and others 2002). This species has increased in 69 percent of forests in the Eastern United States (Fei and Yang 2011). An increase in red maple impacts understory vegetation, has implications for nutrient and hydrologic factors in these forests (Alexander and Arthur 2010), and indicates a compositional shift in areas where their prevalence increases and fire is excluded from the landscape. It has earned the label of 'super generalist' because it can grow as an early- or late-successional species, survive dry and low-light understory environments, and proliferate into canopy gaps following disturbance (Abrams 1998, Rantis and Johnson 2002). Red maple is also able to maintain its under- and midstory dominance in areas where fire has been excluded from the landscape or harvesting occurs (Fei and Steiner 2009).

The increase in red maple has occurred since observations of species composition were made in early colonization of the United States (Lorimer 1984). In unmanaged forests, particularly old-growth forests, small-scale disturbances are the primary agents of change. Such events generate canopy gaps that promote red maple seedling germination in the understory, often for many years following disturbance (Rankin and Pickett 1989, Warren and others 2004). Red maple seedlings are able to persist in the understory, grow into the midstory at the expense of less shade tolerant species, and release following disturbance. Therefore, it is important to assess changes in red maple seedling compositions following disturbance. The objective of this study is to quantify changes in the red maple composition of an urban, old-growth forest and develop a model to determine seedling numbers within a portion of the forest 50 years following a damaging ice storm.

METHODS

The Marshall Forest Preserve, located within the city limits of Rome, GA, comprises approximately 300 acres of forest. In 1960, 40 permanent 0.1-acre plots were established within the forest, including three forest communities, oak-pine, chestnut oak, and mixed forest (Lipps 1966, Lipps and DeSelm 1969, fig. 1). A portion of these plots were remeasured in 1989 and 2015 (Butler and others 2018, Fail 1991). Also in 2015, all plots were located and clearly marked. They were

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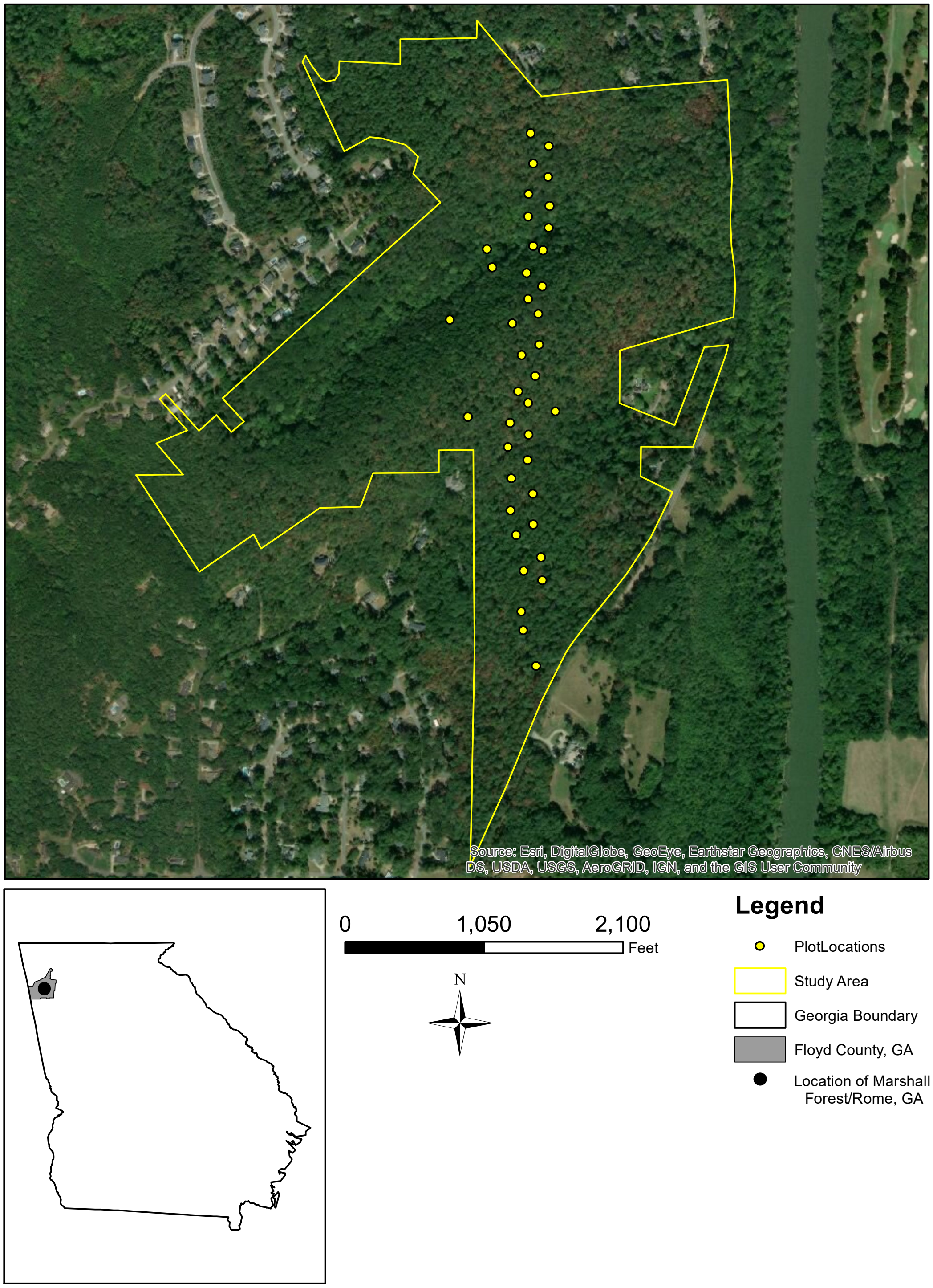
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Figure 1—Study area in Marshall Forest, located in Rome, GA.

remeasured following the original methodology of Lipps (1966). All species on plots were recorded, including seedling counts on each plot. The seedlings were totaled for red maple and expanded to a per acre basis. Geographically Weighted Regression (GWR) was used to estimate seedling numbers throughout the sampled area. The GWR is a regression technique employed when the variables are non-stationary through space (Fotheringham and others 1996). The analysis was performed using ArcMap 10.3.

RESULTS AND DISCUSSION

The initial plots were established following an ice storm that damaged portions of the forest. In the initial study (Lipps and DeSelm 1969), red maple was present in each community and drastically increased in basal area after the ice storm (table 1). In the current assessment,

Table 1—Comparison of seedling and sapling frequency of occurrence (percent of plots with red maple) and basal area between 1961 and 2015

	Seedlings		Saplings		Sapling density		Tree BA	
Community	1961	2015	1961	2015	1961	2015	1961	2015
	----------------percent of plots----------------				*number per acre*			
Pine-oak	30	93.3	33.3	66.7	32	37	0	3.3
Chestnut	60	100.0	80.0	100.0	360	42	1	7.2
Mixed forest	100	100.0	100.0	60.0	220	42	1	4.6

Tree BA=average basal area.

approximately 800 of 1,900 trees measured were red maple. There were more than 1,000 seedlings per acre, on average, for the 40 plots measured in this study and 38 of 40 plots had red maple seedlings present. Generally, the sapling density decreased, but this was likely a consequence of the dramatic increase in the size of the red maple trees growing into the midstory, as indicated by the increase in the basal area of red maples (table 1). This occurred as a result of a lack of recruitment of oak species and was consistent with findings in similar forested areas (McDonald and others 2002). In the understory, sapling-sized trees were predominantly hickory (*Carya* spp.) or red maple and seedlings were dominated by *Pinus* spp. or red maple (table 2). These results indicated that red maple had become widely distributed in Marshall Forest, similar to other results from throughout the region (Fei and Yang 2011) and seemed to fit the 'red maple dominance hypothesis' posited by Lorimer (1984). Marshall Forest is in an urban environment and prescribed fire would be difficult to manage and has been excluded from the forest on a large scale since the 1920s (Petrucelli and others 2014).

Table 2—Seedling and sapling percentages by species in Marshall Forest, 2015

Species	Seedlings	Saplings
	percent	
Acer rubrum	26	36
Cornus florida	0	2
Carya spp.	6	38
Nyssa sylvatica	0	6
Pinus spp.	36	0
Quercus spp.	11	9
Other	21	9

Predicting Seedlings with GWR

Adjusted R-squared values for GWR was 0.77; the GWR model also had spatially random residuals, indicating the model was properly specified (Fotheringham and others 1996, Lu and others 2014). The variables in the best fitting model were basal area and slope. The interpolation of intercept values showed the greatest values along the southern portion of the study area, which was in flatter terrain (fig. 2a). The influence of basal area on red maple seedlings varied throughout the study area (fig. 2b) with greater basal area being related to a decrease in seedling numbers. This trend was different than that observed at the northern end of the study area where greater basal areas had greater numbers of seedlings. It is likely that the greater coverage of herbaceous species and small shrubs (e.g., blueberry (*Vaccinium* spp.)) at the southern end of the forest further inhibited light availability in this area (Warren and others 2004). The influence of slope was important as greater slope was related to greater seedling numbers (fig. 2c).

The GWR predicted values were similar in space to observed values (figs. 3a and b) with the greatest differences occurring in the northern third of the study area where slopes were greatest. The local R-squared values were greatest in the northern and southern quarters of the study area where the terrain was generally more even. The central portion of the study area indicated a transition in coefficient impacts on seedlings numbers. It could be that there was not a good relationship among those variables and seedling numbers in varying terrain. It would be useful in future studies to consider an indicator of diversity, such as Shannon's Diversity Index, to assess the influence of local competition. Interpolating the local coefficients with sparse data points can give the illusion of a trend across the landscape (Cho and others 2009), but this is likely not the case in this study area given its small areal coverage. Increasing the number of plots and their distribution throughout the forest would further improve the model utility.

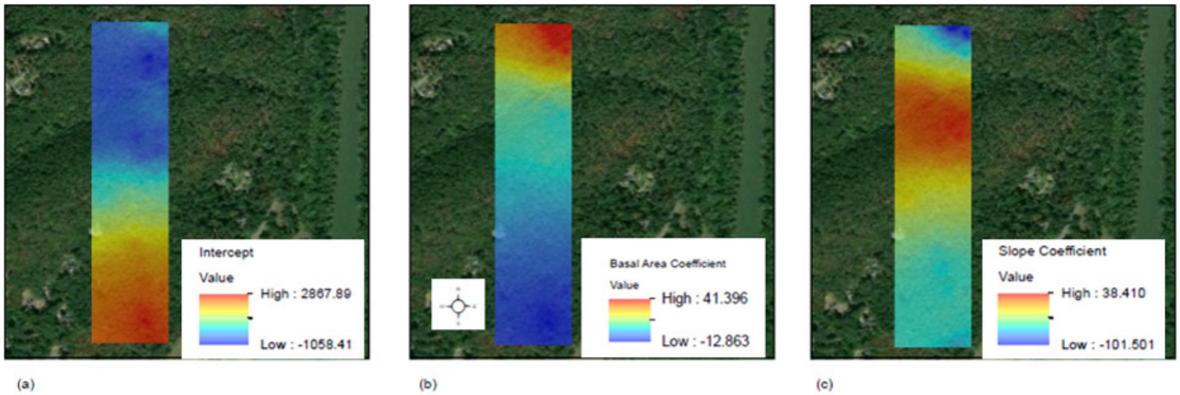

Figure 2—Results of Geographically Weighted Regression showing local values for intercept (a), basal area (b), and slope (c).

Figure 3—Interpolation of observed (a) red maple seedlings and predicted values resulting from Geographically Weighted Regression model (b).

CONCLUSIONS

Marshall Forest will likely continue to transition towards a greater composition of hickory species and red maple. With no sapling-sized pine in the study area, there will be no further recruitment into the canopy. This is similarly true for oak species, although there are oak saplings in the understory and the process will take longer to transition. The GWR model would benefit from more extensive sampling, which would also provide data regarding red maple abundance throughout the forest, particularly within some of the higher elevations where there is a greater area of pine species. Managing the forest for oak-pine cover would be difficult given the urban location with homes bordering the forest and widespread tree removal to generate canopy gaps would impact the natural ecological process. The Marshall Forest remains a natural laboratory to study forest succession and the impacts of disturbance on forests of the Southern United States.

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8. Vegetation Management

Moderator:

Andy Ezell

TESTING FIVE TREATMENTS TO CONTROL *LONICERA* AND PROMOTE NATURAL HARDWOOD REPRODUCTION IN NORTH ALABAMA

Callie J. Schweitzer and Daniel C. Dey

Abstract—We partnered with the Land Trust of North Alabama to implement an invasive species treatment demonstration project on property with high recreational use. The stand had low-quality upland hardwoods with eight dominant or codominant tree species averaging 5.5 inches in diameter at breast height (d.b.h.) and 456 stems per acre (SPA). We treated honeysuckles (*Lonicera* spp.) using mechanical removal, mechanical removal with cut stump herbicide application, foliar herbicide treatment, and a single dormant season prescribed fire, in addition to an untreated control area. The pretreatment density of *Lonicera* in all five treatment areas ranged from 11,000 to 15,300 SPA, which was 84 to 96 percent of all woody stems in the understory. Posttreatment SPA of *Lonicera* was 500 to 39,400, ranging from 16 to 98 percent of all understory stems. Foliar herbicide treatment was most effective in reducing *Lonicera* stems. Hardwood tree reproduction was depauperate.

INTRODUCTION

The issue of invasive flora and fauna in eastern hardwood forests continues to receive heightened attention (Riitters and others 2017). Forest landowners, managers, policymakers, and educators require an understanding of the impact of invasive plants and animals and how forest management decisions and disturbance will affect their distribution and resilience (Martin and others 2009). After all, the services gained from our forested systems depend directly upon the condition of the ecosystem and cannot be taken for granted (Collier and Vankat 2002, Martin and others 2009). Sustaining forested systems will require intensive, active conservation practices to address the extent of invasive plant species coverage, the consequences of different actions, and the effort needed to situationally address problems.

Demonstration areas and case studies can transfer available technology and science to stakeholders to help them gain understanding and assistance in making conservation activity decisions. One such demonstration area with the Land Trust of North Alabama (LTNA) on the Monte Sano Nature Preserve (hereafter, "Preserve") property in Huntsville, AL, has been developed to show how various tending treatments will impact the highly invasive plant species group, *Lonicera* (honeysuckles, family Caprifoliaceae). The Preserve (1,100 acres) is managed by the LTNA, which pursues multiple organizational goals: conservation of sensitive species, conservation of historical sites, encouragement of outdoor recreation, and facilitation of environmental education (https://www.landtrustnal.org). These project goals included targeting a specific plant community in a comprehensive restoration ecology approach, galvanizing the mission of the LTNA to strengthen connections to communities, and sustaining LTNA land holdings by delivering stewardship benefits to the public.

To support this project, over the past 10 years scientists and foresters with the U.S. Department of Agriculture, Forest Service, Southern Research Station, in conjunction with University of Alabama-Huntsville faculty and students, have conducted a survey of the woody vegetation on several properties, including the Preserve. Our vegetation survey of grid points systematically distributed across the landscape allowed us to have data associated with changes in slope, elevation, soils, and land uses. From these data, preliminary modeling of *Lonicera* spp. highlighted a need to target its invasion and spread (Laliberte 2013, Werkheiser 2009).

The primary objectives of this study were (1) to evaluate the most efficient and acceptable method to reduce the density of *Lonicera* in LTNA forested stands and (2) to establish a demonstration project to transfer knowledge related to the detrimental impact of nonnative invasive species and show potential treatment outcomes.

METHODS

Cumberland Plateau forests, which includes those found in northeastern Alabama and the Preserve, are dominated by either oak-hickory (*Quercus*-*Carya*) upland types on the broad tabletops or intermediate mixed

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mesophytic and oak-hickory types on the side slopes or escarpment (Braun 1950). These classifications result from local topographic and edaphic conditions, a consequence of geological uplifting and subsequent erosion. Over 30 canopy species can be found in the highly diverse forests of the Cumberland Plateau (Hinkle and others 1993). A myriad of disturbances has influenced these forests, and most stands are considered second- or third-growth (Hart and Grissino-Mayer 2008). Over the past 50 to 100 years, they have become dominated by oaks, yellow-poplar (*Liriodendron tulipifera* L.), ash (*Fraxinus* spp.), and other important species. More recent disturbance is attributed to the proximity of the Preserve to the metropolitan area of Huntsville, AL. The Preserve has high levels of recreational use and increased potential for the introduction of nonnative invasive species from seed sources on adjacent landowner properties, distribution via birds, and spread along roads and trails (Riitters and others 2017).

Trail access from an LTNA parking lot adjacent to the Preserve provided an opportunity for treatment of *Lonicera* in a highly viewed and foot-trafficked area. The treatment area was located along the Railroad Bed Trail, just south of a parking area. We flagged five treatment units measuring approximately 100- by 100-feet to delineate boundaries. One survey measurement plot was centrally located in each treatment unit. Plot centers were permanently marked with a 24-inch piece of reinforcing steel, and GPS coordinates for plot centers were recorded. At each plot center, a 0.025-acre plot was established. All trees ≥1.5 inches diameter at breast height (d.b.h., 4.5 feet above groundline) were monumented (distance and azimuth measured and recorded from plot center), and species and d.b.h. were recorded. Tree crown position was recorded (dominant, codominant, intermediate, suppressed), and an assessment of tree health following Gottschalk and MacFarlane (1993) was made. Canopy cover was measured using a handheld spherical densitometer in five locations within each plot. Within each plot, we also surveyed a 0.01-acre plot by enumerating the reproduction cohort (trees <1.5 inches d.b.h.) by species and height class. Stems of *Lonicera* were recorded in the 0.01-acre plot, and all stems were counted as they originated at ground level. Several species of honeysuckles occur on the study site; we did not identify *Lonicera* to the species level. Data were collected prior to treatment implementation and at 1 year and 3 years posttreatment.

The five treatments implemented to test *Lonicera* control included: (1) control, no treatment; (2) mechanically remove all *Lonicera* stems; (3) treat all *Lonicera* with a foliar herbicide; (4) mechanically remove all *Lonicera* stems and treat cut surfaces, as well as small stems, with herbicide; and (5) prescribed fire. Mechanical removal (treatment 2) consisted of severing all stems at groundline with pruners and a brush saw, with cut stems removed from the unit boundaries. This treatment targeted larger stems, although all *Lonicera* stems were severed as was feasible. The herbicide treatment (treatment 3) targeted all stem sizes using a direct foliar spray of a commercially available herbicide concentrate that was a mixture of 18-percent glyphosate and 2-percent triclopyr, which we diluted as a 5-percent solution in water. We used a backpack sprayer and spray wand, and all exposed leaf surfaces were wetted. For the mechanical/herbicide treatment (treatment 4), all stems that could be severed were cut and removed from the unit boundaries, and the cut stump surface was immediately treated with imazapyr herbicide (mixed at 20-percent volume/volume with water) using a small utility spray bottle; smaller *Lonicera* stems were treated with the glyphosate/triclopyr solution via the backpack sprayer as in treatment 3. The mechanical and herbicide treatments were done on October 19, 2015. Removal of all vegetation in a 4-foot buffer outside of treatment 5 provided a firebreak for the prescribed fire. We worked with the City of Huntsville, Bureau of Fire Prevention and the Alabama Forestry Commission to implement the prescribed fire on March 17, 2016. We documented the fire using a HOBO® data recorder and a temperature-sensitive probe; we also measured the forest floor litter consumption. Maximum fire temperature reached 170 °F, and approximately 0.5 inches of forest litter were consumed. This was a cool fire that crept slowly over the treatment area, which is typical for areas that have not been recently subjected to fire.

For transferring these activities and their consequences to the public, we installed informative signs at each unit, immediately adjacent to the trail. The demonstration site is frequently used for field tours and related science-delivery activities. Partners involved included the LTNA, Forest Service, University of Alabama-Huntsville, City of Huntsville, and Alabama Forestry Commission.

RESULTS

Overstory and Midstory Trees

Posttreatment canopy cover was 92 percent and did not change with treatment. Trees were primarily in dominant and codominant positions and were assessed as fair-to-poor health based on canopy dieback and low crown density, along with poor bole form. Overstory and midstory tree composition consisted of 12 species. Canopy-level species included white ash (*F. americana* L.), chinquapin oak (*Q. muehlenbergii* Englem.), scarlet oak (*Q. coccinea* Muench.), persimmon (*Diospyros virginiana* L.), slippery elm (*Ulmus rubra* Muhl.), shagbark hickory (*C. ovata* K. Koch), sugar maple (*Acer saccharum* Marsh.), and yellow buckeye (*Aesculus flava* Sol.). Midstory species included eastern hophornbeam (*Ostrya virginiana* K. Koch), eastern redcedar (*Juniperus virginiana* L.), eastern redbud (*Cercis canadensis* L.), and winged elm (*U. alata* Michx.). Species richness did not change by any treatment. Average basal areas and stem densities for overstory trees are given in table 1. No large overstory trees suffered mortality due to the treatments, but one eastern redbud that was 4.4 inches d.b.h. died immediately after the fire, and one 1.7-inch-d.b.h. yellow buckeye died by year 3. At year 3, we found that a single 2.3-inch-d.b.h. stem of eastern hophornbean died in the control, and a 2.3-inch-d.b.h. hophornbean stem died in the herbicide treatment. There were a few changes in stem densities due to ingrowth (table 2). In the prescribed fire treatment, one sugar maple sapling grew from 3.5 inches d.b.h. to 3.6 inches d.b.h., which moved it into another diameter class (class 2, see table 2) and one slippery elm sapling moved from class 2 to class 3. A chinquapin oak in the control unit grew from 9.4 inches d.b.h. to 9.8 inches d.b.h., moving it into the next largest size class (class 5). In year 3, there were no changes in stem densities or diameter class distributions for the mechanical/herbicide and mechanical-only treatments.

Understory Vegetation

Changes were most notable in the understory layer of vegetation. We tallied 12 different species of woody species in the understory in all units prior to treatment and 10 species in posttreatment year 1. Blue ash (*F. quadrangulata* Michx.), blackhaw (*Viburnum prunifolium* L.), and deciduous holly (*Ilex decidua* Walter) were no longer present in the units posttreatment year 1, and eastern redcedar was found in the mechanical/herbicide treatment. The holly was only tallied in the mechanical treatment unit prior to treatment; there were four stems per acre (SPA), all in size class >4 feet tall and <1.5 inches d.b.h., and all were removed in the

Table 1—Overstory tree basal area and stem density by treatment for all trees ≥1.5 inches d.b.h. for the Land Trust of North Alabama Monte Sano Nature Preserve *Lonicera* treatment demonstration project

	Basal area			Stem density		
Lonicera treatment	Pre	Yr1	Yr3	Pre	Yr1	Yr3
	square feet per acre			*stems per acre*		
Control	45.3	45.6	48.2	280	280	240
Mechanical	186.5	189.7	198.9	480	480	480
Foliar herbicide	135.7	134.8	141.7	560	560	520
Mechanical and herbicide	78.4	80.7	85.1	440	440	440
Prescribed fire	106.2	103.1	111.3	520	480	440

d.b.h. = diameter at breast height.

Pre = pretreatment, Yr1 = one growing season posttreatment, Yr3 = three growing seasons posttreatment.

Table 2—Stem densities in stems per acre by diameter class (for all trees ≥1.5 inches d.b.h.) for the Land Trust of North Alabama Monte Sano Nature Preserve *Lonicera* control demonstration project

d.b.h.	Control			Mechanical			Foliar herbicide			Mechanical and herbicide			Prescribed fire		
class	Pre	Yr1	Yr3	Pre	Yr1	Yr3	Pre	Yr1	Yr3	Pre	Yr1	Yr3	Pre	Yr1	Yr3
							stems per acre								
1	160	160	120	160	160	160	280	280	240	160	160	160	200	160	120
2	0	0	0	80	80	80	0	0	0	120	120	120	200	200	160
3	40	40	40	0	0	0	160	160	160	80	80	80	40	40	80
4	80	80	40	80	80	80	0	0	0	0	0	0	40	40	40
5	0	0	40	80	80	80	80	80	80	80	80	80	0	0	0
6	0	0	0	40	40	40	40	40	40	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	40	40	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40
9	0	0	0	40	40	40	0	0	0	0	0	0	0	0	0

d.b.h. = diameter at breast height, Pre = pretreatment, Yr1 = one growing season posttreatment, Yr3 = three growing seasons posttreatment.

d.b.h. classes: 1 = 1.5-3.5 inches, 2 = 3.6-5.5 inches, 3 = 5.6-7.5 inches, 4 = 7.6-9.5 inches, 5 = 9.6-11.5 inches, 6 = 11.6-13.5 inches, 7 = 13.6-15.5 inches, 8 = 15.6-17.5 inches, 9 = 17.6-19.5 inches.

mechanical treatment. One SPA of blue ash and one of blackhaw were found only in the mechanical with herbicide treatment unit; both were in size class >4 feet tall and <1.5 inches d.b.h., and both were removed via treatment. Within these small plots, the changes in understory species diversity was minimal. At year 3, we tallied 11 species; no blackhaw, sugar maple, redcedar, or winged elm was tallied, but blue ash was found in the mechanical treatment and the mechanical/herbicide treatment, and holly was tallied in the mechanical treatment. Two new species were recorded: aromatic sumac (*Rhus aromatica* L.) in the mechanical/herbicide treatment and Osage orange (*Maclura pomifera* [Raf.] Schneid.) in the mechanical treatment. The reproduction cohort was depauperate of desired species such as oaks and hickories.

The pretreatment SPA of *Lonicera* in all five treatment plots ranged from 11,000 to 15,300, which was 84 to 96 percent of all stems in the understory. Posttreatment *Lonicera* density was 500 to 39,400 SPA, with a range of 16 to 98 percent of all understory stems. At year 3, the densities of all understory stems ranged from 7,400 SPA to 16,900 SPA. *Lonicera* densities were lowest in the herbicide treatment at 2,700 SPA and second lowest in the mechanical/herbicide treatment (9,500 SPA), followed by the mechanical treatment (16,700 stem per acre). *Lonicera* densities were greatest in the prescribed fire treatment (16,900 SPA). The control treatment had 12,600 *Lonicera* SPA. Interestingly, we have rarely observed *Lonicera* on the Monte Sano State Park, immediately adjacent to the Preserve.

Changes in *Lonicera* stem densities varied by treatment and size classes. The mechanical and the prescribed fire treatments resulted in increases in the density of *Lonicera* after 3 years, with increases of 1,000 SPA and 5,700 SPA, respectively. For the prescribed fire treatment, although stem density declined for stems that were >4 feet tall up to 1.5 inches d.b.h. (fig. 1), stems ≤4 feet tall increased in density, most likely from sprouting. Total understory stem densities and those of *Lonicera* showed a decline in the other three treatments. The greatest decline was quantified in the herbicide treatment, which had lost 9,200 *Lonicera* SPA, with the majority of these stems >1 foot tall (fig. 2). There was an increase of 400 SPA of ≤1-foot-tall *Lonicera* in the herbicide treatment; these stems may have not been treated due to their location underneath a thick canopy of other *Lonicera* stems. Across all size classes, there was a decrease of 4,900 SPA of *Lonicera* in the mechanical/herbicide treatment, with 10,800 SPA removed that were >1 foot tall, and a concurrent increase of 5,900 SPA in stems ≤1 foot tall, most likely due to omission error during treatment and new germinants.

At study initiation, *Lonicera* averaged 90 percent of stems in the reproduction cohort. At year 3, *Lonicera* was 99 percent of the reproduction stems for each of the control, mechanical, and prescribed fire treatments. For the mechanical/herbicide treatment, 85 percent of the reproduction was *Lonicera*, with 1,400 SPA of white ash, blue ash, shagbark hickory, and aromatic sumac. In the herbicide treatment, the reproduction was only

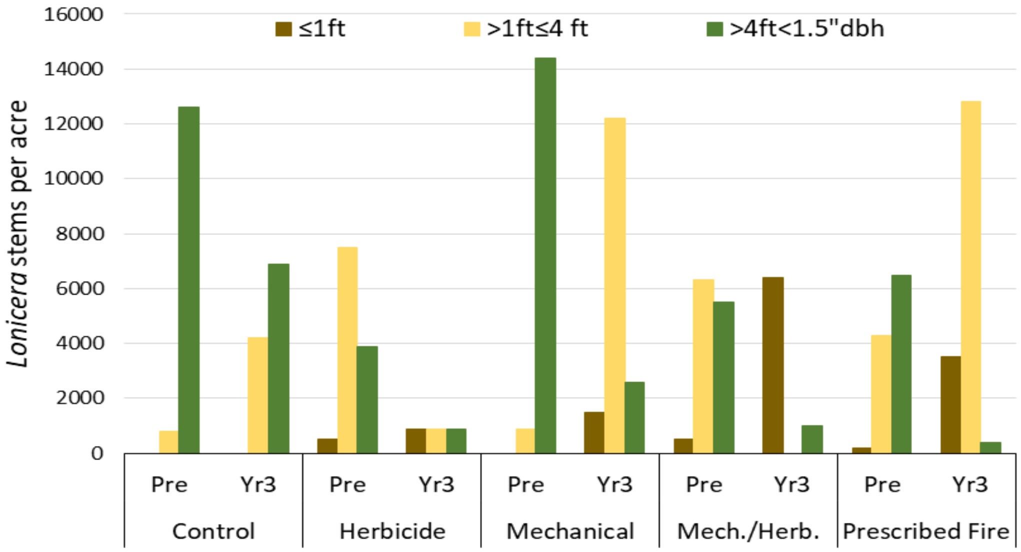

Figure 1—Stems per acre of *Lonicera* by height classes for each treatment at times Pre (pretreatment) and Yr3 (three growing seasons posttreatment) for the Land Trust of North Alabama Monte Sano Nature Preserve *Lonicera* control demonstration project.

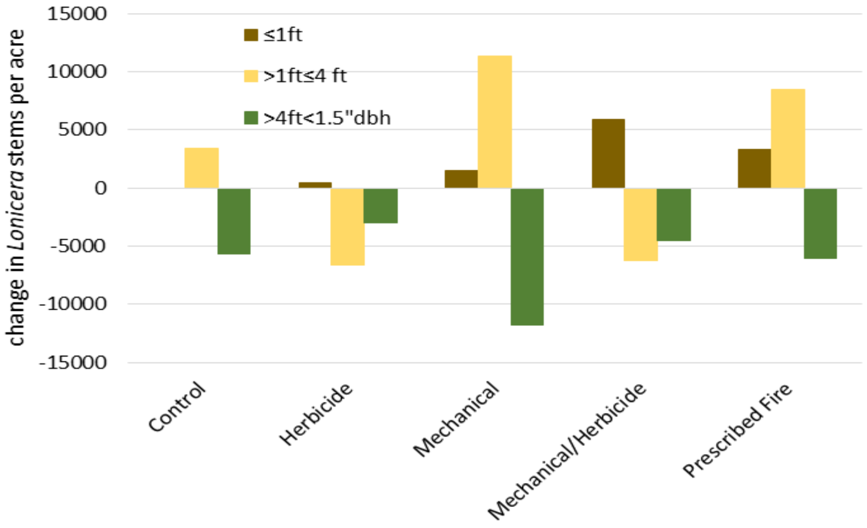

Figure 2—Change after three growing seasons in stems per acre of *Lonicera* by height classes for the Land Trust of North Alabama Monte Sano Nature Preserve *Lonicera* control demonstration project.

36 percent *Lonicera*, with 2,540 SPA of woody species including slippery elm, eastern hophornbeam, white and blue ash, and aromatic sumac.

DISCUSSION

Introduction of invasive plant species may change ecosystem structure and function (Bazzaz 1986, Vitousek 1990). While disturbance is known to open communities to invasion (Honu and Gibson 2006, Medley 1997), proximity to roads and urban areas also contributes (Flory and Clay 2006). Regardless of origin, *Lonicera* in the understory of Preserve property dominates that vegetation layer. We were able to most efficiently reduce the density of *Lonicera* using a foliar herbicide treatment. *Lonicera* stems of all sizes except those in the smallest size class (<1 foot tall) were reduced in the herbicide treatment; these small stems in the herbicide treatment were new seedlings which germinated posttreatment. Across a selection of herbicides, Rathfon and Ruble (2007) also found foliar spray to provide better control than cut stump or basal bark methods for control of bush honeysuckles.

The mechanical/herbicide treatment also reduced *Lonicera* stems, but these stems were concentrated in the >1 foot and larger size classes; stems in the smallest size class increased following treatment, a result of missed application (stems may have been hidden by taller *Lonicera* stems or were cut en masse with an incomplete subsequent herbicide treatment), coupled with release from the removal of larger stems. Similar results related to high densities of targeted species and incomplete treatment application were noted by Love and Anderson (2009), where they demonstrated that cutting invasive shrubs and applying herbicide to stumps was least effective. After one growing season posttreatment, stem numbers in the mechanical-only treatment had the greatest increase, and this increase was noted for *Lonicera* in all but the largest size class. Mechanical removal of the largest *Lonicera* stems resulted in an 11,800-SPA decrease of *Lonicera* in this size class; however, because the stumps were not treated, these stumps will be prolific sprouters (Smith and Smith 2010). In the mechanical treatment, the largest increase in stem density was size class >1 foot but ≤4 feet tall, a result of smaller stems responding to the increased growing space and rapid growth of stump sprouts, which have a well-established root allowing for allocation of resources to the aboveground plant. After one fire, the number of *Lonicera* stems increased, with increases in stems sizes for stems ≤4 feet tall; larger stems sizes were reduced following the fire. Repeated fires should reduce smaller stems and exhaust root reserves of sprouters (Nyboer 1992).

The percentage of the understory dominated by *Lonicera* was reduced to 16 percent in the herbicide treatment, providing growing space for other species. This study did not collect herbaceous plant data, but we observed several patches of wildflowers in this treatment unit in the spring following the treatment. Although there were no oak seedlings tallied posttreatment, parent trees of scarlet oak and chinquapin oak were present and could provide a seed source (acorns). Creating growing space by eliminating *Lonicera* should facilitate acorn germination, although additional treatment to keep the *Lonicera* in check will be needed for oak seedlings to recruit into the midstory (Dey and others 2019, Schweitzer 2019). Small ash seedlings increased from 5 SPA pretreatment to 21 SPA after treatment.

The pending spread of the emerald ash borer (*Agrilus planipennis* Fairmaire) to southern forests will kill overstory ashes (Knight and others 2013); developing a robust cohort prior to that epidemic may be paramount to sustaining ash in these systems, and these preliminary results support the use of herbicide in that process.

The expectation was that the most intense treatment (mechanical/herbicide) would result in the greatest *Lonicera* control. Early results did not support this theory, as the foliar herbicide treatment had the greatest impact in reducing *Lonicera*. In the mechanical/herbicide treatment, stems in the smallest size classes were not reduced. We surmised that small, cut stems were missed during the post-cut herbicide application. The inability of cut and treated stumps to sprout may be manifested in subsequent years. The most efficient treatment, in terms of labor and control, was the foliar herbicide treatment. Because of prolific stump sprouting, the mechanical-only treatment was the least effective, although many believe this to be the most aesthetically pleasing immediately posttreatment. Three years following mechanical treatment, *Lonicera* was the only species tallied in the >1-foot-tall to ≤4-foot-tall height class of understory stems in the mechanical removal treatment. A single fire did impact the larger *Lonicera* stems, but repeated fires will be necessary to diminish reserve resources in the root system and reduce sprouting. Using prescribed fire in this wildland-urban interface is most likely unviable, due to high-risk issues such as smoke management.

CONCLUSIONS

Invasive plants are increasingly impacting forests, and forests in the wildland-urban interface may be particularly prone to alteration and damage. Treating invasive plant species is one step toward conservation in action. Land stewards need to know the extent of invasive species densities and locations, have clear ideas as to the desired future conditions, and plan the most efficient treatment to move toward those goals. After all, hallmarks of good forest stewardship include the consideration of multiple resources, are based on landowner objectives, and use the best available practices. Forest stewardship by nongovernment entities such as the LTNA includes collaborative work to conserve and to advocate for ecological restoration. Oftentimes, these actions must be in concert with public opinions and desires. By involving various stakeholders and including a technology transfer component, this demonstration area on the Preserve will provide a framework for addressing a common issue in wildland-urban interface areas and will commence the process of active conservation and restoration. For example, we designed and posted signs at each treatment unit describing the treatments and the anticipated outcomes, and we have hosted invasive plant workshops and field tours. Although some managers are still reluctant to engage in control practices, especially if that involves the use of herbicides, we are demonstrating that with the correct activities, which includes the use of herbicides, degraded systems can be converted to more healthy and resilient upland hardwood forests. Desired species such as oaks, ashes, and hickories can be ‘life-boated’ as seed sources to assist in the recovery and restoration. The management implications of this project support active conservation methods to ensure desired future forest composition.

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POTENTIAL DETRIMENTAL EFFECTS OF USING GLYPHOSATE FOR HARDWOOD SEEDLING RELEASE

Stephen E. Peairs and Wayne K. Clatterbuck

Abstract—Chemical release treatments are commonly used in regeneration efforts to establish new hardwood stands. These applications target the competing vegetation surrounding the desired seedlings. Research findings have suggested that release treatments improve seedling survival and growth during the initial years after disturbance or planting. Glyphosate is one herbicide that has been used by land managers to accomplish this objective. This study suggests that glyphosate may actually inhibit height growth of natural oak (*Quercus* spp.) and yellow-poplar (*Liriodendron tulipifera*) reproduction. Seedlings treated using glyphosate conducted as radial sprays, treating the immediate 5-foot radius around the crop trees, reduced height growth compared to control treatments. Natural reproduction was measured post spray in the fall of 2014 and two growing seasons later in January and February of 2017. This paper presents the reduced growth response through treatment comparisons of glyphosate with untreated control. Hypotheses are presented to potentially explain the causes of reduced seedling growth following radial release using glyphosate.

INTRODUCTION

Foresters have great difficulty in successfully maintaining adequate oak (*Quercus* spp.) reproduction over time after a disturbance occurs within hardwood stands. Multiple silvicultural interventions are often required to enable oak to develop into competitive size classes. Even when an abundance of oak germinants occurs after a good seed crop, sheer numbers of small seedlings are not enough to ensure oak regeneration success to form the future stand (Beck 1991, Janzen and Hodges 1987, Lockhart and others 2000, Loftis 1983, Sander 1979, Schweitzer and Dey 2011, Smith 1986, Stringer 2005). Silvicultural practices including shelterwoods and clearcuts have been advocated to encourage oak regeneration. However, in most instances competing vegetation emerges after these disturbances that hinders or suppresses the preferred oak regeneration efforts.

Chemical applications have been prescribed to improve the growth and survival of oaks in hardwood stands. For example, seedling diameter and height growth can also be positively affected by chemical release. Hilt and Dale (1987) concluded that increased intensity of pre-commercial thinning resulted in greater diameter growth in stands 13, 17, and 21 years of age. A study by Thompson and Nix (1993) observed that early crop tree release within a 4-year-old clearcut using various herbicides significantly decreased herbaceous and woody plant competition. This reduction in competition resulted in increased seedling ground line diameter growth but did not improve height growth over untreated controls. Nix (2004) remeasured the released natural oak in the clearcut 10 years after the initial chemical release treatments and reported that four herbicide treatments significantly increased diameter growth of released oak seedlings. Various studies (Ezell and Catchot 1998, Ezell and others 2007, Hopper and others 1993, Self and others 2013) have also indicated that chemical release of planted hardwood seedlings improves early survival rates. The use of sulfometuron to control herbaceous weeds improved overall oak seedling survival by 20 percent or greater compared to untreated controls at the end of the growing season of the initial year (Ezell 2000, Ezell and others 2007). A survival rate of 80 to 90 percent is common for oak seedlings that receive chemical release during normal precipitation years (Grebner and others 2004). Likewise, post-emergent applications utilizing glyphosate improves height growth in hardwood species (Hopper and others 1993) in addition to oak seedling survival.

However, there may be some cause for concern with the type of herbicide used for hardwood release treatments. Avoidance of pesticide drift onto crop seedling foliage is paramount but there may be unforeseen effects that occur belowground. The possibility exists that glyphosate or a by-product could be absorbed belowground by the growing stock. Various studies

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(Kremer and others 2005, Neumann and others 2006, Tesfamariam and others 2009, Zobiole and others 2010) have reported that detrimental interaction in the root zone could allow glyphosate to restrict the growth of adjacent plants and seedlings.

This study examined the height growth response of preferred natural oak and yellow-poplar reproduction in response to multiple herbicide applications. We considered all reproduction together as well as separately by new germinants and resprout reproduction. All species were combined, regardless of class (white oak, red oak, and yellow-poplar) for all tests.

METHODS

Study Site

The study site was located on a private landholding in the Western Highland Rim-highly dissected plateau physiographic ecoregion of west-central Tennessee (Smalley 1984). The soils on the study site were Bodine gravelly silt loams (5-40 percent slopes). Site index values for white oak (Section *Quercus*) were moderate (value of 75 feet, base age 50). Most undisturbed forestland in that region was dominated (80 percent or greater) by oak species. The study site was covered by a mixed-mesophytic forest, with white oak (*Quercus alba*), southern red oak (*Q. falcata*), chestnut oak (*Q. montana*), black oak (*Q. velutina*), hickory (*Carya* spp.), blackgum (*Nyssa sylvatica*), red maple (*Acer rubrum*), sugar maple (*A. saccharum*), black cherry (*Prunus serotina*), and yellow-poplar (*Liriodendron tulipifera*) forming the majority of the overstory species composition. Midstory and understory canopy layers also contained flowering dogwood (*Cornus florida*), sourwood (*Oxydendrum aboreum*), sassafras (*Sassafras albidum*), eastern hophornbeam (*Ostrya virginiana*), elm (*Ulmus* spp.), and American beech (*Fagus grandifolia*). As indicated by residual stumps, one or more diameter-limit harvest probably occurred within the area (the most recent harvest likely occurred between 1990 and 1995).

Study Design

The study incorporated a randomized complete block sampling design. Three individual blocks were replicated on sites with uniform site productivity, and these blocks were clearcut in the early spring of 2014. Six individual treatment units, approximately 0.75 acres in size, were installed within each block:

1. Chemical seedling release treatments utilizing equivalent of 2 ounces per acre of sulfometuron methyl (SFM75® by Alligare LLC) only,
2. Alternating banded strip treatment utilizing foliar sprays of glyphosate (5 percent solution),
3. Radial spray release utilizing foliar sprays of glyphosate (5 percent solution),
4. Alternating banded strips plus release using sulfometuron methyl,
5. Radial sprays plus release using sulfometuron methyl, and
6. Untreated control.

The three units that received sulfometuron methyl treatments were applied in May-June of 2014. Glyphosate applications were conducted between July and August of 2014. Banded sprays were approximately 4 feet in width, with alternately treated (foliar sprayed) and untreated strips across the unit. Radial sprays treated vegetation in the surrounding area of approximately a 5-foot radius from the sample seedling. A stove pipe apparatus covered the seedling being released to protect foliage from incidental contact with herbicide solution. The banded and radial spray methods were also applied to two of the blocks that were previously sprayed with sulfometuron methyl. The final treatment unit (untreated control) did not receive any herbicide applications.

Approximately 150 naturally regenerated seedlings (approximately half oak species and half yellow-poplar) in each treatment unit in the three replicated blocks were measured in the fall of 2014 for overall height. Height measurements were taken after treatments with a standard retractable ruler to the nearest 0.5 inch. A total of 2,653 seedlings were measured on the site. Seedlings were measured a second time after two full growing seasons had elapsed in January and February of 2017. Only 1,559 seedlings were able to be relocated for measurement due to the robust response of warm-season grass vegetation. Height growth was the difference between the 2017 measurements and the 2014 measurements.

Statistical Analyses

The experimental design was a randomized complete block with sampling using height measurements taken from white oak, red oak (Section *Lobatae*), and yellow-poplar seedlings. Seedlings were classified as either new germinant or advance reproduction. One analysis looked at all seedlings combined to determine any differences between treatments. A second analysis separately evaluated differences among treatments for the new germinants and the advanced sprout reproduction. Treatment was considered a fixed variable. Random variables included blocks and seedlings. Statistical analyses were performed using linear mixed models (proc glimmix; SAS version 9.4, SAS Institute Inc., Cary, NC) with a normal distribution. The least squares means were separated using Tukey's significant difference test. The significance level was set at alpha = 0.05.

RESULTS

Differences existed among the treatments when all seedlings were combined for the analysis ($F_{5,1553} = 14.02$, $p < 0.0001$). Tukey mean separation tests found a significant difference between the sulfometuron methyl only treatment and the radial treatment compared to all other treatments in regards to the change in height growth. These treatments also differed from one another. The radial release treatment had the lowest mean value of 17.3 inches (table 1).

The type III test indicated potential differences ($F_{5,504} = 2.3$, $p = 0.0481$) in height growth among treatments for new germinant reproduction. The sulfometuron methyl only treatments had the largest height growth for new germinant reproduction, 30.8 inches, approximately 6.5 inches greater than the control germinant reproduction. The radial treatment had the least growth increase with an estimate of only 22.6 inches. This value was also lower than the control estimate (table 1).

There were also differences in height change among treatments for sprout reproduction ($F_{5,1043} = 13.21$, $p < 0.0001$). The sulfometuron methyl treatment had the largest increase in height growth with an estimate of 28.1 inches. The sprouts in the radial treatments had the poorest height change response with an estimate of 15.6 inches (table 1).

DISCUSSION

Seedlings in the radial spray treatment using glyphosate experienced minimal increases in height. Radial application yielded the lowest mean height growth (table 1) of all treatments. The same trend was observed when reproduction was analyzed by size class as advanced sprout reproduction or new germinants (table 1), which suggests that the glyphosate herbicide when applied as a radial spray application had a detrimental effect.

While our treatments applied glyphosate within inches of the covered crop tree seedlings, extreme care was taken to avoid contact with the crop tree foliage during applications. Because seedling foliage was protected, it seems likely that the active ingredient or a by-product could have been absorbed belowground. Glyphosate eventually reaches the soil through either direct contact or by release from dead plant matter (Neumann and others 2006). Once in the soil, glyphosate may be absorbed onto soil particles, experience degradation by soil microorganisms, or leach through pores or root canals into deeper soil horizons. Tesfamariam and others (2009) also proposed that there may be some possibility of toxicity to non-target plants due to rhizosphere transfer of glyphosate. Neumann and others (2006) observed the exudation of glyphosate from treated plant roots into the adjacent soil. Kremer and others (2005) reported that exudation of glyphosate can restrict growth of adjacent plants and seedlings. Negative effects to non-target plants may include heightened sensitivity to plant diseases connected with low magnesium and iron availability in soil, increased nematode infections, inhibition of root growth, and reduced nitrogen fixation (King and others 2001). Glyphosate has been witnessed to alter nitrogen metabolism by directly affecting mycorrihizae or indirectly by causing an effect on plant physiology (Zobiole and others 2010). Glyphosate applications can reduce nodulation due to reductions of symbiotic bacteria in glyphosate resistant soybeans (Zobiole and others 2010, Zobiole and others 2012). This factor leads to a loss of energy and fixed nitrogen that could inhibit plant growth and production.

Table 1—Least squares mean estimates for change in height (inches) for combined oak/yellow-poplar seedlings, sprouts, and new germinant reproduction among treatments for the herbicide seedling release study on the Western Highland Rim of Tennessee

	Combined			Germinants			Sprouts		
Treatment	*n*	lsmean	SE	*n*	lsmean	SE	*n*	lsmean	SE
SFM75 only	271	28.9 A	0.98	88	30.8 A	1.74	183	28.1 A	1.18
Banded	265	24.4 B	0.99	116	25.6 AB	1.52	149	23.4 AB	1.30
Control	294	23.7 B	0.94	87	24.3 AB	1.75	207	23.5 AB	1.10
Radial + SFM75	220	23.0 B	1.09	56	27.3 AB	2.19	164	21.6 B	1.24
Banded + SFM75	262	21.9 B	1.00	104	26.7 AB	1.60	158	18.8 BC	1.26
Radial	247	17.3 C	1.03	59	22.6 B	2.13	188	15.6 C	1.16

n = number of seedlings, lsmean = least squares means, SE = standard error.

Banded = Alternating banded strip treatment utilizing foliar sprays of glyphosate (5 percent solution), Banded + SFM75 = Alternating banded strips plus release using sulfometuron methyl, Control = no treatment, SFM75 only = 2 ounces per acre of sulfometuron methyl only, Radial = Radial spray release utilizing foliar sprays of glyphosate (5 percent solution), Radial + SFM75 = Radial sprays plus release using sulfometuron methyl.

Means in a column followed by the same letter are similar (Tukey's adjusted $p > 0.05$).

Glyphosate is stored within plant metabolic sites including root and shoot meristems after translocation within the plant. Enhanced growth rate areas including nodules, root tips, and shoot apices are important sinks for glyphosate storage. A small transference of herbicide may occur at these belowground locations. A metabolite of glyphosate named amino-methylphosphonic acid (AMPA) forms from glyphosate after degradation by microorganisms. AMPA is a recognized phototoxin that has been suggested to cause glyphosate-induced injuries in glyphosate-resistant plants (Reddy and others 2004). The authors also observed that AMPA affected chlorophyll biosynthesis and caused plant growth reduction. AMPA has also been observed to reduce the amino acids glycine, serine, and glutamate in treated mouse ear cress (*Arabidopsis thaliana*) plants (Serra and others 2013). Thus, a possibility exists on the study site in treatment units receiving glyphosate applications that measured seedlings may have had AMPA transferred through the rhizosphere. The uptake of some limited amount of AMPA could have stunted growth without causing mortality to the affected seedlings.

Though most of these research findings are associated with genetically modified soybeans and other plants, similar effects could have occurred within the oak and yellow-poplar seedlings within the radial treatments. Our data supports the likelihood that glyphosate applied around crop seedlings may somewhat inhibit growth. This may especially be true of the radial treatments as greater amounts (greater volume used to adequately wet at least 70 percent of foliage) of herbicide were applied to live vegetation that completely surrounded the favored seedlings. The banded spray treatments also used glyphosate; however, not all of the sample seedlings were located on the edge of the untreated bands. Thus, the herbicide may not have transferred into the crop seedling due to the buffer distance between the root stock and any movement of the herbicide directly down the soil profile. The sampled seedlings that were on the edge of the treated strip would be potentially exposed to only half (one side) the area compared to the entire area around radial sprays. The radial treatments applied after using sulfometuron methyl, only treated the live woody stems that survived as the herbaceous forbs had already been controlled during the initial spray. The reduced amount of glyphosate applied during the second spray, in conjunction with reduced belowground root contact points also meant less uptake of the active ingredient by crop trees. Thus, the lack of or reduced amount of exposure may have had little to no effect on the sample seedlings.

CONCLUSIONS

Herbicides are often applied at various stages of early development to alleviate high mortality and enhance early regeneration growth. However, in our study the use of glyphosate appears to have had negative impacts on seedling growth and development. A notable detrimental response was observed in seedling height growth when glyphosate only was applied in a radial fashion around the immediate area of the crop seedlings. This treatment was significantly lower than all other treatments including the untreated check. It is suspected that some level of either the active ingredient or a secondary by-product was transferred into the plant within the rhizosphere. It is believed that the transference was enough to suppress height growth but not sufficient to induce mortality of released seedlings. The negative height growth impact was also noted in the advanced resprout reproduction but not in the new germinant reproduction. The larger root stock of the advanced reproduction, which likely had greater contact points with adjacent root stock of treated plants, is likely the notable factor that resulted in this difference. This possible observation being more evident in the resprout reproduction would support the theory of transference of active ingredient through root stock. Overall, our study further suggests that the greater application rate (more active ingredient used to cover 70 percent or more of live foliage) of glyphosate when applied as a radial spray around the crop seedlings reduced height growth to levels lower than all other treatments including the untreated control. Better results could likely be expected if directed sprays targeted only woody stems around the plant as opposed to all vegetation. This would minimize the amount that is available for potential uptake within the crop tree. Targeting woody plants would potentially provide more available growing space that may improve the crop tree's persistence into a greater canopy position as the stand develops over time.

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9. Shortleaf Pine

Moderator:

Don Bragg

INCREASING SURVIVAL PROBABILITY, HEIGHT GROWTH, AND DIAMETER GROWTH OF 1-0 SHORTLEAF PINE SEEDLINGS THROUGH GENETIC SELECTION, SITE PREPARATION, AND VEGETATION CONTROL

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Abstract—Natural regeneration of shortleaf pine (*Pinus echinata* Mill.) has proven difficult due to slow growth, high mortality, and lack of competitive ability. Consequently, artificial regeneration is frequently used for reforestation, although regeneration failures are common. We examine how genetic selection, in conjunction with extensive site preparation and understory vegetation control, can increase reforestation success. We used data from three long-term studies in southeastern Missouri to examine survival of 5,500 1-0 shortleaf pine seedlings. One site contained 2,000 full-sib plus 1,000 orchard-run 1-0 containerized seedlings planted on a mechanically cleared hillslope. Herbicide was applied at initial planting and 1 year after planting to 2,000 seedlings, while 1,000 seedlings received no herbicide. In addition, 2,500 orchard-run bareroot seedlings were planted at two similar sites: one utilizing herbicide understory control for 10 years, and one underplanting in an existing forest with no site preparation or herbicide. Seedling survival after 7 years on sites with no vegetation control was 30 percent. With herbicide treatments before and after planting, survival of orchard-run seedlings was 60 percent 7 years after planting. When pedigreed seedlings were planted on mechanically prepped and herbicide-treated sites, average survival increased to 85 percent after 7 years. Survival of planted shortleaf pine seedlings increased as site preparation intensity and understory competition control increased. Long-term survival was reduced by underplanting seedlings in an existing hardwood stand, where overstory and understory competition was present.

INTRODUCTION

Shortleaf pine (*Pinus echinata* Mill.) has the widest range and distribution of any southern pine in the United States, and is found in at least 22 States from New York and New Jersey in the Northeast, to Oklahoma and Texas toward the Southwest (Lawson 1990). It is the only pine species native to Missouri, naturally occurring throughout the southern and southeastern areas of the State (Brinkman and Rodgers 1967, Liming 1946), where it is commonly found as a component of varying significance with oaks (*Quercus* spp.), hickories (*Carya* spp.), and other hardwoods (Moser and others 2007). Though not generally a commercial species of interest, restoration of shortleaf pine is a priority throughout Missouri to increase wildlife diversity and forest resilience (Eddleman and others 2007, Kabrick and others 2015). Artificial and natural regeneration methods have encountered mixed success due to fire suppression, understory competition, lack of seedling establishment, and slow seedling growth (Gwaze and others 2006a, Jensen and others 2007, Lawson 1990, Stambaugh and others 2007).

There is a need to identify methods for increasing the early survival and growth of shortleaf pine seedlings. Though considerable research into site preparation methods, spacing, herbicide use, and genetics exist for loblolly (*Pinus taeda* L.), slash (*P. elliotti* Engelm.), and longleaf (*P. palustris* Mill.) pines (Baldwin and others 2000, Land and others 2004, Lewis and others 1985, Raley and others 2003, Schubert and others 2004, South and others 2004), there is less current research into these practices for shortleaf pine (Gwaze and others 2005, Gwaze and others 2006b, Smith 2011, Studyvin and Gwaze 2007). Our objectives were to assess the effects of genetic selection, site preparation, and

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vegetation control on first- and seventh-year survival, height growth, and diameter growth of planted 1-0 shortleaf pine seedlings.

METHODS AND DATA ANALYSIS

Site Descriptions

Three datasets were used for this study. The first was from a study conducted at the Wurdack Research Center in Crawford County, Missouri (N 37°47'23.9", W 91°25'12"). The site was a continuous, south-facing slope of 10-30 percent, with two soil series occurring: Reuter (loamy-skeletal, siliceous, active, mesic Typic Paleudalfs) on the upper and lower backslopes, and Goss (clayey-skeletal, mixed, active, mesic Typic Paleudalfs) occurring on lower slope positions (USDA NRCS 2017). The second study was conducted at the Long-Term Soil Productivity site (LTSP) in Shannon County, Missouri (N 37°10'47.9", W 91°6'35.9"). Soils on site were primarily of the rocky, nutrient-poor Clarksville series (loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults), formed from hillslope sediments and cherty residuum from dolomite (USDA NRCS 2017). The third study was conducted at Sinkin Experimental Forest, Reynolds and Dent counties, Missouri (N 37°29'24", W 91°15'36"). Soils included the Clarksville and Coulstone series, (loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults), as well as the Nixa series (loamy-skeletal, siliceous, active, mesic Glossic Fragiudults) (USDA NRCS 2017). At all three sites, the site index (base age 50) for shortleaf pine was between 17.1 m and 18.3 m (California Soil Resource Lab 2017). Thus, height and diameter growth differences among the three sites were likely due to treatments rather than site factors.

At Wurdack, seedlings consisted of genetically improved, 1-0 containerized shortleaf pine stock representing 12 full-sib families, plus standard, orchard-run seedlings from the State nursery at Licking, MO. Families were crossed from elite parents selected in natural stands on the Mark Twain National Forest in the 1970s (Gwaze and others 2005, Smith 2011). The existing hardwood forest was clearcut, and a masticator was used to grind tree stumps and nonmerchantable material. The site was then divided into four blocks. Seedlings were deployed in complete blocks, with 700-1,000 seedlings per block. Three blocks had a silvopasture treatment applied, which involved a double row of trees spaced 3.05 m by 3.05 m followed by a 12.19-m wide alley. A mix of native warm and cool season grasses were broadcast seeded into the alleyways. Herbicide pellets (Velpar®) were applied to the seedling planting rows for 2 years following planting. The fourth block eliminated the alley, leaving rows evenly spaced at 3.05 m. No herbicides were applied in this block and no grasses were seeded. Instead, an additional 12 families (not replicated in the other three blocks) were selected and planted along with the 12 replicated families. Tree heights and diameters were measured in 2010, 2011, and 2017. For purposes of this analysis, trees planted in the no-herbicide treatment will be identified as either genetically improved (G), or orchard-run (O) pedigree. Treatments at Wurdack included VC-O (orchard-run seedlings planted with herbicide application as a vegetation control), No-VC-G (trees belonging to one of the 12 genetic families at Wurdack, planted with no herbicide applied as vegetation control), No-VC-O (orchard-run seedlings planted with no herbicide applied as vegetation control), and the additional 12 pedigreed families each planted with vegetation control.

At the LTSP, a 3 x 3, split-plot factorial study design implemented in three blocks was used to simulate harvest-related soil disturbances including organic matter (biomass) removal, soil compaction, and vegetation control. The study was established in 1995, following a nationally implemented protocol which dictated methodology (Ponder and Mikkelson 1995, Powers and others 1990). Three levels of organic matter removal included removal from site of tree boles only, whole tree (bole, top, limbs), and whole tree plus forest floor (tree bole, top, limbs, and raking of forest floor to remove the organic soil horizon). Three levels of soil (whole-soil) compaction were implemented: no compaction (average bulk density of ~1.30 g/cm^3), moderate compaction (average bulk density ~1.60 g/cm^3), and severe compaction (average bulk density ~1.80 g/cm^3). In addition, half of each treatment plot had chemical herbicide applied annually for 10 years following seedling planting. Bare-root, 1-0 northern red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and shortleaf pine were planted following the application of the treatments (only shortleaf pine data are included in these analyses). Tree height and diameter (basal diameter or diameter at breast height, depending on tree height) were measured annually from 1995 until 2004, with additional measurements in 2013 and 2016. Treatments at the LTSP included for this analysis were VC (chemical vegetation control) and No-VC (no vegetation control). For additional information on study design, plot layout, and site characteristics, see Ponder and Mikkelson (1995) and Lyczak (2019).

At the Sinkin Experimental Forest, treatments included underplanting 1-0 bareroot shortleaf pine seedlings in 48 treatment units in existing second-growth mixed hardwood stands after manipulating the overstory in each treatment unit to a single stocking level between 0 and 75 percent (Gingrich 1967). A windstorm 1 year after seedling planting caused the blowdown and removal of additional overstory trees in some treatment plots, lowering the overstory density and residual basal area. In order to determine the effects of competition on shortleaf pine seedlings, the nearest hardwood competitor was identified, tagged, and measured and tracked throughout the experiment. Hardwood competitors were from either advanced reproduction or stump sprouts. Pine height and diameter (basal diameter or diameter at breast height, depending on height) were measured in 2008, 2009, 2010, 2013, and 2017. Identified hardwood competitors were measured in 2010, 2013, and 2017. Treatments for the Sinkin Experimental Forest included trees less than 80 percent of the height of the nearest competitor regardless of overstory stocking (<80Ht), trees greater than 80 percent of the nearest competitor in height, with an overstory stocking level of 45 percent or more (>45 percent stocking), trees greater than 80 percent of competitor height, with an overstory stocking between 15 and 45 percent (15-45 percent stocking), and trees within 80 percent of competitor height with an overstory of 15 percent or less (<15 percent stocking). For additional information on study design, plot layout, and site characteristics, see Kabrick and others (2011, 2015).

Data Analyses

For each planting site, survival probabilities in relation to pedigree, vegetation control, or overstory treatment were determined using logistic regression for the first- and seventh-year data (table 1). We used a generalized linear mixed model with a binary distribution (survival = 1, mortality = 0), logit link function, and random intercept using PROC GLIMMIX in SAS 9.4 software (SAS Institute Inc., Cary, NC). Treatment effects on the first- and seventh-year tree heights and diameters were analyzed using a generalized linear mixed model with a lognormal distribution, identity link function, and no intercept, using PROC GLIMMIX in SAS 9.4. In these models fixed effects included treatments and random effects included the statistical blocks (Wurdack, LTSP) or treatment units (Sinkin). Least-square means of survival probabilities and tree heights were subjected to pairwise comparisons using the Tukey-Kramer adjustment procedure for multiple comparisons (Kramer 1956) at alpha = 0.05.

RESULTS

First-year survival probability at the LTSP installation was about 60 percent and did not differ significantly ($p = 0.30$) among VC treatment (fig. 1). At the Sinkin installation, first-year survival for seedlings that were shorter than their nearest competitor was about 63 percent and significantly lower ($p < 0.01$) than for seedlings that were similar in height or taller than nearest competitors regardless of overstory stocking level. At Wurdack, seedlings with No-VC had mean survival of probability of 75 percent and was significantly lower ($p < 0.01$) than for seedlings with vegetation control regardless of pedigree.

The same trends among treatments observed during year 1 were also observed at year 7 although the survival probability in the No-VC treatments decreased during the sampling interval (fig. 2). Survival probability from year 1 to year 7 remained above 95 percent for all Wurdack families in the VC treatment, as well as all Sinkin trees taller than their nearest competitor. At Sinkin, the presence of taller competitors reduced survival probability to 35 percent. Several treatment categories appeared to have had an increase in survival probability from year 1 to year 7 from stump sprouts following damage or top kill that had occurred since the first data collection.

Mean height in year 1 was highly variable across studies and treatments (fig. 3). There was no significant difference ($p = 0.99$) in height between VC treatments at LTSP, where first-year height averaged 55 cm. At the Sinkin, underplanted seedlings with an overstory stocking <15 percent had a mean seedling height of 44 cm, but seedlings were not significantly greater ($p > 0.05$) than for other treatments which averaged 29 cm. At Wurdack, mean seedling height was about 70 cm in the No-VC treatment but was nominally (but not

Table 1—Site, primary treatment, vegetation control parameter, and number of trees used in analyses

Site	Primary treatment	Vegetation control	Trees
			n
Wurdack	Genetically improved	Yes	736
Wurdack	Genetically improved	No	756
Wurdack	Orchard-run	Yes	872
Wurdack	Orchard-run	No	408
Sinkin	Stocking level <15%	No	480
Sinkin	Stocking level 15-45%	No	510
Sinkin	Stocking level >45%	No	540
LTSP	-	Yes	384
LTSP	-	No	379

Sites are Wurdack Research Center, Sinkin Experimental Forest, and a Long-Term Soil Productivity (LTSP) site, Missouri.

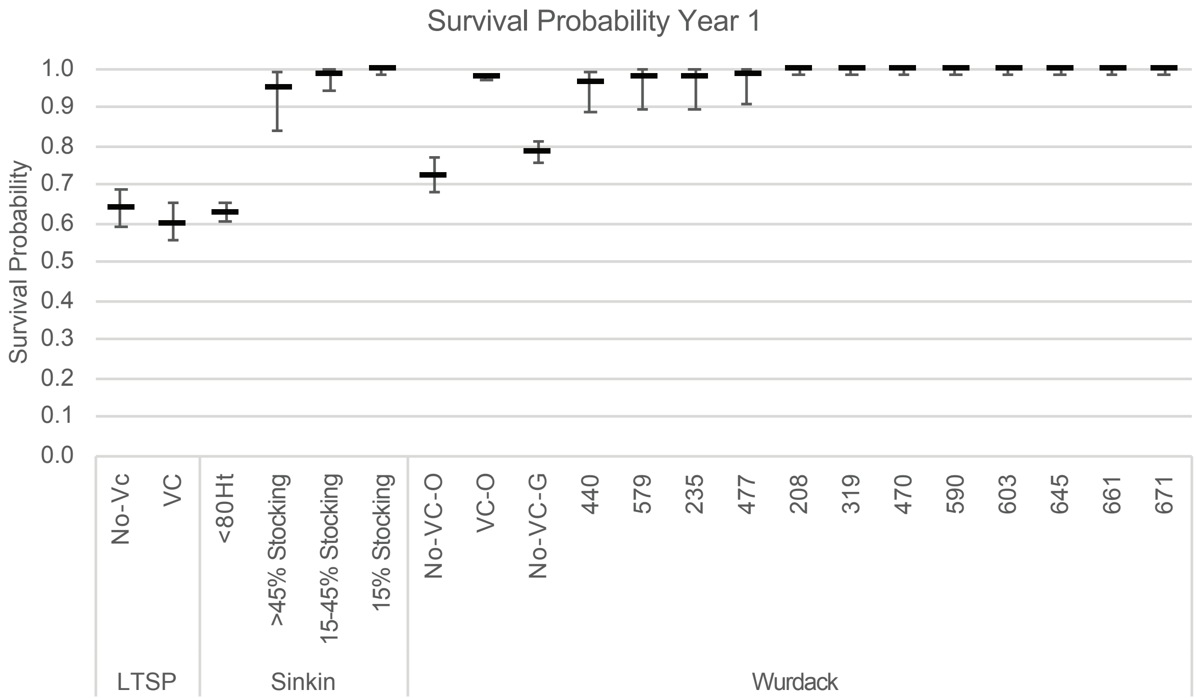

Figure 1—Survival probability 1 year after planting. Error bars represent ± one standard error of the mean. Sites and treatments are defined in the text.

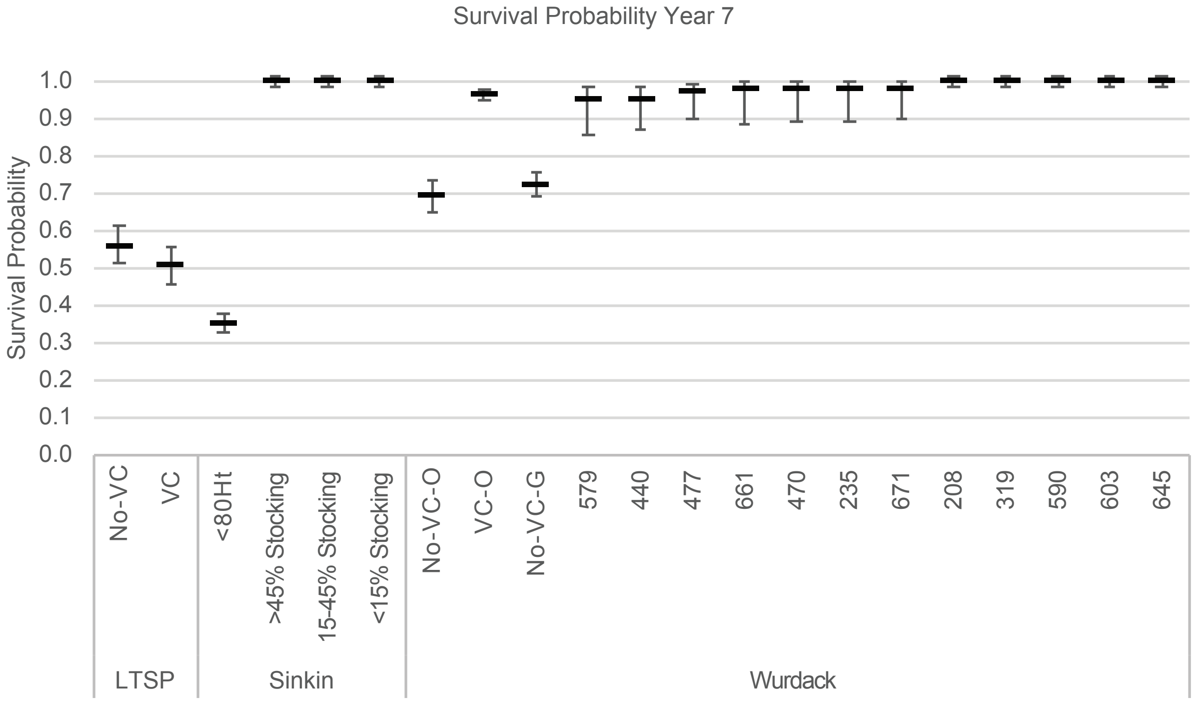

Figure 2—Survival probability 7 years after planting. Error bars represent ± one standard error of the mean. Sites and treatments are defined in the text. Some probabilities may be higher than year 1 due to stump sprouting between measurements.

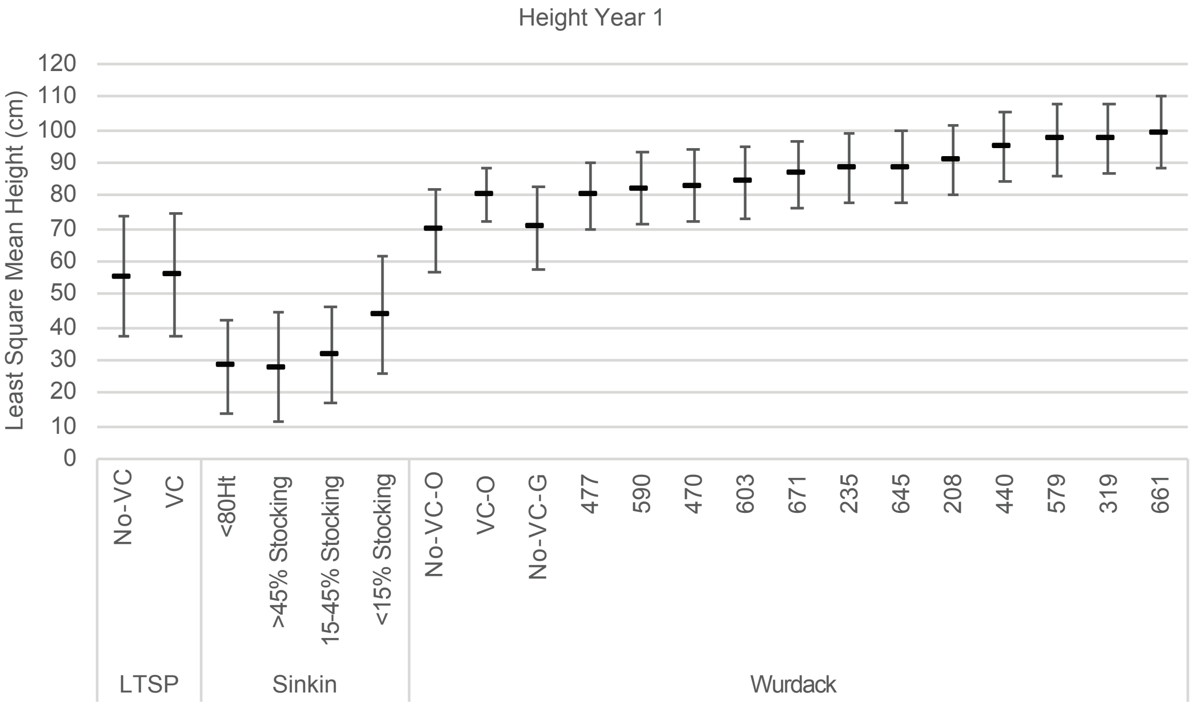

Figure 3—Mean tree height 1 year after planting. Error bars represent ± one standard error of the mean. Sites and treatments are defined in the text.

significantly) greater where VC treatments were applied. At Wurdack, the top five families had a mean height of 96 cm.

At year 7 there were no significant differences ($p > 0.05$) in seedling heights by VC treatment at LTSP and at Wurdack (fig. 4). However, at the Sinkin study, seedlings that were shorter than their nearest competitor were also significantly shorter ($p = 0.01$) than seedlings in the other groups, with a mean height of 84 cm. For seedlings that were as tall as or taller than their nearest competitor, seedling height increased significantly ($p < 0.01$) with decreasing overstory stocking. When the overstory was eliminated, mean seedling height was similar to all but the top five pedigreed families, with an average of 463 cm and the top five families had an average height of 503 cm after 7 years.

At year 1 there were no significant differences ($p > 0.05$) in basal diameter among treatments at each site but there were notable trends (fig. 5). For underplanted seedlings at the Sinkin, the mean basal diameter was 4.5 mm and it appeared to be greatly reduced by the presence of a partial overstory. For pedigree stock at Wurdack, No-VC had a mean of 14 mm and the addition of VC nominally increased mean basal diameter to > 18 mm. Two families had a nominally greater basal diameter, with a mean of 24 mm. Basal diameter was not recorded in year 1 at the LTSP sites.

By year 7, diameter at breast height (d.b.h.) was significantly increased by VC treatment at LTSP ($p < 0.01$) but only nominally increased ($p < 0.05$) at Wurdack where seedling diameter was greater than 80 mm (fig. 6). At Sinkin, underplanted trees with overstory stocking <15 percent averaged 73 mm d.b.h., and had significantly greater d.b.h. ($p > 0.01$) than seedlings having a greater overstory stocking or seedlings that were shorter than understory competitors.

DISCUSSION

Survival

Shortleaf pine seedling survival at 1 and 7 years following planting was primarily affected by the presence of understory competition (figs. 1 and 2). This finding is similar to Blizzard and others (2007), who reported that understory competition density had a greater effect on naturally regenerated shortleaf pine seedling survival than did overstory density. Similarly, Kabrick and others (2015) reported overstory stocking had no significant effect on shortleaf pine survival during the first five years after planting. Genetic selection and site preparation do not appear to have increased survival in this study, as underplanted seedlings within 80 percent of their competitor's height exhibited similar survival probabilities at the Sinkin study regardless of overstory stocking, while seedlings planted in prepared plots at LTSP had significantly lower survival than prepared plots at Wurdack (Lyczak 2019). Further, when pedigreed

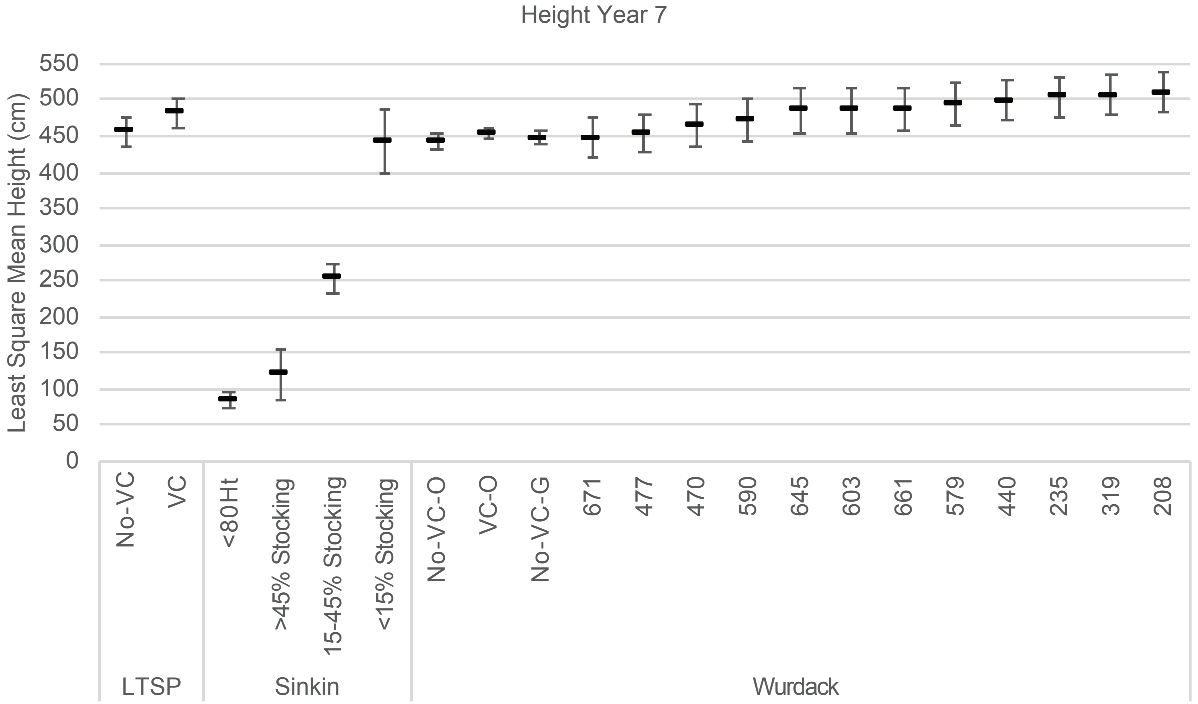

Figure 4—Mean tree height 7 years after planting. Error bars represent ± one standard error of the mean. Sites and treatments are defined in the text.

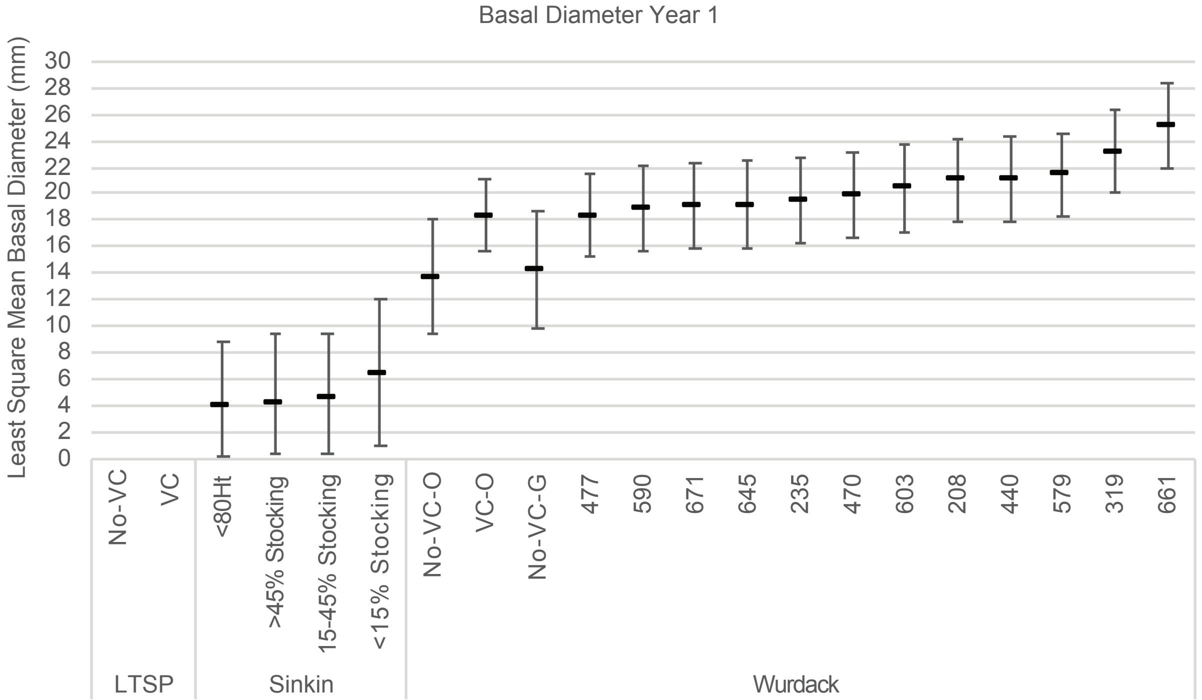

Figure 5—Year 1 mean basal diameter. Error bars represent ± one standard error of the mean. Sites and treatments are defined in the text. Diameter readings were not recorded at LTSP until year three.

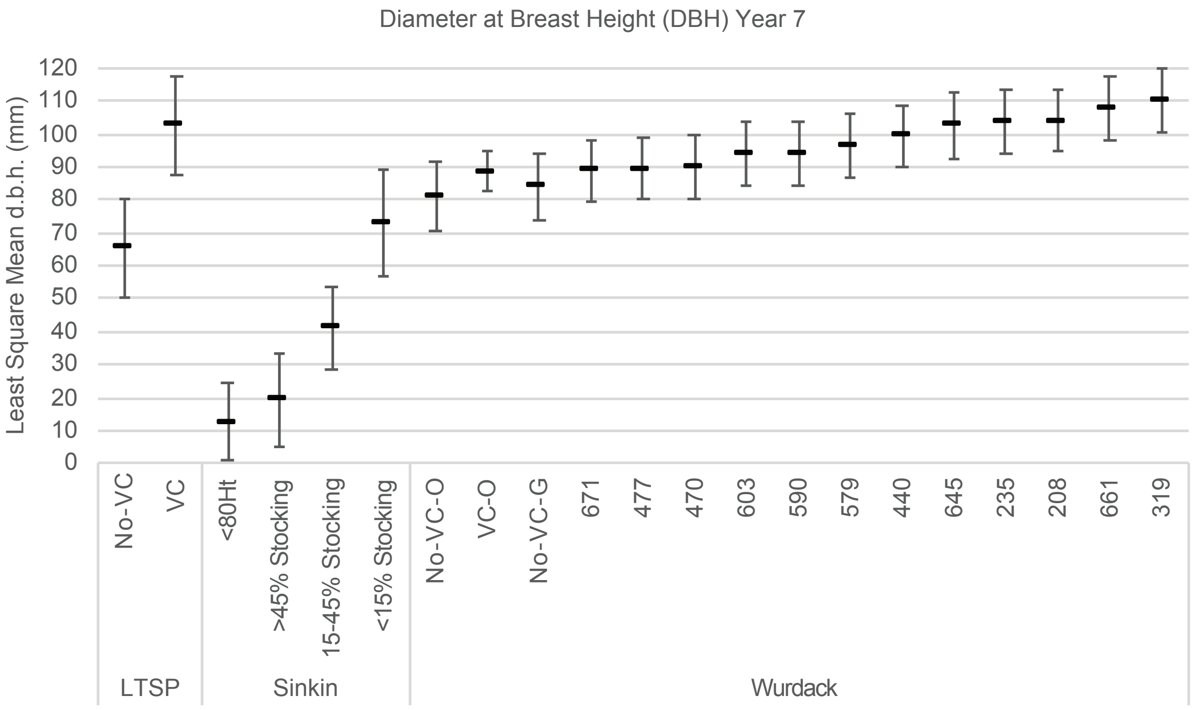

Figure 6—Year 7 diameter at breast height (d.b.h.). Error bars represent ± one standard error of the mean. Sites and treatments are defined in the text.

seedlings were planted without VC, survival was greater by more than 20 percent in year 1, and 30 percent by year seven when compared to the same families in herbicide treatments at Wurdack. These survival numbers are surprisingly and substantially lower than those reported by Brissette and Barnett (2003), who observed 90 percent survival 10 years after planting on half-sib shortleaf pine in northern Arkansas. Other site preparation methods, including ripping and prescribed fire, also result in mean first-year survival rates over 90 percent, suggesting a possible alternative to herbicide application (Cain and Shelton 2000, Gwaze and others 2006a). Though overall survival probability at LTSP was 60 percent, irrespective of VC, we believe this may be due to unique conditions encountered at planting, which included drought and rodent damage (Ponder 1997), rather than a result of treatments.

Height Growth

Height growth is a highly heritable trait in shortleaf pine, according to a study of progeny selected from phenotypically superior wild trees at a first-generation seed orchard in Missouri (Gwaze and others 2005). It was therefore surprising that we found only 2 of 12 full-sib families outperformed standard seedlings after 7 growing seasons. Pedigreed seedlings were only nominally taller after the first year compared to orchard-run seedlings (fig. 3). By the seventh growing season, however, only two families (319 and 208) were nominally taller than orchard-run seedlings (fig. 4). Underplanted seedlings that were shorter than competitors or that had moderate to high levels of overstory stocking appeared to have the greatest height reductions compared to seedlings grown in the open. Unlike survival, the presence of overstory with greater than 45 percent stocking significantly reduced mean height by nearly half, while seedlings that were shorter than a nearby competitors, regardless of overstory density, had a mean height reduction of almost 85 percent. In other studies, site preparation and herbicide application provided the most significant height growth gains for other southern pines (Land and others 2004, Lewis and others 1985, Schubert and others 2004, South and others 2004). As these stands continue to develop, early height growth, especially that above competing vegetation, is an important element in evaluating whether shortleaf pine will recruit to the overstory upon canopy closure (Raley and others 2003).

Diameter

Diameter growth followed a similar trend to that of height (figs. 5 and 6). Greater differences in diameter among treatments suggests that seedling diameter growth may be more sensitive to competition than is height. Year 1 basal diameter was nominally greater in pedigreed seedlings than other treatments, although seedling production and planting methods may account for these differences. Diameter was not measured on the LTSP site until year 3, so we were unable to compare herbicide and site preparation treatments. However, pedigreed seedlings planted without VC at Wurdack had nominally smaller basal diameters (14 mm) than pedigreed seedlings with VC (18 mm) at year 1. When the Sinkin trees are compared to those at Wurdack, it appears that seedlings with any level of overstory will have substantially reduced diameter growth during the first year. By year 7, diameter at breast height (d.b.h.) remained low where a partial overstory was present (Sinkin) but did not vary by pedigree where trees were grown in the open (Wurdack). Heritability estimates for diameter are lower than those for height, which is supported by these results (Gwaze and others 2005). The presence of understory competition significantly reduced d.b.h., even when trees were taller than their nearest competitor (Sinkin) or as tall as site trees in VC plots (LTSP). Diameter growth is considered to be less important than height growth during the stem exclusion stage of stand development (see Oliver and Larson 1996). However, larger diameters are associated with higher survival probabilities, increased resistance to fire and pest damage, as well as greater resilience to the effects of competition (Brinkman and Rodgers 1967, Brinkman and Smith 1968, Kabrick and others 2015, Lawson 1990, Stambaugh and others 2007).

CONCLUSIONS

We found that competition remains the most important factor reducing survival and growth of planted shortleaf pine seedlings. While orchard-run seedlings free from understory competition have similar survival and height growth to genetically improved seedlings, they have nominally lower overall diameter growth. The use of orchard-run stock, in conjunction with understory vegetation competition control during the first several growing seasons, should allow for successful shortleaf pine establishment under most site conditions encountered in Missouri.

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REVISITING SHORTLEAF OUTPLANTINGS OF THE SOUTHWIDE PINE SEED SOURCE STUDY ON THE CROSSETT EXPERIMENTAL FOREST

Don C. Bragg and Shaik M. Hossain

Abstract—In early 1953, eight blocks of the Southwide Pine Seed Source Study (SPSSS) featuring two geographically based series of shortleaf pine (*Pinus echinata*) were planted in Compartment 46 of the Crossett Experimental Forest (CEF). These shortleaf pines originated from Arkansas, Louisiana, Mississippi, Missouri, New Jersey, Oklahoma, Pennsylvania, Tennessee, and Texas seed sources. Their survival, fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) resistance, and height growth performance were tracked closely until the late 1960s, when the original effort to monitor these blocks for the SPSSS was discontinued. Remeasured into the 1980s, these outplantings were largely forgotten until recently, when interest in shortleaf pine reemerged. Although some unplanned harvests and other losses have occurred, enough surviving SPSSS shortleaf pines remained in the latter half of 2018 to reassess their diameters, heights, and derived merchantable volumes. After 65 years in the ground, some significant differences in height, diameter at breast height, and volume by seed source have persisted. In addition to assessing these shortleaf pines for long-term, seed source-based success, the remaining outplantings also present opportunities to further investigate species-based DNA markers useful for describing the genetic variation of this declining yet still important southern pine species. Better documentation of the growth performance and genetic attributes should also help silviculturists hone their strategies for the restoration of shortleaf pine.

INTRODUCTION

Initiated in 1951 by the Committee on Southern Forest Tree Improvement, the program that became known as the Southwide Pine Seed Source Study (SPSSS) represented the first regionally coordinated effort to test the capacity to move seedlings across the distributions of the various southern pines (Subcommittee on Geographic Source of Seed 1956). The four major southern pines (loblolly, *Pinus taeda*; longleaf, *Pinus palustris*; slash, *Pinus elliottii*; and shortleaf, *Pinus echinata*) have long dominated the southern timber industry, and their large-scale propagation and restoration via planting were critical for the development of tree improvement programs. However, prior to the SPSSS, very little research had been done to support the planting efforts of foresters and landowners.

Specifically, the SPSSS sought to better understand the performance (in terms of survival, vigor, productivity, etc.) of a given species when seeds from a given geographic location were germinated and planted in other parts of the South (Subcommittee on Geographic Source of Seed 1956). This study was the first cooperative study of this topic by the Committee on Southern Forest Tree Improvement and was administered by the Southern Forest Experiment Station (SOFES) of the Forest Service, U.S. Department of Agriculture. While SPSSS standardized this research, there were some variations in how the study was implemented based in part on species (for example, seed source areas or outplanting locations) and environmental circumstances (for example, differential mortality of plantations due to regional drought in the early 1950s).

Variation in shortleaf pine for the SPSSS was based on latitude and longitude. In the selection of different "series" for the SPSSS, shortleaf pine seed sources and outplantings were originally placed into "Eastern Temperature" and "Western Temperature" series (Series I and Series II, respectively) (Subcommittee on Geographic Source of Seed 1956). Wells and Wakeley (1970) described the shortleaf pine series and some limited early results. In their paper, Series I represented the "Latitude series" because it encompassed a greater range of latitude than Series II, which they labeled the "Intermediate series." Some of the SPSSS outplantings of all species, including many of the shortleaf pines, were badly impacted by severe drought of 1953–54 and were addressed (in part) by a replanting of the most affected sites with seed collected in the fall of 1955 and planted in 1956–57 (Subcommittee on Geographic Source of Seed 1956, Wells and Wakeley 1970). A

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third shortleaf pine series (Series III) was later added to consider botanical origin and migration (Wells and Wakeley 1970) associated with longitude, as it spanned the east-west distribution of shortleaf pine, but Series III was not installed at all SPSSS locations.

While some may be surprised that shortleaf pine was included in the SPSSS, historically its abundance across the South was much higher than the present day (Bragg 2008). Since the installation of the SPSSS, dramatic declines in shortleaf pine abundance over the last half-century across the region have made this species of particular conservation concern (Anderson and others 2016, Moser and others 2007, Oswalt 2012). Although there are multiple reasons behind this decline, recent conservation and research efforts [for example, the Shortleaf Pine Initiative (http://www.shortleafpine.net/); Anderson and others 2016] offer some promise that this trend can be halted if not reversed in many parts of its range. To this end, we believe that additional lessons can still be learned from the surviving SPSSS-origin shortleaf pine outplantings on the Crossett Experimental Forest (CEF), and this paper represents the first reassessment of these in 30 years.

MATERIALS AND METHODS

SPSSS Series I and II Implementations at the CEF

Even though the CEF is best known for its many decades of naturally regenerated southern pine silviculture research (especially uneven-aged management), it also housed a forest genetics/tree improvement program from the early 1950s until the location was temporarily closed in the early 1970s (Bragg and others 2016). Some of the earliest work of this CEF program, the SPSSS outplantings were from Series I and Series II (Series III was not installed at CEF, and no replantings in 1956–57 were done, either). The shortleaf pine seed sources by series are described in table 1 and figures 1 and 2. Series I consisted of four seed sources from the western portion of shortleaf pine's range, a Burlington County, NJ source, a local Ashley County, AR source, and one from Morgan County, TN. Series II had three different shortleaf pine seed sources from the western portion of its range, plus a Franklin County, PA source and the same Ashley County and Morgan County sources. Each series was replicated four times in a randomized block design, with plots being 0.1 acre in size and containing 121 trees (11 rows of 11 trees) at 6-foot by 6-foot spacing, with only the innermost 49 trees measured in the original analyses (Grigsby 1964).

Shortleaf were the only southern pines planted on the CEF for the SPSSS; relatively limited space, staffing, and other resource constraints kept the CEF from installing loblolly outplantings, and neither longleaf nor slash pine were native to Arkansas. The CEF shortleaf were planted in Compartment 46 in late January and early February of 1953 under the direction of SOFES Forest Geneticist Roland E. Schoenike (Schoenike 1953b). After establishment, a limited set of measurements were taken, including survivorship (percent of live trees), diameter at breast height (d.b.h.) to the nearest 0.1 inch, total tree height (to the nearest 0.1 foot), and rate of fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) infection (as a percent). Measurements were taken at a number of intervals over the first few decades: first annually, then every few years, and finally every 5 years to age 35. The CEF SPSSS results have been summarized elsewhere (for example, Grigsby 1964, 1979; Schoenike 1953a, 1956; Wells and Wakeley 1970) and will only be briefly mentioned in this paper.

Table 1—Description of the Southwide Pine Seed Source Study (SPSSS) shortleaf pine seed sources planted in 1953 on the Crossett Experimental Forest (CEF)

Original study label	Series	Source origin location (# of sources)	Average annual temperature (°F)	Location key (fig. 1)	CEF block numbers (fig. 2)
SPSSS seed source				*This paper*	
C-401	II	Franklin Co., PA (1)	53	10	5, 6, 7, 8
C-403	I	Burlington Co., NJ (1)	53	11	1, 2, 3, 4
C-419	I	Lafayette Co., MS (1)	63	8	1, 2, 3, 4
C-421	I	St. Helena Parish, LA (1)	67	7	1, 2, 3, 4
C-423	II	Angelina Co., TX (1)	67	6	5, 6, 7, 8
C-425	II	Pushmataha Co., OK (1)	63	5	5, 6, 7, 8
C-427	I	Clark Co., AR (1)	63	2	1, 2, 3, 4
C-429	I, II	Ashley Co., AR (2)	63	1	1, 2, 3, 4, 5, 6, 7, 8
C-431	II	Stone Co., AR (1)	58	3	5, 6, 7, 8
C-433	I	Dent Co., MO (1)	58	4	1, 2, 3, 4
C-435	I, II	Morgan Co., TN (2)	58	9	1, 2, 3, 4, 5, 6, 7, 8

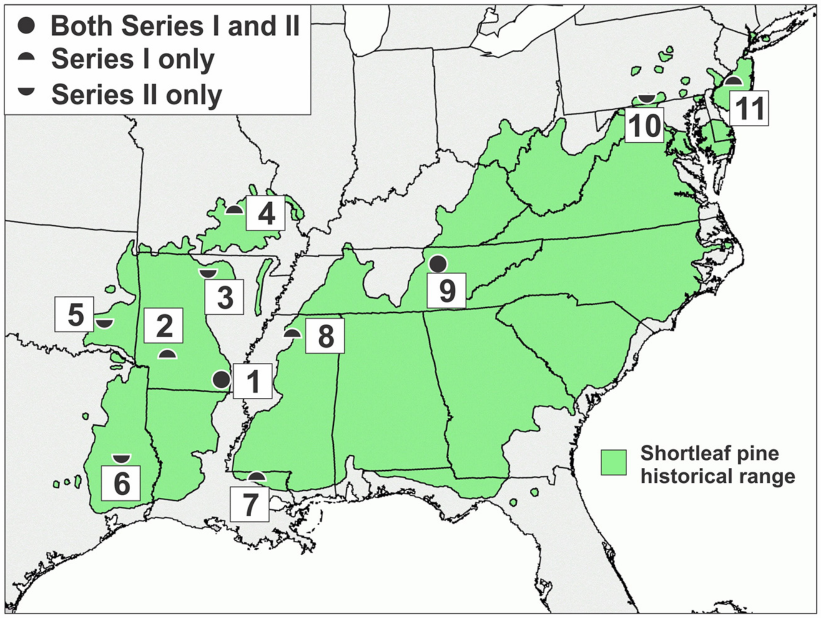

Figure 1—Distribution of Southwide Pine Seed Source Study Series I and Series II outplantings of shortleaf pine. Numeric code locations include: 1: Crossett Experimental Forest, Ashley County, AR; 2: Clark County, AR; 3: Stone County, AR; 4: Dent County, MO; 5: Pushmataha County, OK; 6: Angelina County, TX; 7: St. Helena Parish, LA; 8: Lafayette County, MS; 9: Morgan County, TN; 10: Franklin County, PA; and 11: Burlington County, NJ. Shortleaf pine distribution based on E.L. Little's map (Little 1971).

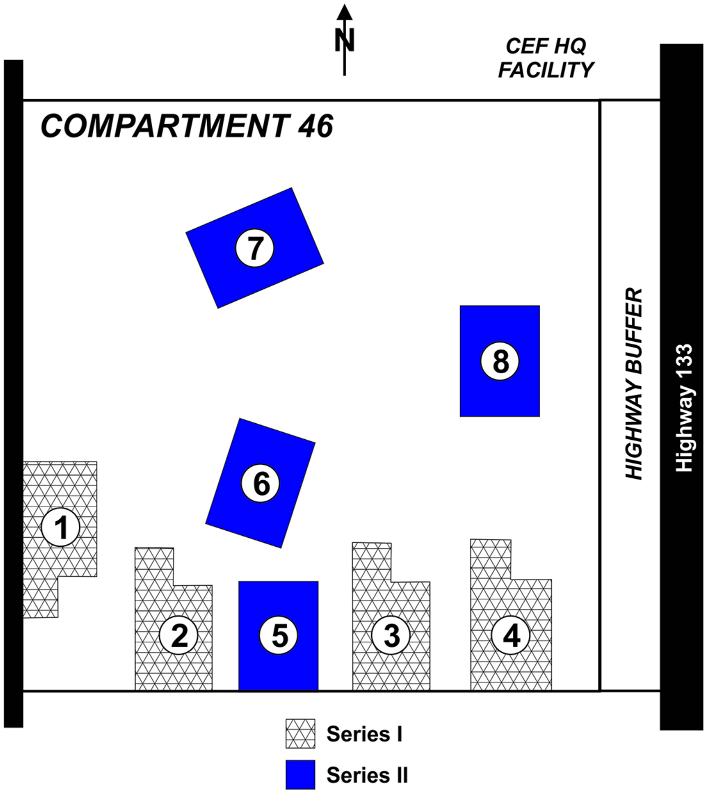

Figure 2—Shortleaf pine planting blocks from the 1953 Southwide Pine Seed Source Study in Compartment 46 on the Crossett Experimental Forest. Blocks 1–4 are from Series I; blocks 5–8 are from Series II.

Other potentially influential factors were documented as they arose. For example, Schoenike (1956) observed substantial impacts of tip moth (*Rhyacionia frustrana*) in all seed sources and also remarked that three of the Morgan County shortleaf actually proved to be Virginia pine (*Pinus virginiana*) seedlings that had somehow contaminated the original seedling pool. Silvicultural treatments were also built into the original design. The CEF SPSSS plots were thinned to "about half" of the original number of trees planted at 15 years, followed by some additional thinning at age 20 (Grigsby 1979). Further thinnings were done after the year 35 measurements, but these were more operational in nature and not well documented. Compartment 46 has been affected by a number of natural disturbances over the years, with unknown impacts on the SPSSS outplantings.

2018 Remeasurement

As a part of a broader study of shortleaf pine genetics, we revisited the SPSSS outplantings in the latter months of 2018 (fig. 2). Because most of the original plot monuments had long been lost, the first step was to relocate the study blocks using available plot maps. Whenever available, old tags attached to planted pines within each block were used to help confirm block identity. After each block was relocated, all of the living, now 65-year-old shortleaf pines remaining in these blocks (not just the interior trees) were measured for their d.b.h. and total tree height. These diameters and heights were then used to estimate total merchantable volume (*V*) (to a 4-inch top) using the following regional loblolly pine equation (Van Deusen and others 1981):

$$V = 0.00296 + 0.00193881 d.b.h.^2\, HT \times R \qquad (1)$$

where

HT is total tree height and *R* is a top-diameter conversion ratio:

$$R = e^{-2.9637 X^{4.7564}} \qquad (2)$$

where

X is top diameter (4 inches) divided by d.b.h.

While Van Deusen and others' (1981) volume model was not developed for shortleaf pine, previous experience on the CEF has shown that equation (1) works well for this allometrically similar species. Given that equation (1) incorporated height, which was expected to vary by seed source, the use of this variable allowed for better precision than the local CEF-based (Farrar and others 1984) equation for loblolly and shortleaf pines that only uses d.b.h. to predict volume.

Numbers of live shortleaf pines per replicate within blocks were also recorded, but no attempt was made to look for any evidence of fusiform rust. We also did not look for differences in seed production capacity, as had been done in some of the earlier analyses. Given that most sources were not shared between series, direct comparisons using traditional approaches were problematic. However, because a present-day comparison between seed sources regardless of series was desired, we tested the two seed sources common to both series. There were no blocking effects indicating that there were no series-based differences. Hence, this suggests that combining all seed sources for this direct comparison would be valid. Differences in seed source performance by d.b.h., height, and merchantable volume were compared in Statistica (version 12) using analysis of variance and then mean separation with Tukey's honestly significant difference test for unequal sample sizes at an $\alpha = 0.05$ (for d.b.h. and height) and $\alpha = 0.10$ for merchantable volume. The higher alpha level for merchantable volume was applied because its substantial variation (culminating from the highly varying d.b.h. and height measurements) may have otherwise masked meaningful differences, thereby resulting in an unnecessarily high Type II error with an $\alpha = 0.05$ (Zar 2010).

RESULTS

After 65 years, an average of 2.5 percent of planted shortleaf pine in the SPSSS plots on the CEF remained alive, including survivors from all seed sources (table 2). In general, there were greater numbers of surviving shortleaf pine from the local (Arkansas region) and western (Texas, Missouri, and Oklahoma) seed sources (2.1 to 4.1 percent) and slightly less from Pennsylvania, New Jersey, Louisiana, and Tennessee (1.8 percent), with the lowest overall survivorship from the Mississippi seed source (1.2 percent). For circumstances that will be discussed later, no further analysis of survivorship was done.

Not surprisingly, shortleaf pine seed sources from the western and southern portions of the sampling distribution produced the largest diameters at age 65, with most of these seed sources averaging between 16 and 18 inches d.b.h. However, only the Tennessee seed sources (average of 14.1 inches d.b.h.) proved to be significantly smaller ($p < 0.05$) than those from Arkansas, Missouri, Texas, and Oklahoma. The Pennsylvania (14.8 inches) and New Jersey (14.6 inches) shortleaf pines were both on the smaller end, but they were not statistically smaller in d.b.h. than the better performing seed sources (table 2). This lack of significance arose from the considerable variability in tree d.b.h. (standard deviation ranged between 1.5 and 3.2 inches) in the diameters measured in 2018.

Table 2—Results from 2018 remeasurement of the shortleaf pines in the Crossett Experimental Forest's Southwide Pine Seed Source Study (SPSSS) planting blocks

			d.b.h.		Total height		Merchantable volume	
Original study label	Alive in 2018		Mean	SD	Mean	SD	Mean	SD
	number	*percent*	-------*inches*-------		----------*feet*----------		------*cubic feet*--------	
C-401	9	1.8	14.8 ab	1.48	73.9 ab	4.68	31.3 ab	6.58
C-403	9	1.8	14.6 ab	2.10	67.4 b	12.74	28.9 ab	11.88
C-419	6	1.2	16.6 ab	1.61	71.7 ab	15.58	39.6 ab	14.03
C-421	9	1.8	17.3 ab	2.64	80.0 ab	13.23	48.2 ab	19.04
C-423	20	4.1	17.8 a	2.70	82.3 ab	7.26	52.4 a	18.14
C-425	10	2.1	17.8 a	2.41	82.8 a	8.27	51.9 ab	16.18
C-427	11	2.3	17.5 a	2.03	79.1 ab	17.75	48.3 ab	18.25
C-429	28	2.9	17.3 a	2.08	84.8 a	5.65	50.1 a	13.65
C-431	18	3.7	16.3 ab	3.17	75.9 ab	7.31	41.4 ab	21.30
C-433	18	3.7	17.5 a	2.31	78.6 ab	11.03	47.9 a	16.79
C-435	18	1.8	14.1 b	2.50	75.2 ab	8.60	29.9 b	12.70
Total	156							
Average		2.5						

d.b.h. = diameter at breast height, SD = standard deviation.

Means in a column with the same letter are not significantly different [$p < 0.05$, Tukey's honestly significant difference (HSD) for unequal sample sizes].

Merchantable volume to a 4-inch top following Van Deusen and others (1981); significance for this column is $p < 0.10$, Tukey's HSD for unequal sample sizes.

When measured in 2018, the New Jersey (67.4 feet) seed source was significantly ($p < 0.05$) shorter than Oklahoma (82.8 feet) and Ashley County, Arkansas (C-429) (84.8 feet) seed sources, while the rest were not significantly different (even though their mean heights ranged from almost 72 feet to almost 83 feet tall). This lack of significance again was due to high variability, as height standard deviations for many of these trees ranged from 11 to nearly 18 feet (table 2).

Because the merchantable volume equation (1) is particularly responsive to differences in d.b.h., the low diameters of the Tennessee shortleaf pine seed sources translated into their having significantly ($p < 0.10$) lower volumes at 65 years compared to the most voluminous trees from Texas and Oklahoma (under 30 cubic feet, compared to about 52 cubic feet). Otherwise, the other seed sources proved to be statistically similar in volume, again attributable to high variation in volume estimates (table 2). This was true even for the New Jersey and Pennsylvania sources, both of which averaged only about 30 cubic feet per tree (comparable to the Tennessee seed sources).

DISCUSSION

Survivorship and Fusiform Rust Occurrence Observations

While differential response to disturbances and stressors is probably at least partially a heritable trait, because this was not controlled for it would be inappropriate to attribute survivorship in 2018 (table 2) as directly related to seed source. Too many unknown (and uncontrolled) circumstances occurred between the last year (1988) that survivorship was measured and the present day. For example, this compartment on the CEF has been inconsistently thinned over the last 3 decades and variably impacted by windthrow, insect attacks, and other environmental factors. Shortleaf pines that had survived fusiform rust infection early in their life may have been preferentially thinned in recent years, when such decisions were made operationally.

Differences in survival as a function of seed source were noted early in the SPSSS study (when this degree of control was possible), especially during the first 5 years after planting (Grigsby 1964; Schoenike 1954, 1955, 1956). Some of the earliest mortality arose from different quality seedlings and planting issues, compounded by an early flooding rain and then a multi-year drought (Schoenike 1954). After the first few observation periods, mortality in all seed sources stabilized, became fairly constant over the years, and eventually became statistically insignificant between sources (Grigsby 1964). During these intervening years, various factors killed shortleaf pine in these blocks, including windthrow, lightning, insects/disease, and thinning (Grigsby 1964, 1979; Schoenike 1955). These early assessments did find that fusiform rust resistance was greatest in the shortleaf pine seed sources from the more westerly portion of the species distribution. Indeed, the only seed source Grigsby (1979) reported with significantly greater amounts of fusiform rust (almost 16 percent) at 20 years was the one from New Jersey (all others he reported had between 1 and 3 percent fusiform rust occurrence).

Size and Volume Trends

This limited set of data supports some of the original conclusions of the SPSSS. With these genetically unimproved shortleaf pine seed sources, local sources generally fared the best—or close to the best—under most circumstances regardless of observed productivity variable (Wells and Wakeley 1970). After 65 years, the local Ashley County, AR (C-429) seed source was consistently amongst the largest sources (whether measured in d.b.h., height, or merchantable volume) in the CEF outplantings. Other western sources (especially Texas and Oklahoma) of shortleaf pine also performed at the highest levels observed, followed by Missouri and Louisiana sources. The Tennessee shortleaf pine source produced significantly less volume than the best performing seed source areas, and the Pennsylvania and New Jersey sources also performed poorly after 65 years. Grigsby (1979) reported similar d.b.h., height, and volume trends at age 20 in the CEF outplantings, with the Ashley County, AR (C-429) seed source performing the best in all three measures and the New Jersey and Tennessee sources faring the worst.

These results in Ashley County, AR, are generally comparable to analyses of the SPSSS outplantings in Dent County, MO, and Pushmataha County, OK, if considered from the perspective of the supremacy of local (or near-local) sourcing. In the Missouri study, Gwaze and others (2007) evaluated provenances from the two tests (Series I and III) and found that the seed sources from the more northerly collections (New Jersey and Tennessee, in the case of Series I) did the best, followed closely by those from more mid-latitudes and with the southerly collections performing worst. The trend of better survival and greater height growth of more northerly seed sources in the northerly Dent County outplanting is consistent with earlier findings from Oklahoma (Tauer 1980) and, not surprisingly, helped support the seed zone recommendations for shortleaf pine (for example, Wells 1973; Wells and Wakeley 1970) derived from the SPSSS.

CONCLUSIONS

Sixty-five years after establishment, we believe the SPSSS shortleaf pine outplantings on the CEF still offer promise for new discoveries, even though following the original study design has little potential given the unplanned thinnings and substantial mortality that have occurred over the decades. The shortleaf pine remaining at CEF today could be combined with any remaining outplantings at the other SPSSS locations to determine if sufficient numbers remain from enough of the seed sources for performance-based meta-analysis across the region. While the results of such a synthesis are not likely to change drastically from their original assessments, the further comparison of growth performance over long periods of time over the region would be a useful means to evaluate seed zone determinations from decades past (especially in the light of a changing climate).

Perhaps the best opportunity for new research from the surviving SPSSS outplantings may lie in the DNA of these surviving trees. Although never intended to be a component of the original study—the structure of DNA itself was not described scientifically (Watson and Crick 1953) until after the early SPSSS plantings—the genetic constituents of these seed sources have already been used to better understand potential changes to hybridization frequency in shortleaf pine (for example, Stewart and others 2010). Locally, we plan to use the CEF outplantings of the SPSSS to supplement other sources of shortleaf and loblolly pine from the Arkansas region in a series of different DNA marker tests to better document genetic diversity of these species. This information could prove useful regionally and nationally, as much of the focus on shortleaf pine is now conservation based, rather than production driven (as when the SPSSS progeny tests were installed).

Such opportunities further demonstrate the value of maintaining carefully controlling progeny tests from establishment through intended completion and beyond. So long as their limited footprint does not interfere with later studies in space-constrained experimental forests, these long-term progeny tests should be retained until mortality ends their usefulness.

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ADDENDUM

An EF-2 tornado struck parts of the CEF on April 25, 2019. While most of Compartment 46 was not affected, winds from this supercell storm toppled five of the SPSSS shortleaf pines (two each in blocks 2 and 5, and one in block 6). These trees came from different States and were 16 to 18 inches in diameter.

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COMPARISON OF SHORTLEAF PINE FAMILIES AND SEED SOURCES IN SOME OUACHITA NATIONAL FOREST PROGENY TESTS

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Abstract—Shortleaf pine (*Pinus echinata* Mill.) has declined significantly (by over 50 percent) across its range due in part to a lack of both artificial and natural regeneration. A series of shortleaf pine progeny tests, established rangewide from the late 1970s into the early 1990s, offers promise for addressing some of the silviculture and restoration concerns related to this decline. Eighty-four of these shortleaf pine progeny tests were established on the Ouachita and Ozark-St. Francis National Forests. These 33-family (on average), full-sib progeny tests were produced from parent trees growing in the Mount Ida Seed Orchard. These parents originated from three geographic seed source regions in Arkansas and Oklahoma: East Ouachita, West Ouachita, and Ozark. In 2018 and 2019, we remeasured diameter at breast height (d.b.h.), tree height, and survival and recorded general tree health conditions from seven well-stocked progeny tests that were installed in the East and West Ouachita regions. We combined our measurements with those taken in the past to help determine if performance differences over time could be found among these shortleaf pine families. Our preliminary analysis indicated differences in d.b.h., height, and survival—information that should help silviculturists making decisions about which shortleaf families may prove most useful for restoration and tree improvement purposes in the region.

INTRODUCTION

Shortleaf pine (*Pinus echinata* Mill.) has the largest natural range of the four major southern pines, occurring in 22 States from New York to Texas (Little 1971). Shortleaf pine was once the dominant pine species across much of this region due to its adaptability to a large variety of edaphic and climatic conditions (Mattoon 1915, Mohr and Roth 1897). The species is also important for wildlife habitat and timber products such as sawtimber and pulpwood (Lawson 1990, Studyvin and Gwaze 2012). However, changes in land use and forest management practices (for example, fire suppression, conversion to intensely managed loblolly pine, and limited artificial shortleaf pine regeneration), insufficient natural regeneration, and other environmental changes and forest health factors over the last half-century have all contributed to a decline in the coverage and importance of shortleaf pine (Stewart and others 2013, 2015). Although this decline has been ongoing over the last century, the most dramatic losses have occurred since the 1980s, with shortleaf pine acreage down by 52 percent by 2012 (Oswalt 2012).

The ecological and economic importance of shortleaf pine, coupled with its genetic diversity, have made the species an excellent candidate for genetic improvement (Studyvin and Gwaze 2007). Consequently, some tree improvement efforts have been undertaken to improve the performance of the species for timber production (Stewart and others 2016). The Forest Service, U.S. Department of Agriculture has studied the genetics and potential for tree improvement of shortleaf pine since at least the 1950s (Kitchens 1986). This effort included the National Forest System's establishment in the 1960s of a formal shortleaf pine tree improvement program and five first-generation seed orchards (located in Arkansas, Louisiana, Mississippi, North Carolina, and Tennessee) representing 12 geographic zones. Each orchard contained breeding material from at least 50 selected superior clones. In the 1970s, full-sib families were developed through controlled breeding for seed production, progeny testing, and potential second-generation orchard establishment (Zarnoch and others 1994).

Intended to help support the Forest Service's reforestation programs at that time, 155 shortleaf pine progeny tests were installed between 1978 and 1990 on various national forests using seedlings from full-sib families (Studyvin and Gwaze 2007). As part of this effort, 84 shortleaf pine progeny tests were placed in the Ouachita and Ozark-St. Francis National

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Forests using full-sib families from the Mount Ida Seed Orchard in Arkansas (Studyvin and Gwaze 2012). These progeny tests were based on three local (Arkansas and Oklahoma) geographic seed source regions—East Ouachita, West Ouachita, and Ozark. Families were selected on the basis of survival, insect and disease resistance, straightness and form, and height and volume growth. Although the three seed sources were designated by ecotype and were not widely separated by distance, they did capture environmental gradients. For example, the West Ouachita and Ozark regions generally have more severe summer droughts than the East Ouachita, offering an opportunity to disentangle some performance-related differences (La Farge 1991).

Only a couple of researchers have revisited these shortleaf pine progeny tests on the Ouachita and Ozark-St. Francis National Forests. In one study, La Farge (1991) found that the three seed sources were not significantly different for height and survival at age 5, leading him to recommend that the three seed sources be maintained as one population for tree breeding purposes. A later analysis—probably the last done on these shortleaf pine progeny tests—by Studyvin and Gwaze (2012) found a significant difference among families and seed sources for both diameter and height at 10 years of age. They concluded that family selection will be effective due to large family differences for all traits selected.

A shift in agency management priorities (less focus on national forest timber production using plantations and more focus on genetic diversity for resilience) led to most of these progeny plantings being abandoned after the mid-1990s (Crane 2014). However, in recent years shortleaf pine has become a species of conservation concern across its range (Anderson and others 2016, Oswalt 2012). Consequently, efforts are underway to halt, if not reverse, the decline of shortleaf pine using ecosystem restoration, particularly in the national forests of Arkansas and Oklahoma (Guldin 2007). Now that these progeny tests are between 30 and 40 years old, it is desirable to see if additional changes in performance have occurred in the remaining outplantings and if that information can help supplement current management strategies. Therefore, the primary objective of this study was to examine the relative performance of trees in a subset of the shortleaf pine progeny tests located on the Ouachita National Forest to determine if significant differences exist in size and survival among tested families.

MATERIALS AND METHODS

Study Area

The study area was located in the Ouachita National Forest in western Arkansas (fig. 1). The east-to-west running ridges of the Ouachita Mountains are composed of Paleozoic rocks consisting of alternating layers of sandstone and shale. Annual precipitation (primarily rainfall) in these mountains usually ranges between 50 and 60 inches, while annual average temperature ranges from 57 to 61 degrees F (PRISM Climate Group 2013, Pugh and Westerman 2014). The Ouachita Mountains have distinct east-to-west bands of vegetation depending upon parent materials, soil moisture

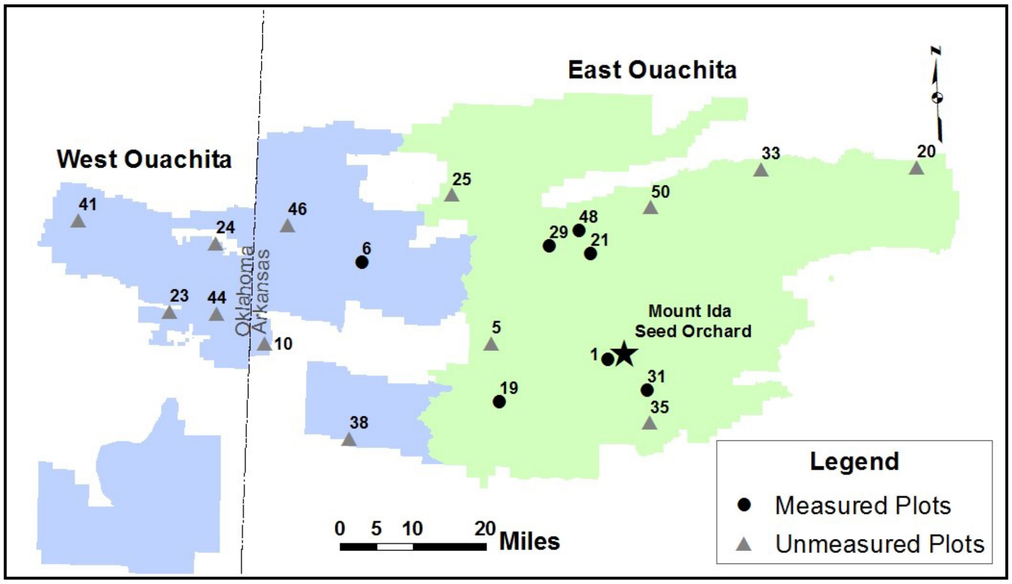

Figure 1—Shortleaf pine progeny test plantings (circles in black and grey triangles) selected for sampling in the East Ouachita (green background) and West Ouachita (blue background) seed source regions. The star symbol denotes the location of the Mount Ida Seed Orchard in the Ouachita National Forest. The circles in black represent the seven progeny test plantings.

availability, and radiation regimes (Foti 2019). The more xeric south-facing slopes, for example, were often covered with pine forests or oak woodlands, while the moister north-facing slopes were covered with denser, more diverse hardwood forests.

Design of Crosses and Outplantings

Details of the original progeny crossing design are presented in La Farge (1991) and Studyvin and Gwaze (2012). In summary, the design of the full-sib shortleaf pine progeny tests was a six-by-six disconnected partial diallel crossing scheme, such that each partial diallel crossing group consisted of six parents, two from each seed source (East Ouachita, West Ouachita, and Ozark). Crossing among all parents using this scheme resulted in 15 groups, which were used to develop 375 full-sib families/crosses. In each of these diallels, there were three crosses between parents from the same seed source, while the other 12 crosses were between parents from different seed sources. To maintain the integrity of the seed sources, care was taken so that crosses used for analysis represented parents of the same seed source and that all crosses were single-pair matings and were unrelated.

The planting design consisted of row plantings (8- by 8-feet) of 10 trees per row (per family, with an average of 33 families in each test) using a completely randomized block design with five replications.[1] Within each test, replicates were not complete as not all families were present in all replicates at that test location. Also not all families were planted in all progeny tests. This planting design was originally installed by the Forest Service and was the basis for two prospective measurements known as first interval evaluation (FIE) and second interval evaluation (SIE) conducted at 5 and 10 years.

Contemporary Remeasurements

Because over the years many of the tests had been heavily damaged or destroyed by ice, insects, fire, wind, or logging, starting in 2018, we chose a subset of the 84 shortleaf pine progeny tests on the Ouachita and Ozark-St. Francis National Forests for further consideration using a multi-step process. First, with a 2013 assessment on the amount of basal area per replicate done by Forest Service contractor and Certified Forest Silviculturist John Blanton, we categorized the still-forested tests into three groups depending on stocking level—excellent [at least two replicates were fully stocked (had at least 100 square feet of basal area per acre of live trees)], good (one replicate was fully stocked), and marginal (no replicates were fully stocked). Of the 20 progeny tests possible on the Ouachita National Forest available (fig. 1), we ended up having 10, 9, and 1 test representing excellent, good, and marginal categories, respectively. Second, we visited the excellent to good tests to determine if any had been destroyed since Blanton's 2013 assessment. Once acceptable progeny tests were located, measurements commenced, with seven being completed by the time of this paper.

In 2018 and 2019, shortleaf pines were identified based on tags placed beside them during planting and their location on maps. All trees in a row (family) were counted either live or dead to account for survival (in terms of percentage). We systematically selected five trees per row in each replicate for diameter at breast height (d.b.h.) measurement (in inches), and two trees were randomly selected to measure total tree height (in feet) from those trees selected for d.b.h. measurement. If a dead or missing tree was encountered, the next live tree would be chosen for both d.b.h. and height measurements. Additionally, status codes were recorded for both live (for example, ice damage, genetic fork, and Ips beetles) and dead trees (for example, dead standing, dead and down, and dead missing).

Statistical Analysis

The statistical analysis used in this study was similar to those used by La Farge (1991) and Studyvin and Gwaze (2012). We employed Proc GLM (General Linear Model) of SAS (SAS Institute Inc. 1989) to estimate if families differed in d.b.h., height, and survival at age 40. Plot means were used for the analysis, and survival was arcsine transformed before the analyses. The GLM was used to account for imbalance of data associated with unequal number of replicates and families. The independent variables tested were full-sib family within seed source and test location. The model assumed was a mixed-effects model, with full-sib family as a fixed effect, test location as a random effect, and a proper error term (random effect) for testing family differences was the family by test location interaction. We chose a subset of families based on their presence in multiple test locations when presenting results related to tree size (for example, descriptive statistics for d.b.h. and height) for the sake of brevity.

RESULTS

We presented results based on the seven progeny tests sampled to March of 2019—six from the East Ouachita and one from the West Ouachita seed source regions. A total of 176 families across the progeny test plantings were sampled in this study, ranging between 4 and 29 per test location (table 1). Of the total families sampled, 140 appeared in only one test, while 36 were represented in more than one test (table 1). Only seven families were found in more than two test plantings, all of which were common in both the East and West Ouachita seed source regions (table 2).

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[1] Personal communication. 2019. B. Rowland, Manager, Mount Ida Seed Orchard, Ouachita National Forest, Mount Ida, AR 71957.

Table 1—Number of families by progeny test and live trees in shortleaf pine progeny plantings on the East and West Ouachita seed source regions

				Live trees	
Test	Location	Number of unique families[b]	Number of shared families[c]	Total	Percent[d]
Test 1	Womble RD	19	9	434	47.7
Test 6	Mena RD[a]	12	31	848	50.5
Test 19	Womble RD	4	31	625	36.3
Test 21	Oden RD	27	9	659	49.1
Test 29	Oden RD	26	7	772	58.9
Test 31	Womble RD	23	6	678	51.8
Test 48	Oden RD	29	5	706	47.7

RD = Ranger District of the Ouachita National Forest.

[a] West Ouachita progeny test.

[b] One hundred and forty families used only in one test.

[c] Thirty-six families were used in more than one test (ranged between two and seven tests).

[d] Percent of planted trees still alive in 2019.

Table 2—Shortleaf pine families appearing in more than two progeny test plantings

		Live trees		d.b.h.		Total height	
Family	Number of tests	Number	Percent[a]	Mean[b]	SD	Mean[b]	SD
				inches		*feet*	
103×201	6	155	57.2	10.1 (4.9–14.3)	1.23	61.1 (34–85)	9.87
115×312	6	139	54.8	9.7 (4.6–13.4)	0.89	58.5 (36–82)	10.60
120×333	5	133	62.7	9.5 (4.1–13.6)	0.92	56.4 (38–80)	9.53
233×135	3	78	56.3	11.2 (6.5–17.6)	1.40	65.5 (48–82)	7.52
901×322	7	129	50.1	9.3 (5.1–15.1)	1.31	57.5 (38–79)	10.60
901×620	7	147	49.4	9.4 (4.5–16.8)	0.79	56.6 (37–77)	10.80
913×319	7	164	56.7	9.6 (5.2–13.5)	1.09	57.8 (37–80)	10.30

d.b.h. = diameter at breast height; SD = standard deviation.

[a] Percent of planted trees still alive in 2019.

[b] The numbers in parentheses denote minimum and maximum values for tree d.b.h. and height.

Growth Performance

There was considerable variation in tree size from family to family at age 40 (table 2). Average tree diameter and height among 7 of the 176 families ranged between 9.3 and 11.2 inches d.b.h. [standard deviations (SD) ranged between 0.8 to 1.4 inches] and approximately 56 and 66 feet tall (SD = 7.5 to 10.8 feet), respectively (table 2). Tree size also varied considerably within 7 of the 176 families—tree diameter ranges varied from 8 to 12 inches d.b.h., while tree height ranges varied from 34 to 51 feet (table 2).

The differences among all families sampled were significant for both d.b.h. ($p < 0.001$) and height ($p < 0.05$) (table 3). Consistent with our results, two prior studies conducted at age 5 and 10, respectively, had also found a significant ($p < 0.05$) effect of family on tree height (La Farge 1991) and d.b.h. (Studyvin and Gwaze 2012). For reasons that will be discussed later, no further analysis of growth performance (e.g., d.b.h. and tree height) was conducted.

Survivorship

Forty years after installation, approximately 49 percent of shortleaf pine trees survived in the progeny test plantings visited (table 1). This is a noticeable drop from earlier measurements of these progeny tests, which showed good early survival. At age 5, for example, seedling survival in these progeny tests was above 91 percent (La Farge 1991), while at age 10, mean seedling survival was about 72 percent (Studyvin and Gwaze 2012). A more recent estimate (2012) showed that

Table 3—ANOVAs for d.b.h., total tree height, and survival at age 40

Metric	Source of variation	Degrees of freedom	Type II SS	Mean square	F value	*p*-value
d.b.h.	Family	175	294.50	1.68	1.83	0.0001
	Test	6	173.90	28.90		
	Family × Test	59	64.83	1.09		
Tree height	Family	175	4513.40	25.37	1.03	0.0320
	Test	6	20060.10	3343.30		
	Family × Test	59	1312.10	22.23		
Survival	Family	175	16.15	0.09	2.01	0.0001
	Test	6	3.13	0.52		
	Family × Test	59	5.24	0.08		

d.b.h. is diameter at breast height.

survival rate was about 65 percent (Stewart and others 2016). There appeared to be a slightly higher rate of survival in the only West Ouachita test (approximately 51 percent) as compared to the six East Ouachita tests (approximately 48 percent). Survivorship also varied among families. Of the seven families that were found in more than two tests, mean family survival rate ranged between approximately 49 and 63 percent (table 2). Furthermore, survival differed significantly ($p < 0.001$) among all families (table 3). Neither the test nor family by test interaction variable showed any significant effect on any of the traits examined (table 3).

DISCUSSION

Although the original intent of this study was to more broadly compare these shortleaf pine progeny tests for differences in d.b.h., height, and survival rate, logistical challenges limited our data collection to primarily the East Ouachita tests, with just one test from the West Ouachita source. This constrained our ability to determine the relative success of various families across the three seed sources in the Ouachita and Ozark-St. Francis National Forests. Nevertheless, even this limited sample can suggest a number of important lessons for managers.

For example, Studyvin and Gwaze (2012) recommended maintaining a single breeding population of shortleaf pine rather than three across national forests based on the presence of good families from all seed sources in a prior study. However, our results indicated the persistence of family differences in tree size (growth performance) even 40 years after planting. The large, significant family differences suggest that there were both superior and inferior families within a seed source that may be of utility not only to family-based selection but also to evaluate seed sources determined in the past.

Family differences in survival also persisted through age 40. These results corroborated the findings of Studyvin and Gwaze (2012), who demonstrated a highly significant effect of family on survival at 10 years. However, given the impact of stressors and environmental disturbances, which were not controlled in this study, it would not be appropriate to attribute all survival-related variances to inherent differences among families. Also, we did not have an unbiased sample of these families—after all, we deliberately selected only those tests that had relatively high stocking to help ensure we had as much growth and yield information as possible on the families being tested. Furthermore, because of data imbalance (stated above) and inadequate representation of all families over the study area, we were not inclined to conduct mean separation between families for d.b.h. and height.

Even in these well-stocked progeny tests, the fact that just under half of the shortleaf pine trees have survived after this length of time is not surprising, given decades of losses to competition, disease, insects, and weather events (including multiple severe ice storms and droughts). Indeed, our field observations over the last couple of years (data not shown) while measuring these tests found that more than 75 percent of all live trees had been damaged by ice storms and/or Ips beetles. Losses due to drought may also affect survivorship as a result of changes in environmental conditions. For example, it is hypothesized that the progeny plantings in the West Ouachita seed source region are likely to have better survival than those from the East Ouachita region, ostensibly due to adaptations to summer drought (Studyvin and Gwaze 2012). Unfortunately, we do not have sufficient data at this time to evaluate this hypothesis.

CONCLUSIONS

Despite data limitations associated with partial coverage of study area, and natural disturbances that affected progeny plantings over the decades, we believe these progeny tests can be used to select families with better survivorship, diameter growth, and height performance, with evidence of both superior and inferior families in a given seed source. The observed family differences for all three traits suggest that the selection process for planting should focus on identifying individuals from the superior families for future second- and third-generation tree improvement efforts. However, within the National Forest System, the current objective of the seed orchards is to maximize genetic diversity in support of adaptation and resilience. Multiple selections will therefore need to be maximized and balanced to meet that objective. As more data are available from all seed sources in the future, further comparison of performance of the progeny tests would be beneficial to determine families that are able to withstand environmental stressors for restoration efforts. Such comparisons would also be useful to not only assess seed source influence on important traits but also to evaluate the rationale for seed source determinations for breeding purposes.

In addition to evaluating the value of genetic selections for tree improvement and genetic diversity, old progeny tests offer opportunities to provide additional guidance for shortleaf pine conservation efforts (Stewart and others 2016). For instance, these shortleaf pine progeny tests could be used in conjunction with DNA fingerprinting to better understand the capacity of this species to adapt to future climate change. After all, concerns of the role of changing environments on hybridization rates in shortleaf pine have been raised by others (for example, Crane and others 2019; Stewart and others 2013, 2015).

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PLANTING SHORTLEAF PINES DEEPER INCREASES RESPROUTING AFTER FIRE

Cassandra Meek and Rodney Will

Abstract—Unlike loblolly pine (*Pinus taeda* L.), shortleaf pine (*Pinus echinata* Mill.) seedlings often resprout following topkill from fire because the basal crook their stem produces places dormant buds at the soil surface which insulates them. The primary goal of our study was to compare resprouting following fire of shortleaf pine and loblolly pine with dormant buds placed at three depths: 2 cm above soil surface, at soil surface, and 2 cm below soil surface. We also compared resprouting of containerized versus bare-root shortleaf pine. Seedlings were planted near Idabel, OK, and burned after 1 year. Regardless of planting depth, none of the loblolly pine seedlings resprouted. For shortleaf pine, 8 percent resprouted when planted above the soil surface, 36 percent resprouted when planted at the soil surface, and 53 percent resprouted when planted below the soil surface. Bare-root seedlings resprouted at greater frequency than containerized seedlings. Therefore, planting shortleaf pine seedlings deeper should increase resprouting following fire.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is the main commercial species in the Southeastern United States. When compared to shortleaf pine (*Pinus echinata* Mill.), loblolly pine grows faster on all but the driest sites (Branan and Porterfield 1971, Dipesh and others 2015, Schultz 1997). Even though it is slower growing than loblolly pine, shortleaf pine has the widest distribution of southern pines and plays an important role in many natural ecosystems. Some nonindustrial private forest landowners, State and Federal agencies, and nongovernmental organizations plant shortleaf, and this is especially important in areas with insufficient natural seed supplies. Additionally, shortleaf pine is often the species of choice for planting when the primary goal is wildlife or ecosystem restoration. Shortleaf pine is also less susceptible to fire and drought (Schultz 1997, Williams 1998) and has greater tolerance to cold, ice, and fusiform rust (Hepting 1971, Mattoon 1915). Given shortleaf pine's greater tolerance, it can serve as a buffer against climate change and disturbance.

Both loblolly pine and shortleaf pine will resprout when top-clipped above the dormant buds, which develop in the axils of the primary needles, but shortleaf pine is a much more aggressive resprouter (Lilly and other 2012a, Will and others 2013). In regard to fire, shortleaf pine seedling and sapling resprouting after topkill is facilitated by a morphological adaptation, i.e., basal crook, which insulates dormant buds during fires (Mattoon 1915, Bradley and others 2016). The basal crook forms when the seedling bends just below the hypocotyl region for a brief period and then resumes upright growth just above the hypocotyl region. This process results in a horizontal section 2.5-7.5 cm long (Mattoon 1915) that places the dormant buds at the soil surface where fire is cooler, and the accumulation of soil and duff may further protect and insulate. While open-grown seedlings develop this crook in the first year, development may be delayed several years in shaded individuals.

Our overall goal was to determine if planting depth of loblolly pine and shortleaf pine seedlings influenced survival after fire. We hypothesized that planting seedlings deeper would facilitate resprouting of loblolly pine by protecting their dormant buds from fire and increase resprouting of shortleaf pine by providing further protection of the basal crook region. We also evaluated whether resprouting after fire would be different between containerized and bare-root shortleaf pines seedlings. A final objective was to determine if bare-root shortleaf pine without basal crooks resprout after fire. Often nursery-grown shortleaf pine seedlings do not develop a basal crook until after planting.

METHODS

Loblolly pine bare-root and containerized seedlings and shortleaf pine containerized seedlings were obtained from Oklahoma Forestry Services. Shortleaf pine bare-root seedlings were obtained from Arkansas Forestry Commission. All seedlings were 1-0. Seedlings were planted in the field in March 2016 in Idabel, OK. Burning to cause topkill was conducted in March 2017 and seedlings were monitored for resprouting for the 2017

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growing season. Diameter of each seedling at root collar was measured with calipers at time of planting and again just prior to burn. Height was also measured just prior to burning. Replanting to replace dead seedlings was conducted 14 days after the initial planting. Planting depths (see below) were initially established at time of planting, but depth to the hypocotyl region was reestablished just prior to burn in cases where there was soil movement or settling.

Fresh, air-dried pine litter (0.6-0.8 kg) was piled in a 5- to 7-cm-deep, 0.5-m^2 circle at the base of each seedling to serve as fuel. A handheld Fluke 51-II thermometer (Fluke, Raleigh, NC, USA) recorder with type k thermocouples positioned next to seedling stem at ground level was used to measure temperature during the burn. Most temperatures exceeded 450 °C and all seedlings sustained topkill. Ambient air temperature ranged from 4.4 to 18.3 °C and relative humidity ranged from 44 to 74 percent during the burning.

Primary Study

The objectives of the primary study were to compare resprouting following fire of containerized and bare-root shortleaf pine and loblolly pine with dormant buds at different depths. Both containerized and bare-root shortleaf pine were planted at three depths: 1) dormant bud 2 cm above soil surface, 2) dormant bud at soil surface, and 3) dormant bud 2 cm below soil surface. Only seedlings with a basal crook were used. Both containerized and bare-root loblolly pine were planted at four depths: 1) root collar 2 cm above soil surface, 2) root collar at soil surface, 3) dormant buds at soil surface, and 4) dormant buds 2 cm below soil surface. The primary study contained 15 replications at time of planting and 14 treatments (shortleaf: 2 (containerized, bare-root) x 3 depths; loblolly: 2 (containerized, bare-root) x 4 depths) for a total of 210 seedlings. Fisher's exact test was used to test for differences in proportion of seedlings resprouting between planting depths, taken two at a time (shortleaf: 3 tests, loblolly: 6 tests). Differences in seedling size among species and planting stock (4 treatments: shortleaf—containerized, shortleaf—bare-root, loblolly—containerized, and loblolly—bare-root) were tested using one-way analysis of variance both at time of planting and immediately before burning.

Secondary Study

The secondary study consisted of bare-root shortleaf pine with and without crooks. Seedlings were planted at three depths: 1) dormant buds 2 cm above soil surface, 2) dormant buds at soil surface, and 3) dormant buds 2 cm below soil surface. The secondary study contained 10 replications and 6 treatments (2 (with and without basal crook) x 3 depths) for a total of 60 seedlings. Fisher's exact test was used to test for differences in proportion of seedlings resprouting between planting depths, taken two at a time (3 tests).

RESULTS

Primary Study

In March 2016, at time of planting, average root collar diameters of bare-root loblolly pine (8.0 ± 0.2 mm; mean ± standard error) and shortleaf pine seedlings (6.7 ± 0.2 mm) were larger ($p < 0.05$) than diameters of the containerized loblolly pine (5.6 ± 0.1 mm) and shortleaf pine seedlings (5.2 ± 0.1 mm).

In March 2017, just prior to burning, average root collar diameters of loblolly pine containerized (10.8 ± 0.3 mm) and bare-root (11.9 ± 0.4 mm) seedlings were larger ($p < 0.05$) compared to shortleaf pine containerized (9.8 ± 0.2 mm) and bare-root (8.3 ± 0.2 mm) seedlings. Loblolly pine containerized (59.4 ± 1.4 cm) and bare-root seedlings (56.8 ± 2.2 cm) were taller ($p < 0.05$) compared to containerized (53.5 ± 1.5 cm) and bare-root (41.6 ± 2.3 cm) shortleaf pine seedlings.

No loblolly pine resprouted following topkill regardless of planting depth or seedling type and loblolly pine was excluded from analyses. There was significant mortality of shortleaf pine during the initial growing season due to herbivory and water stress. At the time of burning in March 2017, there were 94 live seedlings out of the 150 initial shortleaf pine planted. Therefore, for shortleaf pine, data from the primary and secondary studies were pooled to test for planting depth effects as both contained the same treatments.

Overall (containerized and bare-root treatments combined), only 35 percent (33 of 94 burned seedlings) of shortleaf pine seedlings resprouted

Table 1—Number and percent of total burned shortleaf pine seedlings resprouting at three planting depths

			Resprouted	
Dormant bud placement	Total burned	Dead	Number	Percent
Above (shallow)	25	23	2	8.0
At (buds at soil surface)	33	21	12	36.4
Below (deep)	36	17	19	52.8

Bare-root and containerized seedlings are combined from the primary and secondary studies. No loblolly pine resprouted.

(table 1). Seedlings with dormant buds at the soil surface (*p* = 0.01) and 2 cm below the soil surface (*p* = 0.0002) had significantly greater resprouting than the seedlings with dormant buds 2 cm above the soil surface. Seedlings with dormant buds 2 cm below the soil surface tended to have greater resprouting than seedlings with dormant buds at the soil surface, but this difference was not statistically significant (*p* = 0.13).

The comparison of containerized vs. bare-root seedling survival was restricted to the primary study (60 of each type planted, 26 bare-root and 30 containerized survived to be burned). Half of the burned bare-root shortleaf pine seedlings resprouted, which was significantly greater (*p* = 0.01) than the percent of containerized shortleaf pine seedlings that resprouted (table 2). While resprouting was lower in containerized seedlings than bare-root seedlings, both types of seedlings exhibited the same trend in sprouting with planting depth. Containerized seedlings resprouted at rates of 0, 8.3, and 40.0 percent for seedlings with dormant buds above, at, and below soil surface. Bare-root seedlings resprouted at rates of 16.6, 44.4, and 72.3 percent for seedlings with dormant buds above, at, and below soil surface.

Secondary Study

When comparing resprouting of shortleaf pine with and without the basal crook at time of planting (30 of each type planted with only 19 surviving to be burned), no significant differences were observed. Shortleaf pine seedlings with a crook at time of planting resprouted at a rate of 42 percent (8 of 19) compared to 52 percent (10 of 19) of shortleaf pine seedlings with no crook at time of planting (*p* = 0.75).

DISCUSSION

Shortleaf pine resprouts after fire while loblolly pine generally does not (Bradley and others 2016, Williams 1998). In this study, fire killed every loblolly pine seedling regardless of planting depth. Loblolly pine can resprout when topclipped (Lilly and others 2012a, Will and others 2013) or if the dormant buds are protected during the fire (Bradley and others 2016). Bradley and others (2016) mounded soil around the base of loblolly pine to protect dormant buds during fire, but then removed the soil within several hours after burning. In the current study, soil was not removed from around the base of the loblolly pine seedlings and likely hindered resprouting. From this result, it appears that operationally planting loblolly pine deeper will not increase its ability to resprout after fire.

Planting shortleaf pine seedlings deeper increased resprouting. Two seedlings resprouted even when the dormant buds were exposed to fire. This was somewhat surprising and likely due to the aggressive resprouting capacity of shortleaf pine combined with the heterogeneity of fire such that the exposed dormant buds of these two trees were not exposed to temperature high enough to kill them. Seedlings planted with dormant buds at the soil surface resprouted at a rate of around 36 percent which was lower than the 71 percent reported by Bradley and others (2016). The difference could be due to factors such as genetics, fuel conditions, ambient conditions during fire, etc.

Bare-root shortleaf pine seedlings resprouted significantly more than containerized. Although not significant, the root collar diameters of bare-root shortleaf pine seedlings (8.3 mm) tended to be smaller just prior to burn compared to the containerized shortleaf pine seedlings (9.8 mm). Lilly and others (2012b) found that smaller seedlings exhibited greater resprouting, but did not see a reduction in sprouting capacity until root collar diameters approached 20 mm. Only one seed source for each seedling type was compared after a single growing season, so it is possible that genetics or other factors related to seedling type influenced resprouting.

Based on our study, presence of a basal crook at time of planting does not affect ability to resprout after fire. Crook formation often occurs after field planting, and we observed this also, but did not quantify. From an operational standpoint, the presence of crook at time of planting is not crucial to resprouting after fire. Planting deeper, however, will afford protection of the dormant bud, regardless of presence or absence of crook.

Table 2—Number and percent of total burned bare-root and containerized shortleaf pine seedlings resprouting

			Resprouted	
Seedling	Total burned	Dead	Number	Percent
Containerized	30	25	5	16.7
Bare-root	26	13	13	50.0

Management Implications

In our study, none of the loblolly pine seedlings resprouted after fire, supporting that fire is effective in eliminating loblolly pine seedlings. Planting shortleaf pine seedlings deeper increased their ability to resprout after fire and should be considered. Presence of a basal crook at time of planting had no effect on shortleaf pine resprouting success after fire. Seedlings without crooks often form one when planted in the field. Alternatively, placing the hypocotyl region just below the soil surface at time of planting will protect the dormant buds regardless of whether a basal crook eventually forms or not. When planting shortleaf pine seedlings, establishment of unwanted loblolly pine or shortleaf x loblolly pine hybrids can pose a major challenge. However, fire kills most hybrids and loblolly seedlings (Bradley and others 2016) and fosters shortleaf pine-dominated stands (Stewart and others 2015).

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The 20th Biennial Southern Silvicultural Research Conference was held in Shreveport, LA, March 12–14, 2019. This conference provided a forum for silviculturists, researchers, and practitioners to exchange the latest research information on the ecology and management of southern forests. Of the 68 oral presentations and 35 posters presented during the conference, 44 papers and 7 extended abstracts were submitted for these proceedings. The papers cover eight topics, which include Forest Measurements and Modeling; Fire; Longleaf Pine; Soils, Disturbance, and Genetics; Hardwood Regeneration; Intermediate Management and Stand Development; Vegetation Management; and Shortleaf Pine. Papers and abstracts from oral and poster presentations provide managers with the latest research from universities, government agencies, and natural resource agencies.

Keywords: Afforestation, BMP, hardwoods, disturbance, ecophysiology, fertilization, fire, forest mensuration, history, hybrids, invasive species, loblolly pine, longleaf pine, modeling, oak, pine bark beetles, plantations, shortleaf pine, silviculture, soil.

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