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Shortleaf Pine Sprout Production Capability in Response to Disturbances

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To the Graduate Council:

I am submitting herewith a thesis written by David Charles Clabo entitled "Shortleaf Pine Sprout Production Capability in Response to Disturbances." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

Wayne K. Clatterbuck, Major Professor

We have read this thesis and recommend its acceptance:

Arnold M. Saxton, Jennifer Franklin, James M. Guldin

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Shortleaf Pine Sprout Production Capability in Response to Disturbances

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

David Charles Clabo

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Abstract

Shortleaf pine (*Pinus echinata* Mill.) seedlings are capable of sprouting and continuing growth after the stem is killed. The sprouting ability of shortleaf pine could be used to favor the species silviculturally after disturbance. Information is limited on shortleaf pine seedling sprouting after burning and clipping at different periods of the growing season and the effects of these treatments during their first three years after outplanting. Survival, seedling growth, and sprout production of shortleaf pine were evaluated after burning and clipping. The research was conducted on one, two, and three-year-old seedlings on an above average productivity site on the Cumberland Plateau region of east Tennessee. Replicated treatments were analyzed as a randomized block design which included: clipping in March, burning in April (early growing season burn), burning in July (mid growing season burn), burning in November (late growing season burn), and an untreated control completed on one, two, and three-year-old seedlings. Each experimental unit received a treatment once over the course of the study. Variability in burn treatments and their effects on the dependent variables were accounted for by using burn duration and intensity covariates in the analyses for sprout number and height. Results indicate that survival improved with increasing age and was greatest in early and late growing season burns among burn treatments and improved even more with clip treatments. Sprout production following treatments was greatest with the late growing season burn across years and was affected by the maximum burn temperature and mean burn temperature covariates at different seedling ages. Height growth following treatments was greatest with the late growing season burn or clip treatment across years. The burn duration covariate affected seedling height in two-year-old seedlings. Taller seedlings post treatment tended to produce fewer sprouts. These results indicate that late growing season burns may be best to promote the greatest survival rates and sprout growth in the species.

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Chapter 1: Introduction

Shortleaf pine has the widest range of the four native southern pines, but has been declining in stocking and area coverage over the last thirty-plus years. According to Forest Inventory and Analysis surveys (Oswalt 2012), the number of shortleaf pine stems greater than or equal to one inch diameter at breast height (DBH) has decreased 52 percent since 1980. The steady decline in shortleaf pine across its range has prompted more research into its silvical characteristics and management as well as investment in restoration efforts. Shortleaf pine has a basal crook just below the ground surface that contains dormant buds, which allows the species to sprout when the stem suffers topkill or injury. Sprouting can occur in trees up to six to eight inches diameter at breast height or thirty-five years old (Fowells 1965, Guldin 1986, Little and Somes 1956). The sprouting ability of shortleaf pine may aid in its regeneration and perpetuation.

The persistence of shortleaf pine on poor to moderate productivity upland sites with frequent disturbances and its sprouting capabilities provides management opportunities that set it apart from other southern pines. Knowledge of the sprouting capability of shortleaf pine seedlings in response to different disturbances such as burning or clipping at different ages or at different periods in the growing season are not well known, especially in the eastern portion of the species' range. An understanding of when to apply disturbances such as burning or clipping to favor shortleaf pine regeneration by sprouting over more vigorous competitor species would be valuable to forest managers attempting to restore shortleaf pine ecosystems.

The objectives of this research were to investigate the survival rate, sprout production response, and height growth response of one, two, and three-year-old shortleaf pine seedlings burned during the early, mid, and late growing season as well as the impact on these variables on one, two, and three-year-old seedlings clipped during the early growing season. In addition, this research evaluates the effects of burn variables such as maximum temperature and burn duration on shortleaf pine seedling sprouting responses.

Chapter 2: Review of the Literature

The Shortleaf Pine Resource

Shortleaf pine has a wide native range that covers 22 states, over 281 million acres, and occurs as far west as eastern Texas and Oklahoma and as far northeast as New Jersey and Long Island, New York (Guldin 1986, Oswalt 2012). The species is common from the Coastal Plain to the Piedmont and Highland provinces of the Southeast. The only areas of the Southeast where it is absent or rare are the bottomlands of the Mississippi River drainage and along the Gulf and Atlantic coasts. Approximately 65 percent of the present shortleaf pine forests are found in Arkansas, Oklahoma, Louisiana, and Texas (Oswalt 2012). Shortleaf pine is considered the second most important southern pine species behind loblolly pine in terms of softwood timber volume produced (McWilliams and others 1986). There is an estimated 13 billion cubic feet of shortleaf pine growing stock volume in the United States as of 2006. Tennessee has an estimated 437 million cubic feet of that total, whereas in comparison, Arkansas, the state with the greatest acreage of shortleaf pine forests, has an estimated 3.4 billion cubic feet of total growing stock volume. As of 2006, there was an estimated 1.9 billion shortleaf pine growing stock trees in the United States, and Tennessee has an estimated 32 million of that total (Moser and others 2007).

Shortleaf Pine Silvics

Shortleaf pine (*Pinus echinata* Mill.) is capable of growing in a wide variety of temperature and moisture conditions, but grows best in regions that receive from 45 to 55 inches of rainfall per year (Fowells 1965). Many soil types will accommodate shortleaf pine growth, but the best growth is on fine sandy loams or silt loams in northern Louisiana, Arkansas, and the southern Piedmont. The most widespread occurrence of the species is on ultisols that develop in humid climates. Suitable sites range from ridgetops to lowland areas that are not excessively wet. Shortleaf pine is not tolerant of soils with a high pH, high calcium content, or excessively wet or dry conditions. Shortleaf pine can grow at a wide range of elevations from nearly sea level in New Jersey to approximately 3,300 feet in the Appalachian

Mountains. The best growth is at 150 to 1,000 feet in the upper west Gulf Coastal Plain in Arkansas and Louisiana (Fowells 1965, Lawson 1990).

Several forest types contain shortleaf pine as a component, but the three most common are shortleaf pine-oak, loblolly pine-shortleaf pine, and the shortleaf pine type (Eyre 1980). Ecologically, shortleaf pine increases in importance on drier sites and where disturbances such as fire are more frequent and extreme. Loblolly pine (*Pinus taeda* L.) and shortleaf pine are frequently found together throughout much of shortleaf's range and have similar growth rates on average sites, but sites with very poor or good quality will favor one species over the other (Fowells 1965, Guldin 1986, Williston 1972).

Primary and secondary growth of shortleaf pine seedlings is greatest from April through late July or early August, after which growth virtually stops unless major precipitation events occur before the end of the growing season when the first frost occurs. Shortleaf pine has a determinate growth pattern where only one bud may develop on a shoot each year, or multiple buds may form sequentially and develop in the same growing season (Pallardy 2008). The species typically grows one to three feet per year while seedlings are young and vigorous (Hardin and others 2001). Shortleaf pine is considered shade intolerant, yet can survive (with much slower growth) under a full or partial overstory for a short period of time and resume full sun growth rates after overstory shade is removed (Guldin 1986, Lawson 1986, Shelton and Cain 2000). Shade tolerance usually decreases with increasing size and age (Baker 1992). Hardwoods will almost always occur in varying densities in association with shortleaf pine. In even-aged stands, shortleaf pine will maintain dominance over hardwoods on all but moderately good to very productive sites where it may be outgrown by species such as sweetgum (*Liquidambar styraciflua* L.), yellow-poplar (*Liriodendron tulipifera* L.), and red maple (*Acer rubrum* L.). *Quercus* species will eventually outcompete shortleaf pine on most sites due to their longer average lifespan (Guldin 1986, Lawson 1990, Williams 1998). Exemplary individuals may reach heights of 130 feet, diameters of 40 inches, and ages of 170 years or older under optimum conditions. Intraspecific and interspecific competition in even-aged stands results in pruning of the trunk over time, which produces a more desirable tree form (Hardin and others. 2001).

Shortleaf pine may produce new progeny either through seed production or vegetative reproduction. Shortleaf pine possesses the unique ability among the southern pine species to reproduce vegetatively by sprouting. The species is monoecious, yet cones with viable seeds are usually not produced before an individual tree reaches twenty years old. Some seeds have been reported on trees as young as nine years old (Fowells 1965). Female cones take two growing seasons to mature once they emerge, which is usually about two weeks after the male cones emerge (Lawson 1990). Some seed may be produced each year, but bumper crops every three to six years are common in the southern range of the species, while longer intervals between bumper crops are usual in northern populations. Adequate seed crops likely occur every two to three years. (Baker 1992, Guldin 1986). Between 80,000 and 100,000 viable seeds per acre is considered a good seed crop to fully stock a scarified seedbed. In Texas, Georgia, and South Carolina upwards of a million viable seeds per acre have been reported in some years (Wittwer and Shelton 1992). Seeds are spread by wind starting in late October or early November, and dissemination continues until April. A sufficient seed supply, a receptive, scarified or burned seedbed, ample soil moisture, and freedom from competing vegetation are required for optimal regeneration of shortleaf pine from seed. Some residual overstory protection from larger trees can also improve conditions for regeneration from seed by moderating conditions for germination from excessive dryness or late frosts in the spring (Dennington 1992, Guldin 1986, Shelton 1995). Epigeal germination occurs in the spring following dissemination (Baker 1992, Haney 1962).

Sprouting

Sprouting is an induced response to a dramatic change in local environmental conditions or to injury of the tree that results in the creation of a secondary trunk(s). Death or inhibition of the apical buds (apical meristem) typically results in sprouting (Del Tredici 2001). Almost all temperate hardwood species and some conifer species have the ability to sprout from severed stems (Oliver and Larson 1996).

Sprouting occurs most commonly after disturbances such as windstorms, fire, animals (such as beavers or deer herbivory), and human activities, all of which kill the shoots but not the roots of affected trees. Trees use surviving meristems and stored carbohydrate reserves in order to sprout after damage is inflicted (Bond and Midgley 2001). Sprouts from non-clonal trees should be differentiated from sprouts of clones or clonal growth. Clones are usually defined as individual trees that are produced a considerable distance away from the parent tree and are considered autonomous individuals, whereas sprouts develop on the original root system of the parent tree and depend on it for survival. (Bond and Midgley 2001, Del Tredici 2001). Root collar sprouts are the specific type of sprout produced by shortleaf pine. This study focuses on root collar sprout capabilities of shortleaf pine.

The root collar is defined as the point on the seedling axis where the root and shoot systems merge, or the point on a tree's stem midway between the soil surface and the cotyledon node (Chavasse 1977, Sutton and Tinus 1983). Typically with epigeal species such as shortleaf pine, there is a bump or swollen area at the cotyledon node that divides the hypocotyl from the epicotyl portions of a seedling (Menes and Mohammed 1995). Here dormant buds occur on the root collar, and each year they typically grow an amount equal to the growth of the annual ring. This keeps them close to the surface of the trunk, unlike adventitious buds, which can become covered by new secondary growth if they fail to sprout within a couple of years after their formation. Adventitious buds are also found on the root collar and trunk of a tree. These buds lack a bud trace that extends all the way to the pith (Del Tredici 2001 Kozlowski 1971, Pallardy 2008). Dormant buds and adventitious buds can both produce sprouts at or below the ground surface (Barnes and others 1998). The location of these buds on the trunk often determines their future ontogeny. If sprouts originate from buds located above ground level, they are dependent on the existing root system and will be exposed to decay and disease that occurs in the parent trunk and root system over time. Conversely, if the sprouts originate from buds located at or below ground level, it is possible that the sprout could form adventitious roots due to its contact with mineral soil. Sprouts of this origin have a much higher probability of growing into a mature tree (Del Tredici 2001).

Tree species that produce root collar sprouts often are well adapted to regeneration by vegetative means, and in general may be lacking in ability to regenerate by seed or other sprouting means. Species that are capable of sprouting (all sprout types) tend to produce fewer seeds, therefore maintaining smaller or more ephemeral seed banks. As a result of this, many sprout producing species produce fewer seedlings from seed, which results in poorer seedling survival as compared to species that depend on seed as their main source of reproduction (Barnes and others 1998, Bond and Midgley 2001). Shortleaf pine does not reproduce from seed as well as the other southern pine species, but it is fairly well suited for both of these reproductive methods (Guldin 1986).

Shortleaf Pine Sprouting

The ability of shortleaf pine to sprout enables the species to prosper on areas with frequent, low intensity disturbances where other species may decline over time (Lawson 1990, Williams 1998). Sprouting capability in shortleaf pine is extant to sizes of six to eight inches diameter at breast height (DBH). The sprouting capability of trees decreases with age and size much like other species capable of sprouting (Hardin and others 2001, Mattoon 1915, McGee 1978). In shortleaf pine, sprouts typically initiate just above a physiological adaptation called the basal crook (Lilly and others 2011). The basal crook is a root section one to three inches long that grows parallel to the ground surface before turning vertically back into the taproot while the seedling is developing (Mattoon 1915). The basal crook typically begins to develop within two to three months after germination and is usually finished developing in two to three years on vigorous seedlings growing in full sunlight. Seedlings growing in the shade or in crowded conditions of natural stands can take up to ten years to develop a crook if one develops at all (Little and Somes 1956, Little and Mergen 1966, Stone and Stone 1954).

The basal crook lowers the position of sprout-producing dormant buds in the soil surface (Lilly and others 2010). Shortleaf pine can also produce bole sprouts from dormant buds in the trunk or main branches after most of the foliage is consumed by a fire, or in trees that have been in shaded conditions that suddenly become open (Little and Somes 1956). Dormant buds below the ground surface are protected from high temperatures during fires. Buds above the duff layer have lower probability of survival (Stone and Stone 1954). Dormant buds originally form in the axils of primary needles, which determine the height of dormant buds in relation to ground level. With artificially regenerated shortleaf pine, planting depth will have an impact on the location of dormant buds in relation to the ground level and the protection of buds by the duff layer. The depth of the dormant buds in the duff layer and the thickness of the duff layer are more difficult to account for with naturally regenerated shortleaf pine (Will and others 2013). Buds begin growth if the stem is severed (animal herbivory or human disturbance) or burned. As many as eighty sprouts may be produced but typically one to three will become dominant over time (Mattoon 1915).

The Decline of Shortleaf Pine

Forest types containing shortleaf pine as a major component have been on the decline for many decades. In the early 1950s an estimated 16 to 17 million acres of forests dominated by shortleaf pine existed across its range and is considered the peak in the total amount of acreage in shortleaf pine forests (McWilliams and others 1986). Today the vast majority of shortleaf pine forest ecosystems are in mature, late-successional stages with little likelihood for regeneration to occur (Oswalt 2012). Many factors combined to create the present conditions. Agricultural lands were being retired at a rate of 1.5 million acres per year from 1945 to 1965, which provided suitable seedbed conditions for natural regeneration of many pine species including shortleaf pine if a seed source was present nearby (Boyce and Knight 1979). Forest industry favored faster-growing loblolly pine and discriminated against slower-growing shortleaf pine even on areas that shortleaf pine used to occur during aforestation of abandoned agricultural fields. Laws forcing the cessation of free-range livestock grazing on private and public lands across most of the United States by the 1930s and 1940s also have contributed to the reduction in the amount of area with suitable conditions for shortleaf pine regeneration. Tennessee enacted such a law in 1947 for all counties in the State (Todd 1980). The implementation of the Smokey Bear campaign by the United States Forest Service in 1944 became an effective tool for thwarting anthropogenic and naturally occurring wildfires across the Southeast. Prior to this campaign, areas of Arkansas where shortleaf pine is the dominant pine species had fire return intervals of two to twenty years, but after the campaign began this interval increased to fifty years or longer. A reduction in large-scale logging industries at about the same time also reduced favorable regeneration situations (Brose and others 2001, Elliot and Vose 2005, Engbring and others 2008, Guyette and others 2006).

Other causes for reductions in forest dominated by shortleaf pine include urbanization, hybridization with loblolly pine, and the increased establishment of loblolly pine plantations (Lilly and others 2012a, McWilliams and others 1986). Urbanization of crop and forest lands and increases in human populations will remain important factors in the loss of shortleaf pine forests on private lands for years to come. Forest land in the southern United States decreased by 21 million acres during the twentieth century, and seventy percent of this decline was due to losses in southern pine forest types (Smith and others 2001). The percentage of developed land in the southern United States is expected to increase from 5.2 percent in 1997 to 9.2 percent by 2025. Seven of the ten states in the southern United States had the largest average annual additions of developed land between 1982 and 1997. Over the last forty years the southern United States has had the largest population growth increase of any region in the country (Alig and others 2004

The possibility of natural hybridization of loblolly and shortleaf pine was first reported in the early 1950s by Zobel (1953). Since then, hybridization has been proven to occur in their sympatric and allopatric ranges (where loblolly pine plantations have been established outside of its natural range) of these two species. Areas west of the Mississippi River have been confirmed to have higher rates of hybridization than eastern areas of the two species' ranges (Stewart and others 2010). Hybrid trees have intermediate traits of the two parent species including a less developed basal crook that does not sprout as prolifically as pure shortleaf pine. Hybrids also show intermediate fire tolerance. Increasing variability in climate has resulted in overlapping pollen dissemination periods and strobili receptivity, which has helped increase the frequency of hybrids. In addition, fire suppression and planting loblolly with distant seed sources has favored and increased the establishment rates of hybrids where loblolly and shortleaf pine grow together (Lilly and others 2012a, Stewart and others 2013, Williams 1998). Hybrids are generalists between the two species and are intermediate in their ice and cold hardiness, resistance to fusiform rust, drought tolerance, growth rate, and morphology (Hicks 1973, Will and others 2013). Hybrids are undesirable in regions where shortleaf pine is the dominant pine species. The lack of predictability in natural hybrid traits and their moderate level of hardiness to harsh environmental factors such as ice and frequent fire make them less desirable compared to pure shortleaf pine.

Loblolly pine has become the dominant southern yellow pine in the southern United States over the last sixty years. It is planted extensively across the region for pulpwood products and to a lesser extent sawtimber. In the 1970s, there were 2.7 million acres of loblolly pine plantations. By the late 1980's that number had increased to 5.9 million acres (Shultz 1997). By 1990, over half of the 33.8 million acres of southern yellow pine timberland was loblolly pine. As of the late 1990s, over 37 million acres of natural and artificially regenerated loblolly pine existed in the South (Cost and others 1990, South and Buckner 2003). Many areas of natural shortleaf-loblolly pine forests have been converted to loblolly plantations, and loblolly plantations have been created north of its native range where shortleaf pine was the predominant pine species thus altering shortleaf pine presence on the landscape (Stewart and others 2013).

The diminution of shortleaf pine across the landscape continues to occur. During the 1980's, forests dominated by shortleaf pine covered approximately 12.6 million acres across its 22 state native range. By 2010 this acreage had shrunk to 6.1 million acres, a reduction of 52 percent. United States Forest Service Forest Inventory and Analysis data have shown a lack of young shortleaf pine forests. Large and medium size class forests (five inches DBH and larger at a 50 percent stocking level) make up 93 percent of the shortleaf pine resource (Oswalt 2012). Moser and others (2007) indicate that only eight percent of shortleaf pine timberland is in the seedling-sapling size classes, while thirteen percent can be classified as seedling-sapling in shortleaf pine-oak forest types. These statistics predict the continued diminishment of shortleaf pine forest types as older forests succeed into hardwoods or are converted to other uses.

Renewed Interest in Shortleaf Pine

The first interest in restoring degraded shortleaf pine ecosystems began in the early 1990s in the Ouachita National Forest of Arkansas. Shortleaf pine ecosystems in this National Forest were beginning to experience declines in some endemic plant, insect, and animal species due to the dense forest conditions caused by fire suppression and limited timber thinning and harvesting. The presence of the endangered red-cockaded woodpecker on the National Forest forced changes in forest management practices. The inability of past management to create suitable habitat, which usually involved clearcutting on 80 year rotations and subsequent development of hardwood midstories, failed to create suitable habitat for the species. Application of thinnings in the pine component, cutting the midstory hardwood component, and regular, periodic burns were implemented on the forest to restore imperiled ecosystems in which shortleaf pine is a major component (Bukenhofer and others 1994, Bukenhofer and Hedrick 2013). The thinning treatments produce timber volume that is sold following guidelines of the U.S. Forest Service timber program, and some of these revenues can be retained under the Knutsen-Vandenberg Act of 1933for improvement of the sale area. These activities include hardwood midstory removal and prescribed fire application for improvement of red-cockaded woodpecker habitat (Guldin and others 2004).

Major improvements in species diversity and richness have occurred since disturbance treatments were applied. Major restoration efforts were limited to the western portions of the species’ range until 2010 when the Shortleaf Pine Initiative began. This initiative brought together researchers, managers, and professionals from all facets of the forestry profession to address the needs and methods for restoring degraded shortleaf pine ecosystems across its range (Atkinson 2012). Advisory and planning committees have been formed to plan and execute management actions and research needed to increase the acreage of shortleaf pine in its native range

Management Implications

A thorough understanding of the sprouting capability of young shortleaf pine will aid in its management and restoration. Knowledge of how vigorously shortleaf pine seedlings and saplings of different age and sizes sprout in response to disturbance, as well as when during the growing season to apply burns, may result in specific management practices designed to promote shortleaf pine over other less fire adapted species. Past research has suggested that regular, low intensity fires will maintain shortleaf pine on upland sites and hinder dominance of species less adapted to fire such as loblolly pine (Williams 1998). Loblolly pine does not sprout consistently, and typically stops any sprouting by age three thus limiting its ability to survive repeated fires while in the seedling and sapling stages (Shultz 1997). Thinnings combined with regular, periodic burns similar in intensity to Native American and European settlement activities prior to 1900 could reduce the abundance and the competitive influence of species such as red maple on certain site types in shortleaf pine's range (Abrams 1998).

Shortleaf pine is also a suitable species for areas that are maintained as early successional savannas and woodlands due to its silvical characteristics. Larger diameter shortleaf pine trees display rot resistance of fire scars; thick, insulating bark; drought resistance due to a large taproot; low amounts of flammable resins; great longevity (170 years or greater); and a longer available growing season than hardwoods. These characteristics make shortleaf pine suitable for these early successional plant communities (Guyette and others 2007, Mattoon 1915). In the past, these ecosystems were more prevalent in areas of the Cumberland Plateau and Southern Appalachian Mountains on sites with poor edaphic conditions and exposed aspects and often had shortleaf pine as a major vegetation component. Factors such as fire exclusion, drought, and southern pine beetle have depleted these systems over the past seventy-five years and excluded regeneration (Brose and others 2001, Coffey 2012, Fesenmeyer and Christensen 2010). In recent years there has been more interest in shortleaf pine, and steps being taken toward restoring these ecosystems across the Southern Appalachian Mountains where it once was a major or minor stand component (Elliot and others 2012).

In areas of the natural range of shortleaf pine where it is the only or dominant pine species, shortleaf pine is often a critical habitat component, along with open, grassy woodlands or savannas for some vulnerable and uncommon bird species (Masters 2007). Species such as red-cockaded woodpecker, red-headed woodpecker, Bachman's sparrow, pine warbler, indigo bunting, and prairie warbler populations decline without open, pine savannas or woodland habitats of differing successional stages (Conner and others 2002). Frequent fire is associated with these ecosystems, resulting in a need for shortleaf pine regeneration over time as overstory trees succumb. Understanding when to apply fire (seasonality and return interval) to retain acceptable habitat components for these bird species, and obtaining shortleaf pine regeneration from seeds, sprouts, or both is necessary for retaining and expanding these habitats.

The diverse array of timber products that can be produced from shortleaf pine make it a unique species from a management perspective, especially in more northern and western areas of its range. The wood of shortleaf pine can be used for pulpwood (even though this is not common), yet it is denser and heavier than the wood of loblolly pine making it a better option for structural lumber (Lawson 1990, USDA 2007). Shortleaf pine's wood is not as heavy and dense as longleaf pine (*Pinus palustris* Mill.), yet it has a much larger natural range than those species making more production acreage possible if sites allow it. Stands containing shortleaf pine in mixtures with other pines or hardwoods to a lesser degree are a feasible management option for landowners that desire to diversify their forest products and increase pest and disease resistance by not relying on single species monocultures (Nyland 2007, Tomczak 1994). In areas north of loblolly pine's range, shortleaf pine is a much more suited species due to risks from ice and snow damage that can harm loblolly pine. Often, faster growing loblolly pine has been preferred, because greater volumes (fiber) are grown in shorter rotations. However, if slow grown, denser wood is an objective, management favoring shortleaf pine could result in more diverse timber product options for landowners who are not focused on reducing rotation times for pulpwood or biomass production.

Chapter 2: Objectives

Objectives

1. To compare the effects of clipping and burning during the early growing season (March/April) on seedling survival rates, sprout production, and height growth for outplanted one, two, and three-year-old shortleaf pine seedlings.
2. To compare survival rates, sprout number, and sprout height among one, two, and three-year-old shortleaf pine seedlings that were burned in the early growing season (March/April), mid-growing season (June/July), and late growing/early dormant season (November) with seedlings clipped during the early growing season and untreated controls.
3. To determine the effects of burn duration and temperature on shortleaf pine seedling survival rates, sprout production, and height growth for one, two, and three-year-old shortleaf pine seedlings.
4. To examine pre-and post-treatment survival and height growth rate differences for two and three-year-old shortleaf pine seedlings.
5. To determine if there is a correlation between pre-treatment height and the number of sprouts a seedling produces post-treatment for two and three-year-old shortleaf pine seedlings.
6. To evaluate if post-treatment dominant sprout height and number are correlated for one, two, and three-year-old shortleaf pine seedlings.
7. To determine if post-treatment dominant sprout height and number are correlated with the Keetch-Byram drought index (KBDI) for one, two, and three-year-old shortleaf pine seedlings.

Chapter 3: Methods

Study Site

The study site is located at 36°02’57.35” N 84°28’46.56” W on Walden Ridge in south central Morgan County, Tennessee. The land is owned by the University of Tennessee’s Institute of Agriculture Forest Resources Research and Education Center. The study is within the Little Brushy Mountain Unit of the Cumberland Forest (Figures 1 and 2). Walden Ridge is a subregion of the middle Cumberland Plateau. This area is characterized by weakly dissected plateau surface with the bedrock consisting predominantly of shale, but some sandstone may be found (Smalley 1982). Lonewood silt loam is the major soil series and the site has slopes of 5-12% (National Cooperative Soil Survey 2007, USDA 2012). This soil is acidic and has moderately low fertility. Site indices range from 70 feet at base age 50 years for shortleaf pine, white oak (*Quercus alba*), and northern red oak (*Quercus rubra*) to 90 feet for yellow-poplar (USDA 2012, Smalley 1982).

The climate in Morgan County is characterized by long, moderately hot summers and short, mild winters (Thornthwaite 1948). Historically, the area receives about 59 inches of precipitation that is fairly evenly distributed throughout the year. December through March is typically the wettest period of the year, while August-October is the driest period. The mean annual temperature for the region is 56 degrees (Smalley 1982). Climate data from nearby Oak Ridge, Tennessee during the three years of this study are presented in Table 1.

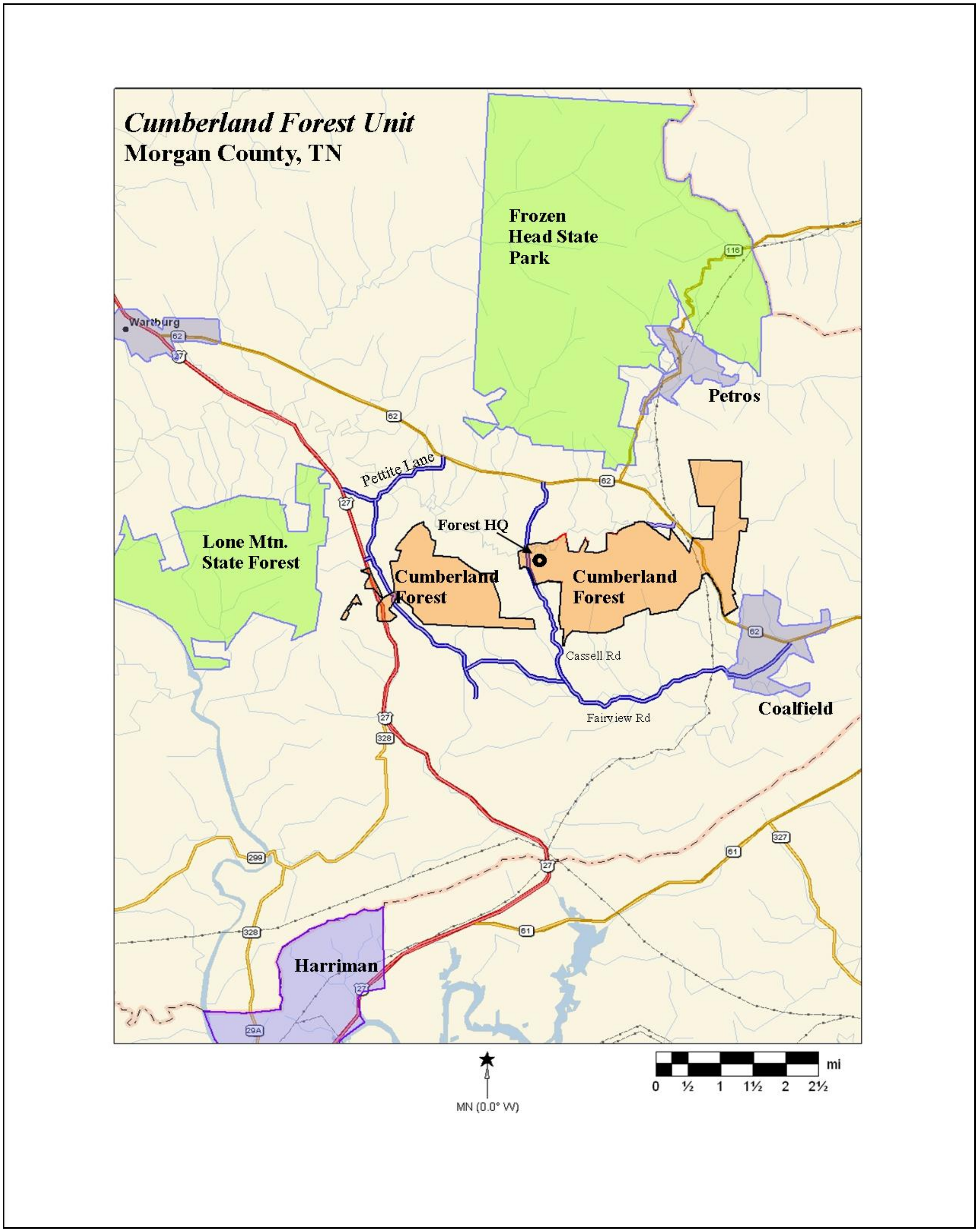

Figure 1. Location of the University of Tennessee Forest Resources Research and Education Center in south-central Morgan County, Tennessee (Map courtesy of Martin Schubert).

Figure 2. Aerial image (1326 feet) of the shortleaf pine seedling sprout study site within the Little Brushy Mountain Unit of the University of Tennessee Forest Resources and Research Education Center. The orange square is the study area and the dark green adjacent squares are white pine plantations. The buildings to the northwest contain the forest headquarters (Image courtesy of Google Earth).

Table 1. Climate data from Oak Ridge, Tennessee for the three years of the shortleaf pine seedling sprout study.

	Study Year		
Climate Variable	2011	2012	2013
Average Temperature (°F)	60	61	58
Maximum Temperature (°F)	99	105	95
Minimum Temperature (°F)	12	17	19
Precipitation Total (Inches)	66.9	48.4	66.2

Establishment

Prior to the establishment of the study, the site was mowed approximately every 2 to 3 weeks (Figure 4). The site was 84x69 feet with an area of 5,796 square feet. Forty-five experimental units were established in February 2011. Each plot measured 4 feet x 9 feet with 6 foot buffers separating experimental units on each side (Figure 3). Seedlings obtained from the Tennessee Division of Forestry Nursery at Delano, Tennessee were planted on a1x1 foot spacing (50 trees per experimental unit) on February 25, 2011. Seedlings were 1-0 stock and were progeny of open-pollinated Tennessee mother trees. They averaged eleven inches tall at planting, and unusually small or unhealthy looking seedlings were culled from the planting. Three blocks were established with fifteen experimental units within each block. Blocks were arranged to account for slope and shading differences on the site.

The experiment was a randomized block design with five treatments by three years by three blocks. Individual treatments were assigned randomly to the fifteen experimental units in each block. Treatments included three controls that received no treatment (one control per year in each block), burning in March 2011, March 2012, and March 2013; burning in July 2011, July 2012, and July 2013; burning in November 2011, November 2012, and November 2013; clipping in March 2011, March 2012, and March 2013. The arrangement of the treatments in each block is shown in Figure 4. Each experimental unit received a treatment once for the duration of the study.

Figure 3. The study site prior to planting in February 2011.

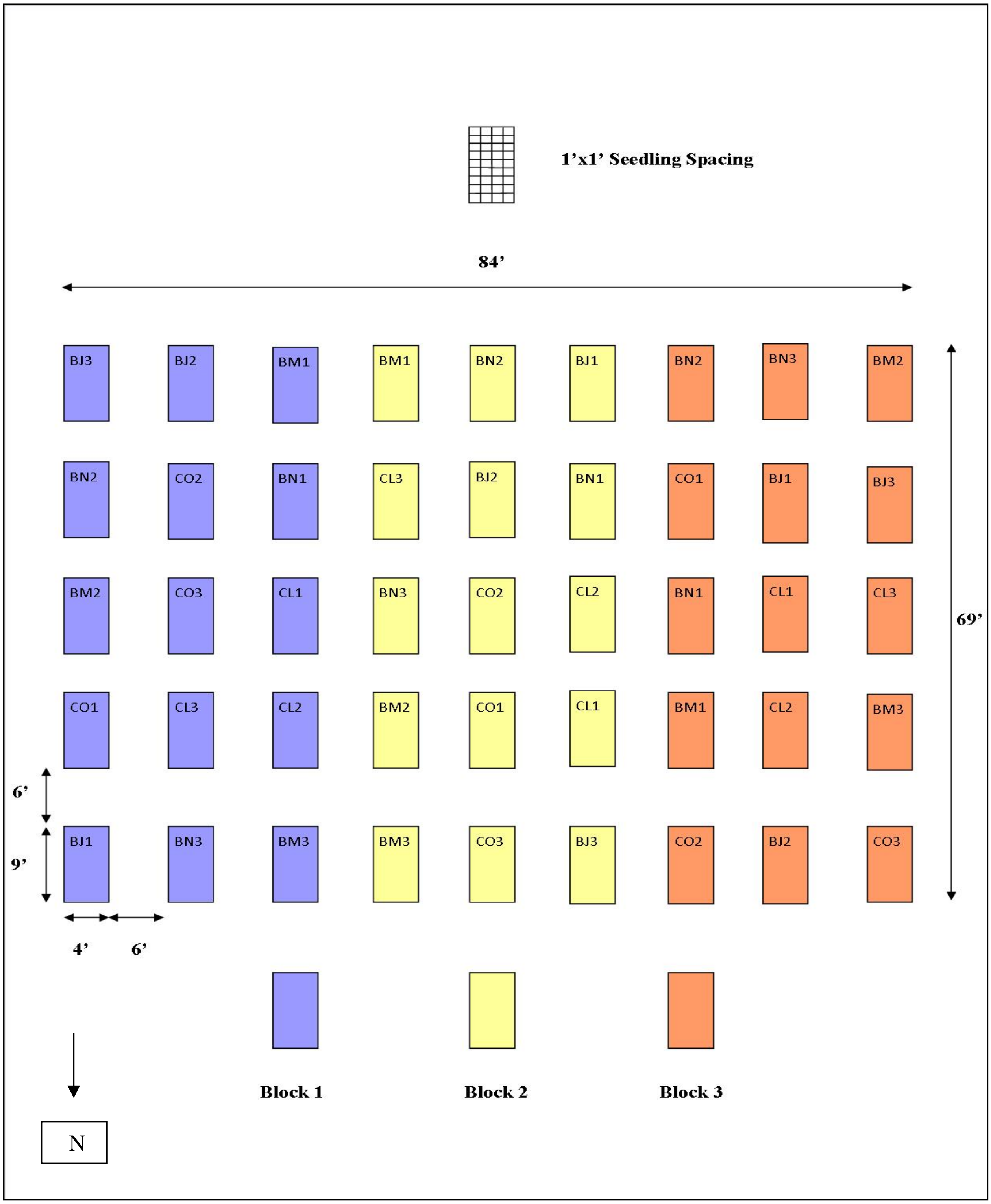

Figure 4. Schematic of the shortleaf pine seedling sprout study site showing blocks, treatment arrangement, and dimensions of the site. The abbreviations are as follows: BM was a March or April burn, BJ was a June or July burn, BN was a November burn, CL was a March stem clip, and CO was the control treatment. The numbers after the abbreviations correspond with the year a treatment was implemented.

Burn Methods

Methods designed to reduce the variability in burns among years and seasons were followed. Dried white pine needles from two adjacent plantations were used as a fuel source. Sticks larger than twigs were removed from the needles to promote a consistent fuel type. Needles were dried on a tarp in full sunlight for at least 2.5 hours prior to burning in order to obtain approximately equal fuel moisture values within the same burn season across years (although some variation was expected across years). Needles were also dispersed in approximately equal volumes within each experimental unit. Five gallon buckets were used to gather the needles. A full bucket of needles was spread evenly down each of the four planting rows in the long direction of an experimental unit, and two full buckets of needles were spread around the perimeter of an experimental unit to approximately nine inches from the outside-edge seedlings. A total of approximately 10 pounds of white pine needles were evenly distributed across the 36 square feet of the burn experimental units, or about 6 tons of pine needles per acre.

Fire weather data including: ambient air temperature, relative humidity, and surface wind speed were monitored and recorded on the days of burns. Across the three years for the March/April burns, the average air temperature was 73 degrees Fahrenheit, the average relative humidity was 27 percent, and the average wind speed was 4 miles per hour. Figure 5 illustrates a March burn during the third growing season. Across the three years for the June/July burns, the average air temperature was 89 degrees Fahrenheit, the average relative humidity was 49 percent, and the average wind speed was 4 miles per hour. Across the three years for the November burns, the average air temperature was 59 degrees Fahrenheit, the average relative humidity was 30 percent, and the average wind speed was 3 miles per hour. Figure 6 illustrates a November burn during the second growing season. The KBDI was calculated using daily precipitation and maximum temperature data gathered from the remote automatic weather station (RAWS) in Crossville, Tennessee. Calculation and interpretation of the index was completed following Keetch and Byram's original manuscript (1968) and the Fire Family Plus version 4.1 (2013) computer program.

Figure 5. A photograph of one of the three March 2013 burns.

Figure 6. A photograph of one of the three November 2012 burns.

Experimental units were ignited in a ring pattern using a drip torch during the mid-afternoon hours. Burn duration and intensity data were measured and recorded for each burn plot. Elapsed time from ignition until complete flameout was noted. Burn temperatures were monitored and recorded every fifteen seconds using a Kintrex digital infrared thermometer. The Kintrex model used for the study had a maximum temperature rating of 932 degrees Fahrenheit, which made recording the actual maximum temperatures difficult on plots that reached hotter temperatures. The 932 degree reading was recorded as the maximum temperature if the heat exceeded the thermometer's capabilities. The thermometer sat on a 45.6 inch tall pole positioned 48 inches away from the center position of a plot, which was exactly the midpoint between the fifth and sixth trees in the third planting row of five. This location placed the thermometer reading approximately 70 inches away from the midpoint of a plot.

The burns conducted on blocks two and three in July 2011 had to be ignited a second time due to poor ignition caused by high relative humidity that day. Burning twice caused high mortality in those seedlings that received this treatment, and this is evident in the results. In addition, many of the seedlings burned during 2013 were not topkilled by the fires due the large sizes they attained. Seedlings that were not topkilled were typically located around the experimental unit edges due to the convective nature of the burns. Accurate temperature readings were not obtained from the July 2013 burn in block one due to the high density of the stems in the plot.

Clip Methods

The seedlings that received the clip treatment were clipped approximately 1 to 2 inches above ground level to avoid damaging any dormant buds at the root collar. Loblolly pine seedlings clipped above the cotyledons have shown much greater survival rates than those that are clipped below this point (Shelton and Cain 2002). Any sprouts initiating from the main stem were also clipped so that all seedlings started with a single above-ground stem. All clip treatments were completed in March of a given year.

Weed and Grass Control

Weed and grass control was completed two to three weeks prior to burn treatments to create more even fuel types and amounts for each burn treatment completed in 2012 and 2013. Thirty-six of forty-five experimental units that received treatments (excluding the controls) were clipped and treated with glyphosate by sponge wicking in May and June of 2012 to improve survival and competitive status. The nine control treatments were mulched with white pine straw. All twelve 2011 treatment experimental units were clipped and treated with herbicide again in September 2012 to facilitate measurements that were completed in the winter of 2013. During May 2013, the March burn and clip treatments were clipped and herbicide was applied to reduce the presence of competing vegetation. Weed and grass control was not necessary again during 2013 due to the heights attained by the seedlings and sprouts. Weed and grass control within experimental units was not performed during the growing season of 2011. Weeds and grass were clipped by hand around seedlings and sprouts, and followed up with a treatment of 2 ounces per gallon solution of glyphosate (Cornerstone Plus®) in water. For woody plants, such as Japanese honeysuckle, triclopyr (Ortho Brush-B-Gone®) was applied as needed following label directions. Special care was taken to not apply herbicide to new pine growth. Herbicide was applied by hand with a sponge around individual seedlings.

Data Collection and Measurements

Pre-burn and pre-clip survival counts and height measurements were completed in 2012 and 2013 prior to treatments being implemented. All 2012 and 2013 control pre-treatment measurements used in pre-treatment analyses were made in March 2012. Height measurements and sprout number counts were completed for all fifteen first year treatment and control plots in January 2013, one full growing season after treatments were applied, and on all forty-five treatment and control plots in December 2013/January 2014. Height measurements were made to the nearest quarter inch on the dominant sprout in a clump or on a stem that was not topkilled by flames. If a stem was partially killed (part of the stem was killed whereas one stem still had green foliage), then its height was measured at the top of the surviving stem or branch. When the original stem was not killed, or was still present, as with the controls, then only new sprouts originating from the root collar were counted.

The one-year -old seedlings treated (burn and clip) in April, July, and November of 2011 were measured in January 2013, one complete growing season after treatments, and December/January of 2013/2014, two complete growing seasons after treatments were applied. The two-year-old seedlings treated (burn and clip) in March, June, and November of 2012 were measured in December/January of 2013/2014, one complete growing season after treatments were applied. The three-year-old seedlings treated (burn and clip) in March and July of 2013 were measured in December/January of 2013/2014, less than a complete growing season after treatments were applied. A timeline of measurements and data collection times is presented in Table 2.

Data Analysis

Analysis of variance (ANOVA) was used to test for statistical differences among treatments for survival rate, sprout number, and sprout height. Data were analyzed as a randomized block design using PROC MIXED in SAS 9.3 (SAS Institute 2012). Pre-treatment and post treatment sprout survival rates were analyzed separately and displayed together to show differences in the two annual periods, and they were analyzed together to investigate time differences within a year. Pre- and post- treatment heights were compared to determine if differences in pre-treatment measurement periods affected heights. Least squares means were separated using Fisher's protected least significant difference, with a significance level of P=0.05. The square root transformation was used on the sprout number and height variables to account primarily for a lack of equal variance in the ANOVA diagnostics. Untransformed means and standard errors are reported in the results.

Simple correlations of post-burn seedling height to post-burn sprout number, pre-burn seedling height to post-burn sprout number, and post-burn sprout number/height to the KBDI value of the days burns were completed were analyzed using the PROC CORR procedure in SAS 9.3 (SAS Institute 2012).

Table 2. Dates of data collection for the shortleaf pine seedling sprout study in east Tennessee. All seedlings were planted in three blocks in February 2011 and treatments were conducted in one block per year in 2011, 2012, and 2013.

Measurement	**2011 Treatment Plots**	**2012 Treatment Plots**	**2013 Treatment Plots**
Controls	[a]	March 2012	March 2013
Pre-Clip, Early Growing Season	[a]	[b]	March 2013
Pre-Burn, Early Growing Season	[a]	March 2012	March 2013
Pre-Burn, Mid-Growing Season	[a]	June 2012	July 2013
Pre-Burn, Late Growing Season/Early Dormant Season	[a]	Nov. 2012	Nov. 2013
Post-Treatment Annual, All Treatments	Jan. 2013, Dec./Jan. 2013/14	Dec./Jan. 2013/14	Dec./Jan. 2013/14[c]

[a] No measurements were taken in 2011

[b] No pre-clip measurements were taken in 2012

[c] Excludes late growing season/early growing season measurement conducted in November. Measurement of early and mid-growing season treatments do not constitute an entire growing season

Correlations (r) in absolute value from 0 to 0.39 were considered weak, 0.4 to 0.7 were considered moderate, and 0.7 to 1.0 correlations were considered strong.

Chapter 4: Results

Survival

There were statistically significant differences in survival rates among treatments (p=0.04) one complete growing season following treatment application in one-year-old seedlings. Survival rates were greatest with the control (CO1) and clip (CL1) treatments, which both had viability rates of 75.3 percent (Table 3). There were no significant differences between the early (BA1) and mid-growing (BJ1) season burns, whereas the late growing season/early dormant season (BN1) burn was statistically similar to the clip and control rather than the other two burn treatments. Numerically, the mid-growing season burn had the lowest survival rate among treatments (38.7 percent).

After two complete growing seasons following treatment application there were statistically significant differences among treatments (p=0.03) in one-year-old seedlings. The 75.3 percent survival rate for the control treatment remained unchanged from the year before and had the highest survival rate among treatments (Table 3). The early growing season burn treatment survival rate did not change between the two years either. The other three treatments all had slightly lower survival rates two years after treatment application than they did one year after treatment application. Again, the mid-growing season burn had the lowest survival rate among treatments and was significantly different from the other treatments (Table 3).

Two-year-old seedlings treated during 2012 and assessed one complete growing season following treatments did not show overall significant differences in survival rate (p=0.06). According to the ANOVA letter groupings, there were no statistical differences among the three burn treatments, which had very similar survival rates and ranged from 49.3 to 58.7 percent (Table 4). The clip (67.3 percent) and control (82 percent) treatments had the highest survival rates.

Table 3. Mean survival (percentage), standard error, and letter grouping are presented for one and two years following treatments on one year outplanted shortleaf pine seedlings completed in 2011 for the shortleaf pine seedling sprout study in east Tennessee.

	2013 One Year Survival			2014 Two Year Survival		
2011 Treatment	Mean	Standard Error	Letter Group	Mean	Standard Error	Letter Group
April Burn	42.7[a]	4.1	B[b]	42.7[c]	4.1	BC
July Burn	38.7	4.0	B	38	4.0	C
November Burn	48.7	4.1	AB	48	4.1	BC
March Clip	75.3	3.5	A	66.7	3.9	AB
Control	75.3	3.5	A	75.3	3.5	A

[a] One full year following treatments p=0.04.

[b] Different letters within the same column indicate significant differences at the p=0.05 level.

[c] Two full years following treatments p=0.03.

Table 4. Mean survival percentage, standard error, and letter grouping are presented for two-year-old shortleaf pine seedlings that received treatments during 2012. Assessments were made one year after treatments were applied.

2012 Treatment	Mean	Standard Error	Letter Grouping
March Burn	58.7[a]	4.0	A[b]
June Burn	49.3	4.1	A
November Burn	52.7	4.1	A
March Clip	67.3	3.8	A
Control	82	3.1	A

[a] One full year following treatments p=0.06

[b] Different letters within the same column indicate significant differences at the p=0.05 level.

Three-year-old seedlings treated during 2013 and assessed at the end of 2013 following treatments did not show overall significant differences in survival rate (p=0.252). The late growing season/early dormant season November burn treatment was not included in the analysis because determination of survival without new sprouts so soon after burning was impractical. Survival rates ranged from a low of 46.7 percent with the early growing season burn to 76 percent with the control (Table 5).

Pre and post-treatment survival differences for two and three-year-old seedlings are presented in Figure 7, excluding the two-year-old clip treatment and the three-year-old late growing/early dormant season burn treatment. There were no significant survival differences among pre-treatment heights (p=0.2435), yet there were treatment differences after treatments were applied (p=0.011). When analyzed together, there were pre- versus post-treatment height differences with the treatment x time interaction (p<0.0001).

Sprout Production

The maximum temperature covariate affected sprout production one year following treatment application with one-year-old seedlings, and there were significant differences in sprout production among the five treatments (p=0.0118). Out of the six covariates tested, the maximum temperature covariate was the only significant one (p=0.0089) among the three burn treatments. Table 6 shows the means, standard errors, and letter groupings of all five treatments without the covariate and the means, standard errors, and letter groupings of the three burns with the covariate included. The control treatment produced the fewest sprouts, whereas the November burn produced the most sprouts of any treatment. Clipping and the early growing season burn produced statistically similar numbers of sprouts.

Table 5. Mean survival percentage, standard error, and letter groupings are presented for three-year-old shortleaf pine seedlings that received treatments during 2013 and were assessed at the end of 2013.

2013 Treatment	Mean	Standard Error	Letter Grouping
March Burn	69.3[a]	4.1	A[b]
July Burn	46.7	3.8	A
March Clip	52	4.1	A
Control	76	3.5	A

[a] At the end of the year treatments were applied p=0.252.

[b] Different letters within the same column indicate significant differences at the p=0.05 level.

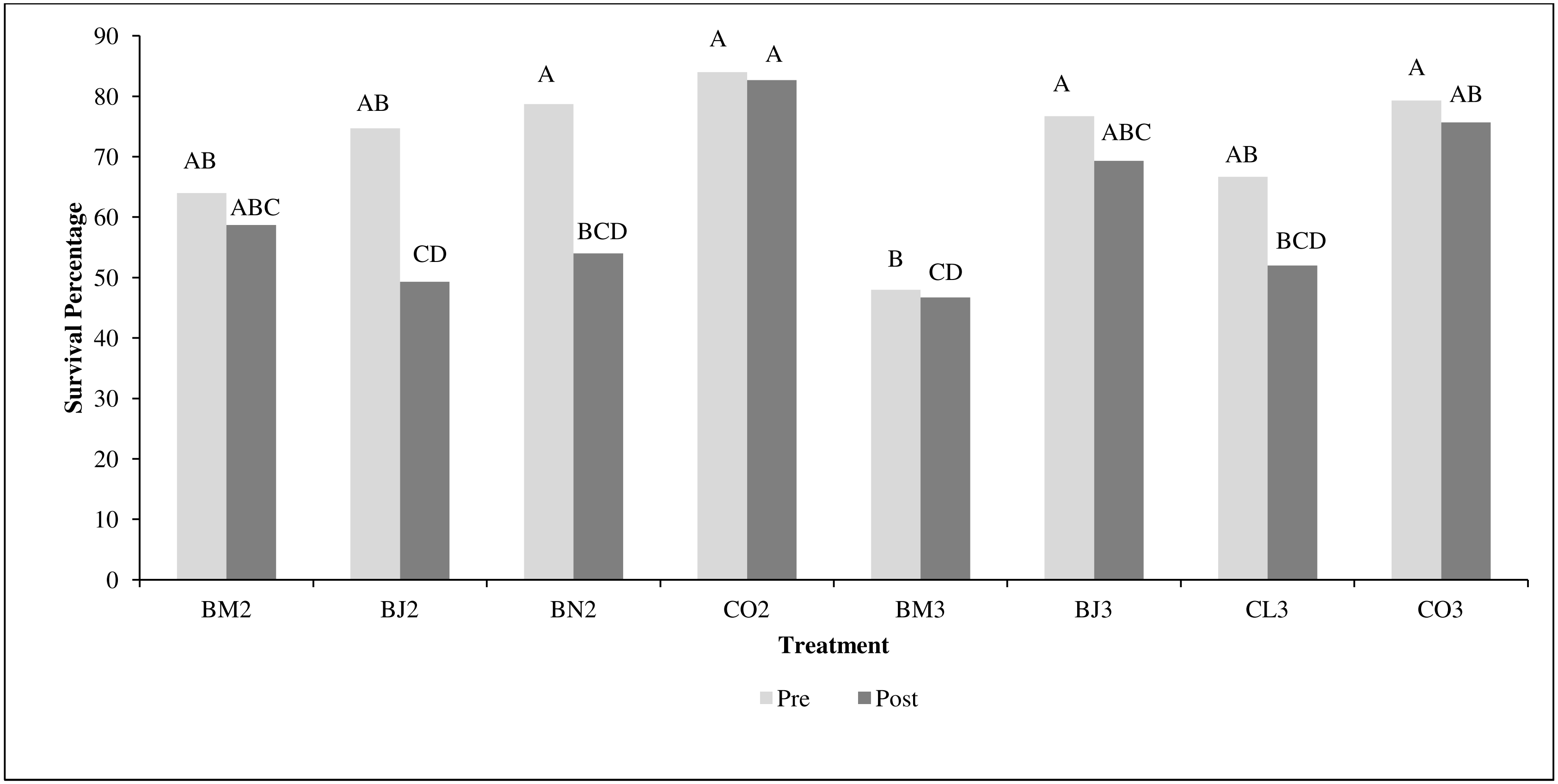

Figure 7. Pre- and post-treatment survival rates for two-year-old and three-year-old shortleaf pine seedlings are presented, excluding the two-year-old clip treatment (missing pre-treatment data) and the three-year-old late growing/early dormant season burn treatment for the shortleaf pine seedling sprout study in east Tennessee. There were no significant differences in the pre-treatment means (p=0.2435), but there were among the post-treatment means (p=0.011). The standard error for all pre-and post-treatment means was 0.1 percent. Means with different letters within the same treatment differ at p=0.05.

Table 6. Mean number of sprouts, standard error, and letter grouping are presented for surviving shortleaf pine seedlings one and two years following treatments completed in 2011 for the shortleaf pine seedling sprout study in east Tennessee. The maximum burn temperature covariate was significant one year following treatments. Adjusted means, standard errors, and letter groupings are presented.

	2013 One Year Sprout Production			2014 Second Year Sprout Production		
2011 Treatment	Mean	Standard Error	Letter Group	Mean	Standard Error	Letter Group
No Covariate						
April Burn	4.8[a]	0.7	B[c]	2.6[d]	0.5	B[c]
July Burn	7.5	0.7	AB	5	0.5	A
November Burn	10.1	0.6	A	2.8	0.4	B
March Clip	6.1	0.6	B	2.1	0.4	B
Control	1.3	0.6	C	0.9	0.4	C
Covariate						
April Burn	4.3[b]	0.7	B			
July Burn	7	0.7	C			
November Burn	11.1	0.7	A			

[a] One full year after treatments were applied with the covariate excluded $p<0.001$.

[b] One full year after treatments ($p=0.00118$) were applied with a significant maximum temperature covariate $p=0.0089$

[c] Different letters within the same column indicate significant differences at the $p=0.05$ level.

[d] Two full years after treatments were applied with no significant covariates $p<0.001$.

No covariates affected sprout production of one-year-old seedlings two years after treatments were applied. However, there were still significant differences among treatments though (p<0.001). The average number of living sprouts decreased for each treatment (Table 6). The control treatment had the fewest number of sprouts (0.9), whereas the mid-growing season burn had the greatest average number of sprouts instead of the late growing season/early dormant season burn. The late growing season/early dormant season treatment experienced the greatest decrease in average sprout number over the course of the year between assessments.

Sprout number in two-year-old seedlings assessed one year following treatments showed significant differences among treatments (p=0.0003). The burn duration covariate was significant among treatments (p=0.0002). Table 7 displays the mean number of sprouts, standard errors, and letter groupings for sprout number with and without the covariate. Without the covariate, the most sprouts were produced by the mid-growing season burn treatment (10.9), which was closely followed by the late growing/early dormant season burn (9.6). Clipping produced fewer sprouts than the early growing season burn, while the control produced the fewest number of sprouts (0.3). With the covariate included in the analysis the early and mid-growing season burns produced more sprouts, whereas the late growing/early dormant season burn produced fewer sprouts on average.

The three-year-old seedlings assessed at the end of the 2013 growing season displayed significant differences (p=0.0011) among treatments in the number of sprouts produced. The late growing/early dormant season burn treatment was not included in the analysis. The mean burn temperature covariate significantly affected the number of sprouts (P<0.0001) produced in the early growing season and mid-growing season burns and resulted in treatment differences (p=0.0043). Without the covariate included in the analysis, the mid-growing season burn (4.5 sprouts) and the control treatment (0.5 sprouts) were statistically the same and produced the fewest sprouts (Table 8). The clip treatment produced a staggering 28.6 sprouts per seedling average, yet was statistically the same as the early growing season burn (16.5 sprouts). The mean burn temperature covariate resulted in 14.8 sprouts per seedling for the early growing

Table 7. Mean number of sprouts per seedling, standard errors, and letter groupings are presented for surviving two-year-old shortleaf pine seedlings one year following treatment completion in 2012 for the shortleaf pine seedling sprout study in east Tennessee.

2012 Treatment	Mean	Standard Error	Letter Group
No Covariate			
March Burn	5[a]	1.5	A[c]
July Burn	10.9	1.5	B
November Burn	9.6	1.5	AB
March Clip	4.8	1.4	A
Control	0.3	1.4	C
Covariate			
March Burn	6.5[b]	1.2	B
July Burn	14.5	1.6	A
November Burn	5.6	1.7	B

[a] One full year after treatments were applied p=0.0003.

[b] One full year after treatments (p=0.04) were applied the burn duration covariate was significant (p=0.0002).

[c] Different letters within the same column indicate significant differences at the p=0.05 level.

Table 8. Mean number of sprouts per seedling, standard errors, and letter groupings are presented for three-year-old surviving seedlings for the shortleaf pine seedling sprout study in east Tennessee. Counts were made at the end of the 2013 growing season. The mean burn temperature affected the number of sprouts produced and was significant. The November treatment was not included due to survival not being able to be ascertained so soon after the burns were applied.

2013 Treatment	Mean	Standard Error	Letter Group
No Covariate			
March Burn	16.5[a]	3.9	A[c]
July Burn	4.5	3.8	B
March Clip	28.6	3.8	A
Control	0.5	3.8	B
Covariate			
March Burn	14.8[b]	1.2	A
July Burn	5.4	1	B

[a] Measurements were made at the end of the 2013 growing season, and there were significant difference among treatments (p=0.0011).

[b] The mean burn temperature covariate was significant (p<0.0001) as were differences among treatments (p=0.0343).

[c] Different letters within the same column indicate significant differences at the p=0.05 level.

season burn and 5.4 sprouts per seedling average in the mid-growing season burn (Table 8). The early growing season burns averaged 242.3 degrees Fahrenheit, whereas the mid-growing season burns averaged 175.7 degrees Fahrenheit, a difference of 66.7 degrees.

Sprout Height

One-year-old seedlings treated during 2011 showed significant differences in height one year after treatments were applied ($p<0.0001$). No tested covariates significantly affected the seedling heights. There were no height differences among the three burn treatments (Table 9). The controls were the tallest at 48.6 inches, while the clip seedlings were the next tallest at 26.1 inches. Seedlings in the mid-growing season burn plot in block one showed signs of browsing when seedlings were measured in January 2013.

The one-year-old seedlings displayed overall significant differences ($p<0.0001$) among treatments when measured two years after treatments were applied. No tested covariates significantly affected seedling heights. Seedlings in most treatments had approximately doubled in height over the 2013 growing season (Table 9). Seedlings in the mid-growing season burn treatment still had the shortest average height (30.7 inches), while the average height of the early growing season burn were similar to the late growing/early dormant season burn. Average seedling height of the clip treatment averaged nearly a foot taller than that found in the tallest burn treatment, while the average height in the controls were the tallest, averaging just less than seven feet tall after three growing seasons.

The two-year-old seedlings displayed overall significant differences in seedling height when measured one full year after treatments were applied ($p=0.0007$). The duration of the burn was a significant covariate ($p<0.0001$) that affected the burn treatment means, which had significant differences with the covariate in the analysis ($p=0.0066$). Without the covariate included, average seedling height in the early growing season burn, the late growing/early dormant season burn, and the clip treatment were statistically the same (Table 10).

Table 9. Mean height (inches), standard error, and letter grouping are presented for surviving shortleaf pine seedlings one and two years following treatments completed in 2011 for the shortleaf pine seedling sprout study in east Tennessee.

	2013 First Year Height Growth			2014 Second Year Height Growth		
2011 Treatment	Mean	Standard Error	Letter Group	Mean	Standard Error	Letter Group
April Burn	19.2[a]	2.4	C[b]	40.5[c]	5.6	D
July Burn	15.5	2.5	C	30.7	5.7	C
November Burn	19.7	2.4	C	39.1	5.5	CD
March Clip	26.1	2.4	B	51.1	5.5	B
Control	48.6	2.4	A	83.6	5.4	A

[a] One full year after treatments were applied $p<0.001$.

[b] Different letters within the same column indicate significant differences at the $p=0.05$ level.

[c] Two full years after treatments were applied $p<0.001$.

The average seedling height for the mid-growing season burn was significantly shorter than that found in the other burn treatments, whereas the seedlings in the control were significantly taller than those in all other treatments. The analysis with the covariate included resulted in the late growing/early dormant season burn seedlings being taller numerically (63.8 versus 42.3 inches) than the early growing season burn, but there were no significant differences. The mid-growing season burn was statistically different and only averaged 8.2 inches tall. The mid-growing season burns only averaged two minutes and fifty seconds long, whereas the late growing/early dormant season burns averaged twelve minutes and fifty seconds long. The early growing season burn average (ten minutes thirty seconds) was much longer than the mid-growing season burn on average as well.

The three-year-old seedlings (excluding the late growing/early dormant season burn treatment) displayed overall significant differences in average seedling height among treatments (p=0.0048). There were no significant covariates in this analysis. The average height of seedlings in the early growing season and mid-growing season burns were statistically similar but still displayed some differences (Table 11). The clip treatment seedlings had the shortest average height (22.2 inches), whereas the controls had the tallest average height (73.2 inches).

Pre-and post-treatment heights for the two and three-year-old seedlings, when analyzed together, displayed significant differences for the treatment x time interaction. The two control treatments showed the greatest differences between pre and post treatment height (Figure 8). The late growing/early dormant growing season burn displayed the smallest difference between pre and post height as they were statistically the same.

Table 10. Mean height (inches), standard error, and letter groupings are presented for treatments completed in 2012 for the shortleaf pine seedling sprout study in east Tennessee. Measurements were made one year after treatments were completed on two-year-old seedlings. The burn duration covariate was significant.

2012 Treatment	Mean	Standard Error	Letter Group
<u>No Covariate</u>			
March Burn	47.8[a]	5.3	B[c]
June Burn	21.3	5.3	C
November Burn	49.1	5.3	B
March Clip	47	5.2	B
Control	80.2	5.2	A
<u>Covariate</u>			
March Burn	42.3[b]	6	A
June Burn	8.2	6.6	B
November Burn	63.8	6.8	A

[a] One full year after treatments were applied p=0.0007.

[b] Treatment differences with the burn duration covariate (p<0.0001) were significant (p=0.0066).

[c] Different letters within the same column indicate significant differences at the p=0.05 level.

Table 11. Mean height (inches), standard error, and letter groupings are presented for shortleaf pine treatments completed in 2013 for the shortleaf pine seedling sprout study in east Tennessee. Measurements were made one year after treatments were completed on three-year-old seedlings. The November treatment was not included due to survival not being able to be ascertained so soon after the burns were applied.

2013 Treatment	Mean	Standard Error	Letter Group
March Burn	39.9[a]	9.1	BC[b]
July Burn	50.2	8.9	B
March Clip	22.2	9	C
Control	73.2	8.9	A

[a] At the end of the 2013 growing season there were significant differences among treatments (p=0.0048).

[b] Different letters within the same column indicate significant differences at the p=0.05 level.

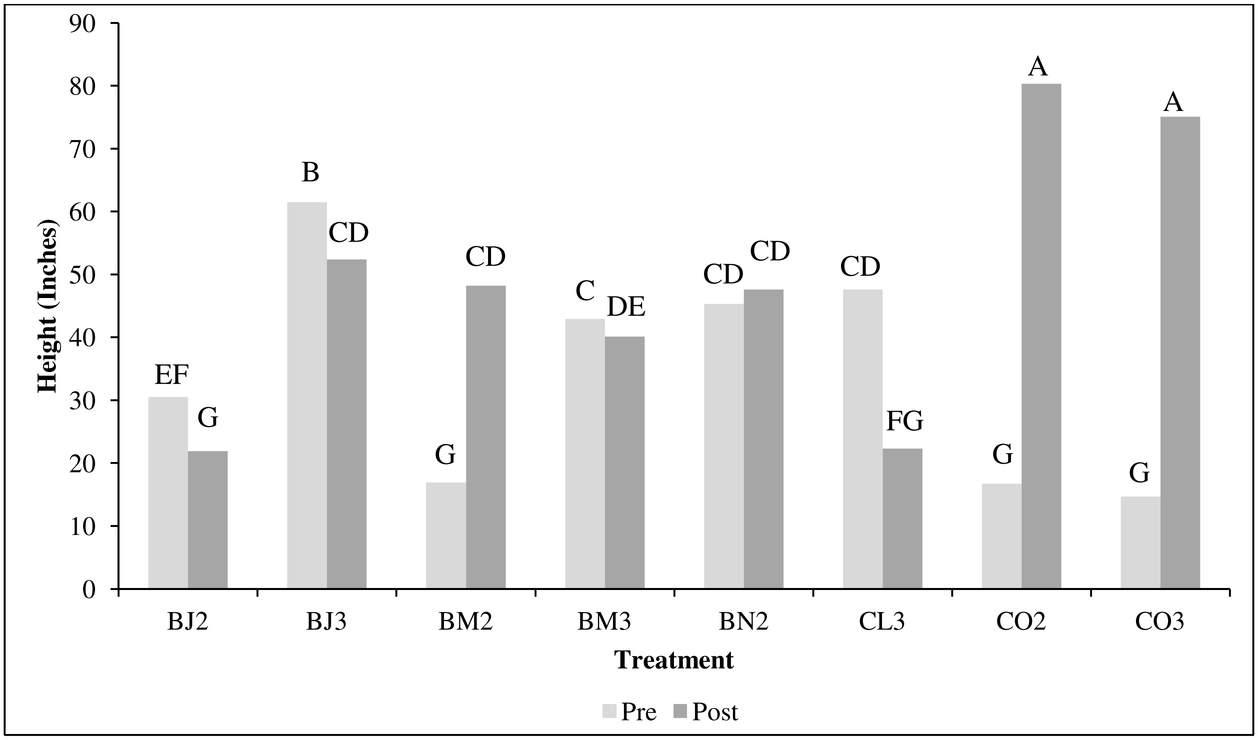

Figure 8. Pre- and post-treatment dominant sprout heights are presented for two and three-year-old shortleaf pine seedlings treated during 2012 and 2013, excluding the clip treatment for the two-year-old seedlings (missing pre-treatment data) and the three-year-old late growing/early dormant season burn treatment for the shortleaf pine seedling sprout study in east Tennessee. There were significant differences in the treatment x time interaction ($p<0.0001$) meaning that height differences caused by other factors than the timing of when pre-treatment height measurements were taken were evident. The standard error for all treatments was either 4.6 or 4.7 inches. Treatments with different letters differ at the $p=0.05$ level.

Sprout Height to Sprout Number Correlations

The one-year-old treatments displayed a statistically significant negative correlation between sprout height and number one and two years after treatments were applied. One year after treatments were applied, dominant sprout height and number had a moderately negative -0.4388, p<0.0001 correlation. Two years after treatments were applied, dominant sprout height and number had a weaker -0.29, p<0.0001 correlation. The two-year-old seedlings, when assessed one year following treatments, had a moderately negative (-0.47, p<0.0001) correlation. Three-year-old seedlings, when assessed at the end of the growing season in which treatments were applied, had a weak, negative (-0.25, p<0.0001) correlation. The correlation of pre-treatment height to post-treatment sprout number for two and three year-old-seedlings (excluding the two-year-old clip treatment and the three-year-old late growing/early dormant season burn treatment) displayed a weak, negative correlation (-0.02, p=0.59).

Sprout Height and Number to KBDI Correlations

The KBDI values across the growing season periods and years of the study ranged from a low of 2 on the March 14, 2013 burns to a high of 432 on the November 19, 2011 burns. The correlation of sprout production to KBDI value ranged from a weak, positive (0.05, p=0.0005) correlation in the one-year-old seedlings measured one complete year following treatments to a moderate, positive (0.367, p<0.0001) correlation in the two-year-old seedlings measured one complete growing season later. Three-year-old seedlings, when assessed at the end of the growing season in which treatments were applied, had a moderate, negative (-0.541, p<0.0001) correlation. The correlation of sprout height to KBDI value ranged from a weak, negative (-0.245, p=0.0005) correlation in the one-year-old seedlings measured one complete year following treatments to a moderate, positive (0.367, p<0.0001) correlation for the two-year-old seedlings measured one complete growing season following treatments.

Chapter 5: Discussion

Survival

Survival rates of one-year-old seedlings were the same or shared similarities among the three burn treatments one year after treatments were applied. The mid-growing season burn's low survival rate was likely affected by two of the three blocks being burned twice, yet another study that focused on the effects of burning on oak and shortleaf pine seedlings in the coastal plain of Arkansas found that mid-growing season burns in one-year-old seedlings produced even poorer survival rates (zero percent) than this study (Cain and Shelton 2000). Differences in the two studies could have been a result of climate differences before or after the burn and burn intensity or duration, but another prescribed fire study in Texas found poorer survival rates in loblolly and shortleaf pine after burns conducted in August compared to burns conducted in December (Ferguson 1957).

The early growing season burn survival rate for the one-year-old seedlings in this study (42.7 percent) was nearly identical to results found in another study (43 percent) in Arkansas conducted with six-year-old, naturally regenerated seedlings that were burned in April (Lilly and others 2012b). The late growing season/early dormant season burn treatment in this study had a much lower survival rate compared to one-year-old seedlings burned in January in Arkansas (48.7 to greater than 95 percent) indicating that seedlings may respond even more favorably to burns completed later on in the dormant season (Shelton and Cain 2002). The clip and control treatments in this study had the same survival rate (75.3 percent) one year after treatments were applied indicating that seedlings can readily recover from heavy browse and other disturbances that do not involve heating of the seedlings. The survival rate of the control seedlings was somewhat lower than the 80 percent survival standard for seedlings planted on National Forests in Arkansas (Mexal 1992).

The late growing season/early dormant season burn treatment is hypothesized to have had a slightly higher survival rate than the other burn treatments due to longer seedling establishment times and translocation of sugars to the roots in preparation for the dormant season even though the late growing/early dormant season burns were more intense and longer than the other first year burns on average. Lower survival rates with the early growing season and mid-growing season burn treatments may have been affected by poor root/soil contact with the root hairs and solum (early growing season directly after planting), the combination of burning two plots twice, and poor root/soil contact in the mid-growing season burn treatment during the first growing season (Grossnickle 2005, Rietveld 1989). In addition, bareroot seedlings lose as much as 75 percent of their total root length when they are lifted from the nursery, making new root growth and mass imperative (Brissette and Chambers 1992). A previous study observed translocation patterns throughout an entire year in three-year-old eastern white pine (*Pinus strobus* L.) seedlings and found that total sugar content is highest in the roots in November (late growing season/early dormant season burn), lowest in July (mid-growing season burn), and moderate in late March throughout April (early growing season burn) (Shiroya and others 1966). Translocation of carbohydrates in other species of pine seedlings is limited in seedlings with poorly developed root systems as compared to those with larger root systems (Shiroya and others 1962). These translocation patterns, if similar in shortleaf pine, could help explain why the November burn had the highest survival rate among the burn treatments.

Two years after treatments were applied, few reductions in survival were seen in the one-year-old seedlings. The early growing season burn and the control treatments did not suffer any attrition, while the mid-growing season burn and the late growing/early dormant season burn treatments lost less than one percent of their surviving seedlings from the year before. The clip treatment was the only treatment to lose an appreciable percentage of seedlings, which amounted to 8.7 percent. This illustrates that seedlings will not easily succumb to insects and diseases for at least two-years after burning or clipping is applied. Density-dependent mortality from intraspecific competition once the stem exclusion stage begins would likely be the first phenomenon to cause major mortality in seedlings planted at such narrow spacings (Smith and others 1997).

Survival rates among two-year-old seedlings assessed one year after treatments were greater than one-year-old seedlings among every treatment except the clip treatment. There were no differences among the burn treatments in the two-year-old seedlings, and again the clip and control treatments had higher survival rates than the burn treatments. The difference between the survival rates of one and two-year-old seedlings was the early growing season burn replacing the late growing/early growing season burn as the burn treatment with the highest survival rate by one percent. Aside from possible differences in weather for those burn treatments across the two years, the burn treatments in the early growing season of 2012 were much shorter and more intense on average than the late growing/early dormant season burns that year (Appendix 1). Better root establishment and larger seedling sizes may have helped the seedlings survive the early growing season burns more effectively. Also, breaking of dormancy may have not occurred yet in the seedlings, which can greatly influence sprouting capacity. Burning prior to bud break usually results in greater sprouting capacity (Kozlowski and others 1991). The early growing season burn of the two-year-old seedlings was conducted 25 days earlier in the year than the one-year-old early growing season burn, which may have made a major difference in sprouting capability based on seedlings' break from dormancy.

Two reasons that may explain the greater survival rates in two-year-old seedlings than one-year-old seedlings are more established ectomycorrhizae in older seedlings and increased seedling sizes enabling them to tolerate higher temperatures. Shortleaf pine does not have endomycorrhizae that are common in the roots of many hardwood species (Pope 1993). At least one past study has shown that two-year-old bareroot shortleaf pine seedlings achieve greater survival rates and sizes with increasing presence of ectomycorrhizae fungal species such as *Pisolithus tinctorius* and *Thelephora terrestris* along with natural ectomycorrhizae that develop over time after the seedlings have been planted (Ruehle and others 1981). Natural ectomycorrhizae may not always be present in nurseries where bareroot seedlings are grown due to soil sterilization. The seedlings used in this study were not inoculated prior to planting. The development of natural ectomycorrhizae along with root size could likely be a major contributor to increased survival rates of two-year-old seedlings over one-year-old seedlings. Larger seedlings typically have thicker bark, larger basal crooks, and larger root collars, which all contribute to better survival potential following a burn (Little and Somes 1956).

Three-year-old seedlings showed a decline in survival for the mid-growing season burn, clip, and control treatments, whereas the early growing season burn treatment survival rate increased compared to the two-year-old seedlings. Some seedlings treated during this year may not have had time to recover fully and produce sprouts after treatments were applied (especially the mid-growing season burn) before assessments were made at the end of the 2013 growing season. Other observations indicated that sprouting occurs less frequently after midsummer disturbances and that sprouting may not initiate until the next spring after such disturbances depending on weather conditions in the remainder of the growing season following the disturbance (Mattoon 1915). The declining survival rate for clipped seedlings each successive year after they are planted may be a universal trend and not limited to this study. A study in Arkansas by Campbell (1985) on four-year-old seedlings clipped two inches above ground level in February found a fifteen percent survival rate one year after the clipping. These results may indicate that shortleaf pine seedlings that are clipped in the early growing season do not recover vigorously as age increases. In addition, in this study many of the three-year-old seedlings attained large enough sizes so that they were not killed by the burns. The convective nature of the burns, due to the ring ignition pattern, left many of the seedlings on the outside edges of the plots alive and relatively undamaged. Flame heights were much taller in the center of the plots than they were around the edges. Some seedlings along the edges did not produce sprouts at the time of the assessment conducted at the end of the 2013 growing season.

The pre-treatment and post-treatment survival rates show that treatment timing and seedling age may have a significant impact on two and three-year-old seedling survival. The control treatments for both age classes displayed little mortality from the initial pre-treatment assessment until post-treatment assessments indicating that the seedlings were vigorous and hardy and that mortality could mostly be attributed to the treatments. Early growing season burns resulted in less post-treatment mortality than mid-growing season burns in both ages. Actively growing seedlings (mid-growing season) have active plant tissue that is less tolerant of high burning temperatures than plant tissue in paradormancy (early growing season burn treatment timing) or ecodormancy (late growing /early dormant season burn treatment timing) (Kayll 1968).

Sprout Number

The maximum burn temperature covariate affected the number of sprouts produced one year after treatments were applied. The covariate resulted in the early growing season and mid-growing season burns to produce more sprouts on average, whereas the late growing/early dormant season burn had more sprouts as compared to the analysis without the covariate. The tendency for the late growing season treatment to have more sprouts was likely a result of the seedlings being better established after the burn. The early growing season burn seedlings in this study produced fewer sprouts (4.8+/-0.7) compared to the study by Lilly and others (2012b) conducted on six-year-old seedlings where they found 9.6+/-0.8 sprouts per seedling. The fewer number of sprouts produced in the mid-growing season burn than the late growing/early dormant season burn would typically be attributed to high lethal burn temperatures in the summer season, but the mid-growing season burn treatment had lower average burn temperatures and durations compared to the other two burn treatments confounding this reasoning. Similar results were reported by Cain and Shelton (2000) where higher burn intensities and lower relative humidities during the burn yielded greater growth than dormant season burning. Kayll (1968) suggests that dormant seedlings of conifer tree species can survive higher temperatures than actively growing seedlings when both are exposed to high temperatures for the same amount of time. The lower temperatures in the mid-growing season treatment may not have been enough to overcome the physiological differences between dormant and active tissue and resultant growth and survival.

The average number of sprouts per seedling declined in each of the five treatments in one-year-old seedlings when they were reassessed two years after treatment application. This finding agrees with reports by Lawson (1990) and Mattoon (1915) who each stated that the majority of sprouts that are produced after a disturbance will decrease over time as one to three sprouts establish themselves as the terminal leaders. Further sprout thinning is possible in these seedlings as they age, especially the mid-growing season and late growing/early dormant season treatments.

The two-year-old seedlings followed the same sprout production trends as the one-year-old seedlings, except that the mid-growing season burn produced the greatest number of sprouts instead of the late growing season/early dormant season burn. Burn conditions on the day of the mid-growing season burn are most likely the main factor contributing to change in sprout production from one-year-old seedlings to two-year-old seedlings. The mid-growing season burn in late June 2012 was much flashier and more intense than the burn done the previous year. Weather during the summer of 2012 was drier and hotter than summer 2011. The 2012 mid-growing season burns had an average temperature of 416.3 degrees Fahrenheit and an average duration of four minutes and fifty seconds, whereas the 2011 mid-growing season burns had an average temperature of 273.9 degrees Fahrenheit and an average duration of six minutes. The fugacious nature of the 2012 burns was just long enough to topkill the stems, and many stems around the edges of the burn plots most likely did not receive enough heating for a long enough period of time to decrease the subsequent sprouting response. In southern pines, exposure to 147 degrees Fahrenheit for three seconds is enough time to kill needles, while for loblolly pine stems 129 degrees Fahrenheit for a minimum of five minutes is usually considered lethal (Hare 1961). Hotter temperatures for longer time periods would be necessary to kill roots that are protected by varying soil depths. Shortleaf pine is typically considered more fire tolerant than loblolly pine in mature trees and seedlings, so a higher maximum temperature and longer burn duration would likely have to occur to kill the stem and upper roots or reduce sprouting response from dormant bud death in shortleaf pine (Chapman 1944, Williams 1998).

Sprout number in three-year-old seedlings was affected by the mean burn temperature covariate. The average burn temperatures between the two burn treatments were widely divergent (242.3 degrees Fahrenheit early growing season versus 175.6 degrees Fahrenheit mid-growing season). The mid-growing season burn did not ignite and spread satisfactorily due to the combined effects of the seedlings attaining large sizes prior to treatment and having very high survival rates resulting in few areas for sunlight to reach and desiccate the ground. Together, these two factors caused the surface to be much more shaded, humid, and damp (even though needles were dried and applied in the same amounts) resulting in lower temperature readings. Other contributing factors that probably resulted in reductions in survival are the temperature recording, infrared laser being blocked by the thick needle conditions and the long, smoldering burn conditions. Thus, the effects of the covariate might have been insignificant if accurate temperature readings could have been attained during the mid-growing season burn.

The large average number of sprouts produced by the clip treatment was likely a result of not enough elapsed time to significantly reduce the number of sprouts between the time the clip took place and the assessment for the number of sprouts. The trend in sprout numbers produced by three-year-old seedlings in this study were similar to results reported by Grossmann and Kuser (1988), of greater sprout numbers in early growing season clip seedlings (11.9+/-3.6) were observed than early growing season burn seedlings (6.8+/-4.0) in eight to ten-year-old saplings. They also reported that sprout survival decreased with increasing basal diameter size of the parent tree. This study and the research by Grossmann and Kuser (1988) indicate that seedlings may produce more sprouts from clipping once they reach older ages, but long-term survival rates of the sprouts may decrease at the same time.

Sprout Height

The timing of the three burn treatments did not cause significant differences in height growth in one-year-old seedlings. Average dominant sprout heights in the early growing season and late growing/early dormant season treatments of this study one year after treatment application were very similar to heights attained by one-year-old seedlings (19.7 inches) burned in January in Arkansas (Cain and Shelton 2000). The clip seedlings grew taller than the burn seedlings most likely due to the lack of heat damage to the dormant buds of the clip seedlings and a quicker growth response following treatment application (especially between the early growing season burn and clip). Past studies have shown that sprouting following a burn will only occur below areas exhibiting char (Little and Somes 1956). Seedlings grew within the expected one to three foot range common for vigorous, young seedlings (Williston 1972). Browsing was limited to seedlings in the mid-growing season burn plot in block one, indicating that the numerically shorter average heights, compared to the other two burn treatments, could have been a result of browsing.

When the one-year-old seedlings in this study were measured two years following treatments differences in the burn treatments were evident. No known information is available in the literature that assesses height growth of shortleaf pine more than one year following treatment applications. Seedlings in each treatment nearly doubled in height except for the control treatment even though the controls grew the most out of any treatment during the second year (35 inches). Differences that were diminutive after one growing season became more pronounced after two growing seasons resulting in treatment differences. Above average precipitation amounts during the most favorable months (April-June) for shortleaf pine growth in 2013 likely resulted in these increased growth rates (Fowells 1965).

Two-year-old seedlings were significantly affected by the burn duration covariate. The late growing/early dormant season burns averaged twelve minutes and fifty seconds, nearly six minutes longer than the next longest treatment average. The late growing/early dormant season burn was also the only treatment where height growth increased with the covariate included. Less intense and longer burns seem to result in less topkill thus producing greater average heights. There were 79 living seedlings before burns in the late growing/early dormant season treatment when measurements were made, and 34 of those seedlings did not receive topkill as a result of the burns. Many of these seedlings were again located around the perimeter of plots. All of the seedlings that survived the burns had smaller basal diameters than the four to six inch threshold reported in other studies, and no trees were taller than the approximately 98 inch minimum height threshold reported as necessary for survival (Dey and Hartman 2005, Lilly and others 2012b). The likely reason seedlings survived these burns is the convective nature of the burns. Most that did not receive topkill were located around the plot edges where flame heights and flame exposure times were shorter. The mid-growing season burn had a much shorter average seedling height after treatment than the other four treatments. All three mid-growing season plots in the study received some browsing in the 1.5 years between burn application and measurements.

Few three-year-old seedlings in either burn treatment were topkilled, but for the few seedlings that were, their height growth was so small in the amount of time between treatment and measurement that the means of the two treatments were probably skewed. Twenty-six of the 70 early growing season burn seedlings did not experience topkill, while 71 of the surviving 104 mid-growing season burn seedlings did not experience topkill. No seedlings in either treatment were larger than the recommended size thresholds to survive early growing season burns reported by Dey and Hartman (2005) and Lilly and others (2012b), but many seedlings that survived the early growing season burn were around the plot edges. In addition, the mid-growing season burns completed on July 12, 2013 had a low average burn temperature of 175.6 degrees Fahrenheit, however, the temperature readings from block one were probably inaccurate because of needle obstructions in the path of the laser and the burns were relatively short in duration (six minutes and ten second average). The larger seedlings in this treatment were likely not exposed long enough to lethal temperatures to experience significant topkill. A study by Phares and Crosby (1962) on sprout production of three-year-old seedlings found that taller seedlings that are topkilled produce taller dominant sprouts post-burn if they survive. A similar trend was seen in this study.

The three-year-old clip seedlings were on pace to exceed the heights attained by one-and two-year-old seedlings for a full growing season of growth. The three-year-old seedlings were averaging 2.4 inches of height growth per month, whereas the two-year-old and one-year-old seedlings experienced 2.2 and 1.2 inches per month growth averages. Well above average precipitation amounts in 2013 likely contributed to the increased growth rates, yet this finding also supports information from Lawson (1990) who reported that height growth increases after one to two years in seedlings after the taproot becomes established.

The expected differences in the pre-treatment and post-treatment heights also show that there are differences in the individual treatment x time interaction across the two year intervals of the study (2012 and 2013). The statistical significance of this interaction indicates that seedlings in different treatments had different growth rates based on some other factor(s) such as burn intensities, browsing influence, and/or lack of topkill than the elapsed time differences that would be expected to cause differences in height growth from treatment implementation to post treatment measurement. The differences due to elapsed time since pre-treatment measurements were expected. Precipitation amounts increased from 48.4 inches in 2012 to 66.2 inches in 2013, which may have influenced annual height growth rates.

Sprout Height to Sprout Number Correlations

Sprout height to sprout number correlations across all three ages were negative, indicating that as dominant sprout height increases, sprout number tends to decrease. As seedlings aged, the correlation increased slightly from one-to two-year-old seedlings measured one year after treatments, but the correlation became weaker in three-year-old seedlings. The decline in the three-year-old seedlings may be due to some of those seedlings not producing sprouts during the same growing season they were burned or the exclusion of the late growing/early dormant season burn treatment. Other studies with shortleaf pine sprouts have shown that sprouting does typically initiate during the growing season a disturbance was applied if available moisture is adequate (Little and Somes 1956). Three-year-old seedlings in Missouri were burned during April in a study by Phares and Crosby (1962) where they examined mortality, number of basal sprouts, and height of the tallest sprout. Their seedlings were similar on average (42 inches) with the seedlings in this study at the same age (42.9 inch average), but contrary to this study, dominant sprout height did not appear to be affected by the number of sprouts. Their findings also may partially explain the weaker correlation found with the three-year-old seedlings in this study.

Sprout Height and Number to KBDI Correlations

Sprout height and number post-treatment likely showed weak or moderate relationships (negative or positive) with the KBDI values on burn days because fuel types and amounts were controlled throughout the experiment. Fuels were primarily placed on exposed mineral soil with virtually no natural duff or vegetation layer present because of the herbicide and clip treatments applied to burn experimental units prior to treatment. The KBDI value uses climatic variables such as maximum temperature and daily precipitation amounts to account for the drought level in the duff or predominantly upper organic layer(s) of the soil (Keetch and Byram 1968). The drying of fuels for this study, as well as the utilization of similar fuel amounts, likely mitigated the effects of natural drought or moisture surpluses during the duration of this study. The effects of the KBDI on the burns in this study would likely be dissimilar to studies conducted with natural, unmodified duff and upper soil layers.

Management Implications

Shortleaf pine can be regenerated naturally or artificially using a number of silvicultural systems. Even-aged systems such as the clearcut, shelterwood, and seed tree regeneration methods have long been used because of shortleaf pine’s shade intolerance. Natural disturbances, such as wildfires and insect damage that often emulate these regeneration methods are often how shortleaf pine stands originate and develop (Guldin 1986, Lilly 2011). Regeneration methods in the uneven-aged system have also proven to be viable, although small reductions in growth rate and total merchantable cubic volume will occur based on residual overstory density levels. The ability of shortleaf pine to respond favorably following release has made single tree and group selection regeneration methods practical alternatives in the species’ western range where they have been tested (Baker and others 1996, Guldin and others 2004, Kabrick and others 2011, Williston 1978). With any natural regeneration method intended to favor shortleaf pine, establishment of advanced regeneration and control of the hardwood component once regeneration is present are necessary. Prescribed burning is the least intensive and most economical method to achieve either of these objectives over mechanical or herbicide treatments (Yocom and Lawson 1977). In combination with one of the regeneration methods above, a dormant season prescribed burn to reduce fuel volumes prior to a hot, growing season burn typically results in seedbed conditions suitable for natural regeneration for up to four years following the growing season burn (Cain 1987, Stambaugh and others 2007).

When adequate shortleaf pine regeneration is obtained either naturally or artificially, promoting it over competing hardwood species becomes necessary if shortleaf pine dominance is desired. Artificially regenerated shortleaf pine, based on results from this study, will suffer complete topkill from burns applied during its first year with greater mortality after early growing season and mid-growing season burns. Two-year-old seedlings may reach sizes large enough by the end of the growing season to survive low intensity burns. This study has shown that survival increases each year with burning regardless of timing except with mid-growing season burns. Sprout numbers increase with increasing age and height as well, which bodes well for the success of regeneration establishment even if a burn does manage to topkill larger-sized seedlings.

Artificial regeneration of shortleaf pine will likely be necessary on many areas of the Cumberland Plateau in Tennessee and Kentucky due to a lack of consistent seed sources. Forests with varying amounts of shortleaf pine mixed with hardwoods were more prevalent prior to fire exclusion initiated in the early 1950s and recent southern pine beetle outbreaks in this region (Coffey 2012, Coffey 2013). On poorer sites of the Cumberland Plateau, without a shortleaf pine seed source, underplanting shortleaf pine in shelterwood areas or areas with at least fifty percent overstory light available among residual overstory trees could be a viable method to initiate pine-hardwood mixtures (Baker and others 1996). If undesirable species begin to overtake the shortleaf pine component, intermediate treatments such as periodic prescribed burning may be used to take advantage of the sprouting ability shortleaf pine to favor it over other species. Burn conditions in a more variable shelterwood situation with logging slash, understory vegetation, etc. would be different in regard to fuel type, moisture content, and amount than the controlled conditions in this study. Minimum seedling size thresholds may differ based on fuels, weather conditions, and season of burning. Planting widely spaced shortleaf pine seedlings in clearcut areas (300 per acre or less) with adequate site preparation (burning) would also likely be a viable even-aged regeneration option in this region to form pine-hardwood mixtures. This procedure has been effective for establishing loblolly pine-hardwood mixtures on moderately productive sites in Tennessee and South Carolina (Mullins and others 1998, Waldrop 1997).

More options exist for regeneration of shortleaf pine when seed trees exist on the site. Even-aged regeneration methods, such as the shelterwood, have been successful in western areas of the shortleaf pine range to initiate pure or mixed shortleaf pine or mixed pine-hardwood stands when shortleaf pine was already a major component of the overstory and a natural seed source was present (Shelton and Baker 1992). Shortleaf pine seedlings could be planted in areas that received a first cut for a shelterwood or seed tree harvest to compensate for a poor seed fall year. A burn prior to planting to scarify the seedbed and reduce any unwanted competition allows natural regeneration from seed to accumulate with the planted seedlings in subsequent years. Once both natural and planted seedlings reach adequate size to survive burning, the final shelterwood overstory cut is made and advanced seedling reproduction is released (Guldin 2007).

Natural regeneration of shortleaf pine can be achieved through a variety of site preparation methods (e.g. burning, foliar herbicide, hack-n-squirt, mowing, and disking or economical combinations thereof) to adequately stock canopy gaps and areas adjacent to mixed hardwood-loblolly-shortleaf pine forests. In even-aged stands, natural regeneration of shortleaf pine is considered successful when at least 300 to 415 free-to-grow seedlings per acre are present after the third year following site preparation treatment(s) (Cain 1987, Cain 1991, Phillips and Abercrombie Jr. 1987). When using artificial regeneration, a commercial clearcut followed by a summer burn and planting of approximately 415 shortleaf pine seedlings per acre can create productive mixed-shortleaf pine stands (Phillips and Abercrombie Jr. 1987). Whether using artificial or natural regeneration methods, if species composition is undesirable after site preparation and seedling establishment, burning is typically the most economical way to increase shortleaf pine prevalence and decrease densities of less fire tolerant species (Wade and others 2000, Yocom and Lawson 1977). This study indicates that shortleaf pine growing on upland areas of east Tennessee with average site indices in the 60 to 75 feet range at 50 years, can survive late growing/early dormant season burns at an acceptable level (40 to 50 percent) once they reach large enough sizes at approximately three years of age. The size of three-year-old seedlings in this study falls within the two to six year old range where seedlings reach fire resistant size reported by Walker and Wiant (1966). They report that seedlings over five feet tall and greater than 0.5 inches in basal diameter can survive crown scorch induced mortality if less than 70 percent of a sapling's crown is singed. Reaching these sizes at three-years-old is somewhat earlier than the age reported for areas in the western areas of the species' range where shortleaf pine seedlings can outcompete hardwood species on a site in five to seven years if they are of equal sizes and have similar growth rates (Cain 1991). Greater precipitation in the Eastern range of shortleaf pine may shorten or alter these response times.

Research in mixed pine-oak forests of the Missouri and Arkansas Ozarks indicates that if one-year-old shortleaf pine seedlings survive a first burn, they suffer the least damage (percent mortality and percent shoot dieback) of any regenerating species after a series of three or more periodic burns (Stambaugh and others 2007). Another study in the Missouri Ozarks showed that if large enough shortleaf pine advanced regeneration is present on a site, it will maintain its competitive position with competing species with repeated dormant season prescribed burns (Fan and others 2012). Given that sprouts and germinants are the same age, the growth rate of sprout origin shortleaf pine is also greater than seed origin seedlings until at least the fifth year when growth rates may become more similar (Mattoon 1915). If shortleaf pine seedlings of multiple ages are present on a site, repeated burning to promote sprouting may improve shortleaf pine competitive status as well. The sprouting ability of shortleaf pine has the potential to be used silviculturally by managers to establish and perpetuate the species on upland, average productivity areas (site index of 60 to 75 feet at 50 years for shortleaf pine) of east Tennessee.

Adequate site preparation outlined by Cain (1987) prior to outplanting of 1-0 stock seedlings may improve shortleaf pine survival and size advantages over other species increasing its likelihood of reaching the overstory at canopy closure. Once shortleaf pine seedlings are established, a waiting period of two to three years follows for seedlings to achieve adequate sizes to withstand an initial burn. Then repeated burns can be conducted every three to four years to retard competition and allow shortleaf pine to develop. This process should favor shortleaf pine on landscapes in east Tennessee where it once was prevalent.

Conclusions

Clipping produced greater survival, number of sprouts, and taller sprouts in one- and two-year-old shortleaf pine seedlings than burning. The opposite occurred with three-year-old seedlings; burning resulted in greater survival and sprout heights than clipped seedlings. Seedlings achieved large enough root collar diameters, stem heights, and bark thickness to survive the burns conducted during the third year of the study (Objective 1).

Shortleaf pine sprout survival, sprout production, and height growth was not affected by times of seasonal burning. Data analyses suggest no distinction in sprouting response for the three seasonal burns across years. Therefore, timing of burning (within seasons and across years) was not a major factor in sprouting of shortleaf pine seedlings (Objective 2).

Burn duration and temperature covariates affected the shortleaf pine sprouting response when there were major differences in temperature or duration among the experimental units in a treatment. Survival was not affected. Burning during the mid-growing season is hypothesized to damage seedlings more than early or late growing season burns, because of hotter burn and air temperatures as well as shorter burn durations inflict more damage on actively growing plant tissue. However, the variable weather conditions (particularly cooler than normal ambient temperatures) of the mid-growing season burn can result in more sprout production as exhibited in the two-year-old seedlings in this study (Objective 3).

Pre-and post-treatment survival rates for two- and three-year-old shortleaf pine seedlings did not show a definitive trend for any burning or clipping treatments or seedling age (Objective 4).

Shortleaf pine seedling height of two- and three-year-old seedlings prior to burning or clipping had a weak, insignificant correlation to seedling sprout production post-treatment, indicating that size prior to burning or clipping does not affect sprout production in surviving seedlings after these disturbances (Objective 5).

A significant, but weak negative (e.g. three-year-old seedlings) to moderate negative relationship (e.g. two-year-old seedlings) was observed for post treatment sprout height to sprout number correlations for all seedling ages. This relationship suggests that taller dominant seedlings have fewer total sprouts than shorter seedlings of any age that has been burned or clipped (Objective 6).

The KBDI value had weak to moderate relationships with sprout height growth and sprout production for one, two, and three-year-old seedlings. The KBDI would likely be a much more telling variable of shortleaf pine sprouting responses for seedlings burned with natural fuel conditions present (Objective 7).

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Appendices

Appendix 1.

Burn covariates and values used for each analysis of height and sprout production during 2011 for the shortleaf pine seedling sprout study in east Tennessee.

Treatment	Date	Block	Mean Burn Temperature (°F)	Median Burn Temperature (°F)	Maximum Burn Temperature (°F)	Burn Duration (Secs.)	Burn Temperature Standard Deviation (°F)	Sum of all Temperature Recordings (°F)	Keetch-Byram Drought Index
April Burn	4/14/2011	1	258.1	180.7	770	360	193.74	4130.3	25
April Burn	4/14/2011	2	270.2	177.6	736	360	210.8	4323.9	25
April Burn	4/14/2011	3	281.6	196.3	512	360	208.7	4505.4	25
July Burn	7/14/2011	1	325.8	327	595	360	162.9	8146	230
July Burn	7/14/2011	2	266.6	236	720	360	150.6	6663.9	230
July Burn	7/14/2011	3	229.2	147.6	833	360	192.4	5730.4	230
November Burn	11/10/2011	1	388.6	376	762	870	146.7	22928.2	44
November Burn	11/10/2011	2	347.1	312	849	660	201.2	15620.6	44
November Burn	11/10/2011	3	301	238	932	660	176.2	13547	44

Appendix 1. (Continued)

Burn covariates and values used for each analysis of height and sprout production during 2012 and 2013 for the shortleaf pine seedling sprout study in east Tennessee.

Treatment	Date	Block	Mean Burn Temperature (°F)	Median Burn Temperature (°F)	Maximum Burn Temperature (°F)	Burn Duration (Secs.)	Burn Temperature Standard Deviation (°F)	Sum of all Temperature Recordings (°F)	Keetch-Byram Drought Index
March Burn	3/20/2012	1	269.9	174	849	300	193.8	5668	57
March Burn	3/20/2012	2	406.3	394	728	540	152	15034	57
March Burn	3/20/2012	3	459.4	449	932	420	192.9	13323	57
June Burn	6/26/2012	1	365.1	329	932	240	214.1	6206.7	381
June Burn	6/26/2012	2	479.3	435	932	390	190.9	12722.5	381
June Burn	6/26/2012	3	404.5	346	785	240	191.8	6876	381
November Burn	11/19/2012	1	191.2	75	932	1050	215.1	13379	432
November Burn	11/19/2012	2	201.8	178	932	720	131.5	9886	432
November Burn	11/19/2012	3	160.7	127	581	540	120	5946	432
March Burn	3/14/2013	1	337.8	293	932	480	227.5	10472	2
March Burn	3/14/2013	2	184.6	120	566	690	134.6	8677	2
March Burn	3/14/2013	3	204.6	102.5	802	1020	186.5	12273	2
July Burn*	7/12/2013	1	93.8	92	122	390	11.09	2533	34
July Burn	7/12/2013	2	220.1	140	716	300	157.9	4623	34
July Burn	7/12/2013	3	213	155	653	420	154.9	6178	34
November Burn	11/11/2013	1	186.9	108	820	660	171.8	8412	278
November Burn	11/11/2013	2	350.6	324	932	660	146.3	15778	278
November Burn	11/11/2013	3	125.8	68	681	1020	126.8	8683	278

Appendix 2.

Covariate means and standard deviations for each season and year of the shortleaf pine seedling sprout study in east Tennessee.

Treatment Period and Year		Mean Burn Temperature (°F)	Median Burn Temperature (°F)	Maximum Burn Temperature (°F)	Burn Duration (Secs.)	Burn Temperature Standard Deviation (°F)	Sum of all Temperature Recordings (°F)
2011 April Burns	Mean	269.9	184.9	672.7	360	204.4	4319.9
	Standard Deviation	11.8	10	140.2	0	9.3	187.6
2011 July Burns	Mean	273.9	236.9	716	360	168.6	6846.8
	Standard Deviation	48.7	89.7	119.1	0	21.5	1218.1
2011 November Burns	Mean	345.6	308.7	847.7	730	174.7	17365.3
	Standard Deviation	43.8	69.1	85	121.2	27.3	4927.9
2012 March Burns	Mean	378.5	339	836.3	420	179.6	11341.7
	Standard Deviation	97.8	145.5	102.6	120	23.9	4987.5
2012 June Burns	Mean	416.3	370	883	290	198.9	8601.7
	Standard Deviation	58	56.9	84.9	86.6	13.1	3584.3
2012 November Burns	Mean	184.6	126.7	815	770	155.5	9737
	Standard Deviation	21.3	51.5	202.6	258.7	51.9	3718.7
2013 March Burns	Mean	242.3	171.8	766.7	730	182.9	10474
	Standard Deviation	83.3	105.3	185.5	272.2	46.6	1798
2013 July Burns	Mean	175.6	129	497	370	108	4444.7
	Standard Deviation	70.9	32.9	326.3	62.4	83.9	1829
2013 November Burns	Mean	221.1	166.7	811	780	148.3	10957.7
	Standard Deviation	116.2	137.7	125.7	207.8	22.6	4176.7

Appendix 3.

All six covariate slope estimates, standard errors, and p-values are presented for the sprout number and height growth variables for each of the three years of the shortleaf pine seedling sprout study in east Tennessee. Bolded values indicate a statistically significant treatment factor and a significant covariate.

Variable Year	Parameter	Mean Burn Temperature (°F)	Standard Deviation Burn Temperature (°F)	Burn Duration (Seconds)	Sum of Burn Temperatures (°F)	Median Temperature (°F)	Maximum Burn Temperature (°F)
Height 2011	Slope Estimate	0.0019	0.00000052	0.002	0.00002	0.0017	-0.0005
	Standard Error	0.0029	0.000042	0.0014	0.00004	0.0016	0.0009
	P-value	0.51	0.99	0.16	0.55	0.31	0.62
Number 2011	Slope Estimate	0.0062	0.000064	0.0006	0.000062	0.004	**-0.0017**
	Standard Error	0.0019	0.000039	0.0015	0.000029	0.0012	**0.0006**
	P-value	0.002	0.1	0.67	0.03	0.002	**0.009**
Height 2012	Slope Estimate	**-0.0107**	**-0.031**	**-0.0043**	**-0.00018**	-0.0025	-0.0028
	Standard Error	**0.0043**	**0.0055**	**0.0001**	**0.00005**	0.0042	0.0024
	P-value	**0.0152**	**<0.0001**	**<0.0001**	**0.0006**	0.56	0.25
Number 2012	Slope Estimate	**0.0082**	**0.0187**	**0.003**	**0.00011**	0.002	0.0036
	Standard Error	**0.0019**	**0.004**	**0.0008**	**0.00003**	0.0007	0.0012
	P-value	**<0.0001**	**<0.0001**	**0.0002**	**0.0002**	0.006	0.0025
Height 2013	Slope Estimate	-0.0098	-0.0121	-0.002	-0.0007	-0.01	-0.0031
	Standard Error	0.0027	0.0032	0.0038	0.00017	0.003	0.0008
	P-value	0.0005	0.0002	0.0002	<0.0001	0.001	0.0002
Number 2013	Slope Estimate	**0.0082**	0.0098	0.0098	0.00029	0.009	0.0024
	Standard Error	**0.0018**	0.002	0.002	0.00015	0.0021	0.0005
	P-value	**<0.0001**	<0.0001	<0.0001	0.07	<0.0001	<0.0001

Vita

David Charles Clabo was born in Maryville, Tennessee on November 9, 1988. In 2007, he graduated from Gatlinburg Pittman High School in Gatlinburg, Tennessee.

David became interested in forestry during his sophomore year of undergraduate studies. He completed an internship with the Great Smoky Mountains National Park's Vegetation Management Division in summer 2010. The following summer he completed another internship with Great Smoky Mountains National Park, but this time with the Forest Ecology Division. David received a Bachelor of Science degree with a major in Forest Resource Management with honors from the University of Tennessee in December 2011.

In January 2012, David accepted a position as a Graduate Teaching and Research Assistant within the Department of Forestry, Wildlife, and Fisheries at the University of Tennessee. While working, taking classes, and teaching silviculture labs at UT, he researched disturbance type and timing impacts on shortleaf pine seedling sprout production. His career goals include obtaining a PhD in forestry/natural resources, and an extension/research based position that focuses on statistics, biometrics, forest ecology, and silviculture.