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# Shortleaf Pine-Hardwood Mixture Establishment and Release in Two Physiographic Regions of Tennessee

David Charles Clabo
*University of Tennessee*, dclabo@vols.utk.edu

To the Graduate Council:

I am submitting herewith a dissertation written by David Charles Clabo entitled "Shortleaf Pine-Hardwood Mixture Establishment and Release in Two Physiographic Regions of Tennessee." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Natural Resources.

Wayne K. Clatterbuck, Major Professor

We have read this dissertation and recommend its acceptance:

James M. Guldin, Benjamin O. Knapp, Arnold M. Saxton, John M. Zobel

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-Hardwood Mixture Establishment and Release in Two Physiographic Regions of Tennessee

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## Abstract

Shortleaf pine (*Pinus echinata* Mill.)-hardwood forest types have been declining in area across shortleaf pine's native range for at least forty years. Interest in restoring this forest type has increased in recent years, yet knowledge on restoration of mixed shortleaf pine-hardwood forests is limited. The objectives of this study were to investigate five site preparation or release treatments at two sites using different silvicultural systems and their effects on artificially regenerated shortleaf pine (due to the lack of a seed source) and naturally regenerated woody species. The first study investigated establishment and development of even-aged, mixed shortleaf pine-hardwood forests on the Highland Rim physiographic province of Tennessee, whereas the second study investigated establishment and development of two-aged mixed shortleaf pine-hardwood forests after a partial harvest in the Cumberland Mountains physiographic province of Tennessee. At the Highland Rim Site, shortleaf pine was planted at two wide spacings (12x12 and 18x18 ft.) to allow natural regeneration development among the planted pines. Treatments tested included: herbicide and burn (brown-and-burn), burn, herbicide, strip-burn, and a control. Three years after study establishment, statistical differences among treatments occurred for shortleaf pine survival, basal diameter, and height. Survival was greatest in the herbicide treatment and height and basal diameter growth were greatest in the brown-and-burn treatment. Natural regeneration stem densities reflected the intensity of the treatment, and no differences in height were detected. Invasive species such as privet and callery pear were prevalent in most treatments. At the Cumberland Mountains site, shortleaf pine was planted in clusters within canopy gaps at narrow spacings. Treatments investigated at this site included: brown-and-burn, burn, herbicide, scarification, and a control. Two years after planting, no treatment differences were observed for shortleaf pine survival or basal diameter growth, yet seedlings in the scarification treatment were significantly taller than those in the other treatments. Statistical differences for natural regeneration stem densities among treatments were found for cluster interiors, yet not for cluster exteriors. Woody shrubs were prevalent in the regeneration with a minor component of desirable oak species. Both management scenarios offer promise for reintroducing shortleaf pine as a component of mixed stands.

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### *Silvics and Development of Shortleaf Pine*

Shortleaf pine is adapted to a wide variety of climatic and soil conditions across its native range. The species has the widest geographic range of any native southeastern pine species (Critchfield and Little 1966). Precipitation ranges from 40 inches (in.) in western portions of the species range to 64 in. along areas of the gulf coast (Guldin 1986). Annual temperature averages range from 45° F in the northern areas of its range to 75° F along the southern Gulf Coastal Plain (Lawson 1990). Soil types are highly varied across shortleaf pine's natural range. Soils are classified predominantly in the order Ultisols with Udic moisture regimes. These soils have thick clay horizons with significant amounts of weathered materials. Shortleaf pine growth is greatest in soils having fine sandy loam or silty loam textures (Lawson 1990). In association with the multitude of soil conditions found in shortleaf pine's range, site indexes vary greatly as well. On upland sites throughout shortleaf pine's range, site indexes typically average between 50 and 75 feet (ft.) at base age 50 years, but indexes as low as 20 ft. and as high as 100 ft. at base age 50 years occur in some areas (Fowells 1965, Lawson 1990, Williston and Dell 1974).

A wide range of elevations support shortleaf pine establishment and growth. Elevations range from 10 feet in southern New Jersey to 3,300 ft. in the Appalachian Mountains. The best growth and most abundant populations are at 600 to 1,500 ft. in the Piedmont physiographic region and at 150 to 1,000 ft. in areas or Arkansas and Louisiana (Fowells 1965). The species occurs as far north as Long Island, New York and southward into eastern Texas. The only areas in that 440,000 $mi^2$ geographic range where it is not prevalent are near the Gulf and Atlantic coasts and throughout the Mississippi River alluvial valley. Twenty-three states are known to have shortleaf pine populations (Lawson 1990). The most concentrated populations are found in the Ouachita and Ozark mountains in western Arkansas and eastern Oklahoma north of the native range of loblolly pine where rainfall averages from 45 to 55 in. per year (Fowells 1965).

Shortleaf pine is monoecious, producing male and female flowers, which are present on the same tree (Krugman and Jenkinson 1974). Staminate flower emergence dates vary from late March in Texas to late April or early May in New Jersey during a typical year (Zobel and Goddard 1954). Most individual trees are not capable of flowering and producing viable seed before they reach 20 years of age or a diameter at breast height (DBH) of approximately 10 in. (Shelton and Wittwer 1996). Seedfall begins in October during average years and continues throughout April, though most seed falls in October and November (Little, Jr. 1940, Dorman and Barber 1956). Seed production can be increased during good or bumper seed crop years by reducing stand density with a regeneration harvest (e.g. shelterwood at 30-45 sq. ft./acre) and releasing potentially good seed producing individuals in a stand in advance of expected seedfall (Wittwer et al. 2003). The number of seeds produced per cone range from about 25 to 35 seeds, and there is an average of 48,000 seeds per pound. Intervals between bumper seed crops can be sporadic and average 3 to 10 years in northern regions of its range, but are typically more regular at 3 to 6 years in southern regions of its range (Fowells 1965). In addition, sound seed production typically increases in more southern regions of shortleaf pine's range (Shelton and Wittwer 1996). Seeds are disseminated in a V-shaped from the parent tree pattern by prevailing winds. Dispersal distances may be up to ¼ mile in some instances (Siggins 1933). Fresh shortleaf pine seed has a cold stratification period of 0-15 days (Krugman and Jenkinson 1974). Epigeal germination (above ground) occurs in the spring after seeds have laid on the ground all or part of the winter.

Most seeds are eaten by small mammals and birds in a given year unless a bumper crop occurs (Stephenson et al. 1963). Site preparation methods such as scarification and burning that expose bare mineral soil have improved germination rates. Retention of some hardwoods can improve shortleaf pine seedling survival by protecting and shading them from drying winds and late spring frosts (Yocom and Lawson 1977). Seedlings grow slowly their first year or two after germination due to the development of an extensive taproot (Lawson 1990). After taproot development has slowed, seedlings and saplings can be expected to grow 1 to 3 ft. per year depending on climate and site productivity (Williston 1972). Shortleaf pine growth is multinodal, and most growth is completed by July unless favorable growing conditions occur late in the growing season (Fowells 1965).

The sprouting ability of shortleaf pine sets it apart from other southern pine species that typically cannot or unreliably sprout after stem injury or death. Seedlings usually develop a J-shaped basal crook two to three months after germinating. The basal crook is a section of the taproot that grows horizontally in the soil before turning vertical again. The number of years required for full development of the basal crook depends on the amount of shading the seedling is receives. More shading results in a less developed basal crook (Little and Somes 1956, Little and Mergen 1966, Stone and Stone 1954). Sprouts originate from dormant buds located just above the basal crook at the root collar (Lilly et al. 2010, Lilly 2011). Sprouting occurs in response to loss of apical dominance and the resulting oxidative stress that occurs when fatty acids are broken down to provide energy for sprouting (Liu et al. 2011). As many as 80 sprouts may be produced by vigorous seedlings, but usually three or fewer will remain as the seedling grows and matures (Mattoon 1915). Shortleaf pine can sprout at up to six to eight in. DBH, but sprouting is much more common in smaller seedlings.  Sprouting ability then progressively decreases with age and increasing size (Hardin et al. 2001, Mattoon 1915). The basal crook and dormant buds are located just below the soil surface and duff layer, which provides more protection from lethal temperatures that may occur during a surface fire (Lilly et al. 2010, Stone and Stone 1954). With artificially regenerated shortleaf pine, planting depth can have a major impact on basal crook location in the soil and dormant bud survival following a burn (Will et al. 2013). Spouting allows shortleaf pine to persist on sites with frequent disturbance (natural or anthropogenic), compared to other species that may decline over time.

Shortleaf pine is intolerant of shade, but it can grow in dense stands and survive some overstory shade when it is young (Guldin 1986, Kabrick et al. 2011, Shelton 1995). The ability to tolerate some overstory shade and crowded conditions enables shortleaf pine to respond well to release even at older ages (Fowells 1965).  On quality sites, 35 year-old trees can attain heights of 60 ft. and 8 in. DBH, while 60 year-old trees may reach 80 ft. and 12 in. DBH. Individual trees can grow 120 ft. tall, 36 in. DBH, and live nearly 400 years (Guldin 1986, Hardin et al. 2001).

***Shortleaf Pine Forest Types and Silvics of Common Overstory Associates***

Shortleaf pine grows with a variety of other tree species throughout its extensive range. It is a major component of four Society of American Foresters (SAF) cover types: the shortleaf pine type (type 75), the shortleaf pine-oak type (type 76), the shortleaf pine-Virginia pine type (type 77), and the loblolly pine-shortleaf pine type (type 80) (Eyre 1980). Shortleaf pine is a minor component of fifteen other SAF forest types (Fowells 1965). Several of these forest types are located on the Cumberland Plateau and Highland Rim physiographic provinces. These include: white pine (type 21), post oak-black oak (type 40), scarlet oak (type 41), chestnut oak (type 44), eastern red cedar (type 46), eastern red cedar-pine (type 47), eastern red cedar-pine-hardwood (type 49), white pine-chestnut oak (type 51), northern red oak-mockernut hickory-sweetgum (type 56), Virginia pine-southern red oak (type 78), Virginia pine (type 79), Loblolly pine (type 81), and loblolly pine-hardwood (type 82) (Eyre 1980, Fowells 1965, Smalley 1982, 1983). Table 1 introduces common competitors along with their silvical characteristics and sources.

Table 1. Shortleaf pine-hardwood forest types common overstory associates and species silvics or the Cumberland Mountains and Highland Rim physiogrpahic provinces of Tennessee.

| Species | Comparative Growth Rate to Shortleaf Pine | Shade Tolerance | Site Conditions | Competitive Status | Sources |
|---|---|---|---|---|---|
| *Quercus coccinea* | Quick compared to most other oaks and shortleaf pine. | Intolerant | Poor to moderate sites performs well. Found on ultisol soils. | High, sprouts vigorously after burning when young, climax species on poor sites | Johnson 1990; Gingrich 1967; Brown 1960; Green et al. 2010 |

Table 1. Continued.

| Species | Comparative Growth Rate to Shortleaf Pine | Shade Tolerance | Site Conditions | Competitive Status | Sources |
|---|---|---|---|---|---|
| *Quercus velutina* | High, quicker than most associated oaks | Intermediate | Similar to SLP, Udult Ultisols, Inceptisols | Moderate, not very fire tolerant | Sander 1990; Sander and Clark 1971; Eyre 1980 |
| *Quercus falcata* | Similar to *Quercus velutina* | Intolerant | Similar to SLP, Ultisols, and poor to moderate upland sites | Moderate, not very fire tolerant | Belanger 1990 |
| *Quercus alba* | Slower growing than SLP and most other oaks | Intermediate | Variety of sites, but can grow on all but the poorest SLP sites | Major, not as sensitive to fire as red oaks and can sprout vigorously, climax species | Gingrich 1971; Rogers 1990; Johnson 1977 |
| *Quercus prinus* | Quicker growth rate than *Quercus alba* but slower than most red oaks | Intermediate | Similar to SLP, found on dry, upland sites, Ultisols and Inceptisols | Moderate, susceptible to fire damage, but resprouts vigorously when young, climax species | McQuilkin 1990; Carmean 1972; Wendel 1975 |

Table 1. Continued.

<table>
<tr><th>Species</th><th>Comparative Growth Rate to Shortleaf Pine</th><th>Shade Tolerance</th><th>Site Conditions</th><th>Competitive Status</th><th>Sources</th></tr>
<tr><td>Carya cordiformis and Carya tomentosa</td><td>Slower growing than SLP and most other red oaks, but similar to white oak</td><td>Intolerant</td><td>Similar to SLP, poor to moderate sites, Ultisols, grows best on more productive sites</td><td rowspan="2">Moderate to susceptible to fire damage but resprouts vigorously when young</td><td rowspan="2">Smalley 1990; Smith 1990a; Smith 1990b; Nelson 1965; Trimble 1975; Whittaker 1956</td></tr>
<tr><td>Carya glabra</td><td>Slower growing than SLP and most other red oaks, but similar to white oak</td><td>Tolerant</td><td>Similar to SLP, occurs on dry upland sites, tolerant of sandy soils</td></tr>
<tr><td>Acer rubrum</td><td>Quicker growth rate than SLP and other competitors when young but decreases growth rate once the pole stage is reached</td><td>Tolerant</td><td>Competitive on all site types in eastern North America</td><td>Major, considered a pioneer and subclimax species, responds well to release. Sensitive to fire, but sprouts vigorously</td><td>Walter and Yawney 1990; Hutnick and Yawney 1961; Green et al. 2010</td></tr>
</table>

Table 1. Continued.

| Species | Comparative Growth Rate to Shortleaf Pine | Shade Tolerance | Site Conditions | Competitive Status | Sources |
|---|---|---|---|---|---|
| *Nyssa sylvatica* | Growth rate depends greatly on site conditions. Growth rates are slow on most SLP sites. | Tolerant | Grows on most sites in eastern North America. Udult Ultisols, growth is slower on dry, upland sites | Moderate, very susceptible to fire, responds well to release, can root sprout | Putnam et al. 1960; McGee 1990 |

***Stand Dynamics***

The shortleaf pine and shortleaf pine-hardwood stands that exist today developed across much of the Piedmont region in the southern United States during the twentieth century after agricultural land abandonment (Billings 1938). Agricultural cultivation and settlement removed large acreages of forests. Soil conservation practices such as fertilization and terracing were not practiced, resulting in erosion and unproductive fields. Once a field became infertile, it was usually abandoned and secondary succession began (Oosting 1942). Loblolly, shortleaf, and Virginia pine typically seed and establish on bare mineral soil among grasses and herbaceous plants after about 3-5 years forming even-aged mixed or pure stands. Without further disturbance, these stands become very dense in terms of stems per acre and have a minimal amount of available growing space. Then the stand reaches the “stagnation/mortality” phase of the stem exclusion stage of stand development where growth rates are reduced (diameter followed by height). Less vigorous trees begin to die either from disturbances or competition pressure (Oliver and Larson 1996). This relinquished growing space provides opportunities for hardwood species such as sweetgum (*Liquidambar styraciflua* L.), red maple (*Acer rubrum* L.), blackgum (*Nyssa sylvatica* Marsh.), white oak (*Quercus alba* L.), post oak (*Quercus stellata* Wangenh.), etc. to establish in the understory and compete with the pines (Halls and Homesley 1966). From about 45-100 years, K-strategist species that are spread mostly by small mammals establish within the stand. The thick understory and duff layer that develops during this time is not conducive for R-strategist species, such as mostly shade intolerant southern pines. Long intervals without disturbance will cause these stands to transition to hardwood species (Halls and Homesley 1966, Switzer et al. 1979). Mixed pine-hardwood stands are considered a transitional successional forest type with pure pine stands being an early successional stage and mixed hardwoods a later successional stage (Cooper 1989, Halls and Homesley 1966).

Pine-hardwood forests in mountainous areas of the Southeast, such as the Cumberland and Appalachian Mountains often develop following intense anthropogenic or lightning-caused wildfires. Fesenmyer and Christianson (2010) dated charcoal fragments and discovered that fire had occurred regularly in oak-pine and mesic hardwood stands for 4,000 years before present on a site in the Appalachian Mountains indicating that it is possible for these sites to have many disturbances such as fire that could result in possible regeneration events. Site aspects where these forest types occur are often southern or western facing slopes that receive more sunlight than other aspects. These areas were often inoperable (not cleared) for agricultural activities due to infertile, rocky soils, and steep terrain, resulting in them not undergoing old field succession (Barden and Woods 1976, Vose et al. 1997). Repeated high-grading of hardwood species on more accessible sites may have promoted pine species at irregular intervals (Cooper 1989). Ridge tops and upper slope positions with southerly aspects throughout the southern Appalachians and Cumberland Mountains are more prone to recurrent fires than other aspects and slope positions from dryer conditions caused by greater solar radiation levels (Barden and Woods 1976, Harrod and White 1999). Stand replacing fires, either caused by lightning or anthropogenic ignition sources, are more likely on these sites, but still uncommon (Barden 1974, Harrod and White 1999). The dry and infertile edaphic conditions on some of these sites favors pine species and excludes many hardwood species (Eyre 1980, Vose et al. 1997).

Mild to moderate natural canopy disturbances resulting in multi-tree gaps caused by a wide range of mechanisms can be catalysts for pine regeneration in areas that do not experience anthropogenic disturbances such as large scale timber harvests or repeated burning (Hart et al. 2012). Gap sizes and proximity of overstory trees as a seed source as well as sprouting capabilities of remaining rootstocks of trees inside the gap determine future species composition and the likelihood of the younger cohort reaching the overstory. Differences in crown architecture among species (especially hardwoods and pines) can affect how quickly gaps close following a disturbance as well (Stambaugh and Muzika 2007, Weber et al. 2014). Hart and Grissino-Mayer (2009) investigated natural canopy gap dynamics in predominantly mesophytic mixed hardwood and oak-hickory forests of the Cumberland Plateau and observed that gaps that ranged in area from 12-1,698 $ft^2$ in this forest type close more often by lateral crown expansion, rather than subcanopy recruitment. Conversely, a study by Weber et al. (2014) examined canopy gap dynamics in pine-hardwood forests of the Cumberland Plateau where observed gaps were slightly larger overall and occurred naturally due to uprooting, a snapped stem, or a snag and ranged from about 43-2,174 $ft^2$ in size. Their work suggested that gaps were more likely to fill by subcanopy recruitment rather than lateral canopy expansion. There were no overstory pines in the Hart and Grissino-Mayer (2009) study, whereas the Weber et al. (2014) study had only 10% of overstory stems consisting of pines. Pine species were predicted to become a component of the overstory in only 6.7% of the inventoried gaps, indicating the unlikelihood of natural pine regeneration with this method. Another gap dynamics study in the Missouri Ozarks where shortleaf pine composed at least 25% of the basal area in each inventoried stand reported that recruitment of shortleaf pine into the overstory was only expected in larger gaps (e.g. tenth-acre openings compared to half-acre openings) and gaps with more overstory shortleaf pine trees proximal to the gap (Stambaugh and Muzika 2007). A study in Atlantic Coastal Plain loblolly pine-hardwood forests concluded that pines rarely can compete with hardwoods in natural canopy gaps (Rantis and Johnson 2002).

### ***Mixed Shortleaf Pine-Hardwood Forest Distribution, Range, and Status***

Pine-hardwood forests are defined as forests that contain approximately 25 to 75% hardwood species and 25 to 75% pine species by basal area or stems per unit area (Knight and Phillips 1987, Moser et al. 2007). Shortleaf pine-hardwood forest classification follows the same guidelines. The greatest concentrations of shortleaf pine-hardwood forests occur in Missouri, Arkansas, Texas, and Louisiana where shortleaf pine is more prevalent (Lawson 1990, Oswalt 2012). The Piedmont physiographic region, as well as areas of northeast and north-central Mississippi, have the highest concentration of shortleaf pine-hardwood forests east of the Mississippi river (Moser et al. 2007). In Tennessee, shortleaf pine-hardwood forests are most concentrated on the Cumberland Plateau, the western Highland Rim, and elevations below 2000 ft. in the Appalachian Mountains (Eyre 1980, Oswalt 2013).

Across shortleaf pine's native range, 18% of all shortleaf pine stems occur in the shortleaf pine-oak forest type. In this forest type, 93% of all shortleaf pine stems were 5 in. DBH or larger illustrating that conditions suitable for regeneration of younger age classes are unlikely or unsuitable across shortleaf pine's range (Moser et al. 2007, Oswalt 2012). Declines in shortleaf pine and shortleaf pine-hardwood forest types have been evident for at least 30 years east of the Mississippi River. Between 1953 and 1997, shortleaf pine forest types had an estimated loss of 4.4 million acres of land (South and Buckner 2003). Most land with a shortleaf pine component (62%) is privately owned. On private lands with shortleaf pine, volume removal has been greater than growth, whereas the opposite is true on public lands. Hardwood growth has increased more than removal in all areas of shortleaf pine's range. In Tennessee, removal of shortleaf pine has exceeded volume growth across all land ownerships (Moser et al. 2007, Oswalt 2012). Reasons for shortleaf pine decline on private lands include but are not limited to urbanization, forest conversion to loblolly pine (*Pinus taeda* L.) plantations, mesophication, southern pine beetle outbreaks, and fire suppression resulting in unfavorable regeneration conditions for shortleaf pine (Brose et al. 2001, McWilliams et al. 1986, Nowacki and Abrams 2008, Oswalt et al. 2016). Based on these reasons, without active management prospects for shortleaf pine regeneration are poor throughout its native range.

***Justification for Mixed Forest Establishment***

Mixed shortleaf pine-hardwood forest types offer many ecological, land-use, and economic benefits that pure shortleaf pine or mixed hardwood forests alone do not offer. Mixed stands offer more niches and microenvironments for a greater number of wildlife species than do pine plantations alone and some hardwood forest types (Cooper 1989, Tomczak 1994). Trade-offs in mast production and forage production occur at varying basal area ratios of pines to hardwoods, with forage increasing at greater pine basal areas per unit area and mast production increasing with greater hardwood basal areas per unit area (Wigley et al. 1989). Increased tree diversity reduces the probability of catastrophic insect and disease outbreaks and losses that are risks associated with plantation forestry (Tomczak 1994). Mixed shortleaf pine-oak forest types are likely more compatible with the possibility of a changing future climate and may respond more favorably than either pure pine or mixed hardwoods to significant changes in climate (Kabrick et al. 2017) Multi-resource goals can be achieved with pine-hardwood mixtures, such as the possibility for more wildlife game species (excluding quail) on a given acreage, and the possibility for multiple timber products produced from a given acreage. Mixed pine-hardwood forest types are more aesthetically pleasing to some landowners as well (Baker et al. 1996, Cooper 1989, Tomczak 1994). Pine-hardwood mixture establishment, depending on choice of site preparation method and use of natural or artificial regeneration for pine, can cost roughly half the price of pine plantation establishment and require less maintenance than pine plantations (Phillips and Abercrombie Jr. 1987, Waldrop 1997). Uncertainties in future market conditions make the diversity offered by mixed pine-hardwood stands more favorable (Zedaker et al. 1989). The shorter-lived, faster-growing pine species will grow to merchantable size classes more quickly than slower growing hardwood species in most instances, especially on lower productivity sites. The timing of when operations are conducted for hardwoods and pines are different, which can result in incomes from harvests at different times during the rotation of the stand. Decisions for managing mixed pine-hardwood stands are more of an art than a science and they will be based more on site productivity, timber markets, and landowner objectives than any other factors (Tomczak 1994).

### *Establishment of Mixed Stands*

Mixed shortleaf pine-hardwood stands pose more of a challenge to establish than pine plantations or mixed hardwood stands on most sites due to the varying silvical requirements of pines and hardwoods, especially if timber management is a landowner objective (Baker et al. 1996). Subtle changes in site productivity can also drastically change how a pine-hardwood mixture will develop over time. Drier, less fertile sites will often favor pine dominance whereas wetter, more fertile areas will shift dominance towards hardwood species (McGee 1989). When efforts to regenerate these forest types are made, the presence of a pine seed source on or near a site to be regenerated is the deciding factor when determining whether natural or artificial regeneration should be pursued for pine establishment.

Natural regeneration of shortleaf pine-hardwood mixtures can only occur if a shortleaf pine seed source is present in or adjacent to the stand in need of regeneration (Phares and Liming 1960). Exacting conditions are required for shortleaf pine seeds to germinate. Bare mineral soil exposure from either fire or machinery improve reproduction but may not be necessary during bumper seed crop years (Baker 1992, Yocom and Lawson 1977). Weather conditions following seed dissemination should not be excessively dry in the spring or summer for successful germination following any type of disturbance or harvest because seed only remains viable for one year (Lawson 1990). On more productive sites, hardwood and herbaceous vegetation should be controlled for shortleaf pine to grow and survive, yet more vigorous trees can endure many years of intense hardwood and/or herbaceous competition before they succumb (Yeiser and Barnett 1991, Baker 1992). Hardwoods typically regenerate most successfully from stump or root sprouts, and unless an area is undergoing afforestation, hardwood regeneration is easily obtained east of the Mississippi River in shortleaf pine's native range.

The need for artificial regeneration of shortleaf pine combined with natural regeneration of hardwoods is the most common scenario landowners and managers who desire this forest type will encounter. Sources of artificial shortleaf pine regeneration can come from bareroot or containerized seedlings as well as seed (Lawson 1990). In Tennessee, planting 1-0 stock bareroot seedlings is most common due to their greater availability (Conn 2012). Planting is typically done in March at this latitude to avoid greater chances for freezing temperatures and desiccation from wind earlier in the winter and to reduce the chances of planting during dry periods later during the early spring.

Even-aged silvicultural systems are most suitable for regeneration of shortleaf pine-hardwood stands, but two-aged or even uneven-aged group selection methods may be feasible on less productive sites (Baker et al. 1996). Performing a clearcut followed by a site preparation (burning) or release treatment has been extensively tested for establishing pine-hardwood stands in the Southeast, but not always necessarily with shortleaf pine (Clabo and Clatterbuck 2015, Phillips and Abercrombie Jr. 1987, Steinbeck and Kuers 1996, Waldrop 1997, Zedaker et al. 1989). After a silvicultural clearcut in which all stems greater than approximately six feet tall are cut, a prescribed burn is conducted soon after to facilitate planting and control less fire tolerant hardwood regeneration. Pines are then planted at wide spacings allowing natural hardwood regeneration to grow among the pines. This method is called the fell-and-burn technique (Phillips and Abercrombie Jr. 1987). Following a silvicultural clearcut, other variations of the fell-and-burn technique can be used to control species composition and stem densities as needed. These variations include a broadcast herbicide application after which a prescribed burn (termed brown-and-burn) is conducted, broadcast herbicide only or spot herbicide treatment and/or basal bark herbicide treatment for larger, undesirable stems within a certain distance of planted pines (Mullins et al. 1998). If burning is a viable option for a landowner, the fell-and-burn technique will often result in the most even ratio of pine to hardwood basal area on moderate productivity sites if pines are planted at 15x15 to 20x20 ft. spacings (Clabo and Clatterbuck 2015, Waldrop 1997). This type of management promotes more shade intolerant hardwood species but tolerant species such as red maple may respond well. More intolerant species such as yellow-poplar, black oak, scarlet oak, southern red oak, mockernut hickory, and black locust (*Robinia pseudoacacia*) are common competitors.

Planting seedlings under a residual overstory and initiating a two-aged or uneven-aged stand is not as well studied as the even-aged methods of initiating pine-hardwood mixtures. Survival of planted seedlings is rarely affected by the amount of overstory stocking (Blizzard et al. 2007, Guldin and Heath

2001, Kabrick et al. 2011). The growth rates of seedlings planted under dense residual canopies does decrease compared to seedlings grown in more open conditions. Guldin and Heath (2001) reported that shortleaf pine seedlings planted under a residual hardwood overstory of 40 $ft^2$ $ac^{-1}$ still remain competitive with regenerating hardwoods in the Ouachita Mountains of Arkansas where competition from more mesic species such as yellow-poplar and red maple are not as prolific as they are in eastern regions of shortleaf pine's range. Kabrick et al. (2011) had similar results in the Missouri Ozarks, except levels of percent stocking were used instead of residual basal area. For each 20 percent increase in overstory stocking, shortleaf pine seedling diameter decreased by 0.01 in. and shoot growth by 0.7 inches. These studies demonstrate that planted shortleaf pine seedlings can successfully survive and grow under partial overstory shade conditions, albeit at reduced rates as compared to completely open conditions.

Group selection has been proposed, but not extensively tested as an uneven-aged method to manage shortleaf pine-hardwood stands. The typical opening size for group selection harvests is one to two times the height of mature trees in the stand (Nyland 2007). Openings used in group selection harvests for shade intolerant species such as shortleaf pine or red oaks should have widths no less than half the opening length and should be 0.33 to 1.5 acres in size with irregular opening shapes throughout the stand. Openings of this size are favorable to pine regeneration (either natural or artificial) in the center of the openings with enough light so as not to reduce growth rates, and provide sufficient light levels for intermediate and shade intolerant oak regeneration (depending on location in the group) (Baker et al. 1996, Murphy et al. 1993). Areas where openings should be made for group selection harvests depend on factors such as the financial maturity of the trees, damage from insects or disease, poor form or storm damaged groups of trees, or poorly stocked stands with little likelihood of becoming well-stocked (Murphy et al. 1993). Area regulation, or harvesting and regenerating the same amount of acreage during each entry to achieve a sustained yield, is advised as a method to determine how many openings should be created throughout the stand during each cutting cycle in creating uneven-aged stands from even-aged stands (Murphy et al. 1993). Cutting should be made more frequently on better productivity sites (site index greater than 85 ft. at 50 years) and less often on poor to moderate sites (site index less than 65 ft. at 50 years) (Baker et al. 1996). Overall, group selection may be a beneficial regeneration method to establish pine-hardwood stands from periodic harvests leading to improved aesthetics, more varied wildlife habitat, and greater stand resiliency to disturbances and pathogens (Baker et al. 1996, Williston 1978).

The shade levels created by a partial harvest may have the added benefit of being conducive to the development of natural oak regeneration. White and chestnut oak are both intermediate shade tolerant species and would likely gain a competitive advantage in the shade conditions created by a partial harvest (Hardin et al. 2001). Even-aged methods such as shelterwood harvests that leave 50-70 percent of overstory trees may produce suitable light conditions for oak regeneration especially on poorer productivity sites (Johnson et al. 2009, Schweitzer et al. 2016). Release treatments such as prescribed burning in the spring season may increase the presence of oaks over less fire tolerant species, such as eastern white pine and reduce the germinative capacity of competitor species with epigeous germination such as yellow-poplar (Brose et al. 1999).

***Cluster Planting***

Cluster planting, also termed nest planting or group planting, though uncommon, is not a new artificial regeneration silvicultural technique. The technique was first proposed and studied in Europe by German and Polish foresters in the 1940s, 50s, and 60s (Saha et al. 2012). Cluster planting consists of small areas (typically less than 0.02 acre) that are planted with seedlings at close spacings to either increase stocking with many clusters planted per unit area or to introduce scattered, desirable regeneration to canopy gaps in disturbed stands on more productive microsites throughout a stand (Anderson 1951, Saha et al. 2012).  Cluster planting has many variations, which include planting pure species clusters or a mix of species that typically has at least one shade intolerant or intermediate species (e.g. oak) that will become the final crop tree and a shade tolerant species (e.g. beech (*Fagus* spp.) or Norway spruce (*Picea abies)*) that will act as a trainer tree to promote straight bole growth and pruning of lower limbs of preferred species. Clusters typically contain 3 to 30 trees per group and can be arranged at systematic spacings in favorable planting areas. An individual cluster planting arrangement is usually a symmetrical shape, such as a square or rectangle, but any arrangement that is financially practical for a site preparation, planting, and release can be used. Spacing among trees within a cluster are based on species' silvics and silvicultural objectives for the site. Narrow spacings of one foot can be used for a poor pruning species and/or slow growing species on poor productivity sites to reduce competition from naturally regenerating species. Wider spacings of three to four feet can be used for fast growing species that are good, natural pruners on more productive sites or to encourage growth of naturally regenerating species among the planted trees (Anderson 1951).

Cluster planting offers several advantages over standard area-wide grid plantings. Site preparation and release treatment costs are reduced, especially on steep, rough topography or in stands that have been recently harvested where logging slash is left in place. For instance, herbicide applied as a release treatment in cluster plantings can be completed with backpack sprayers with herbicide sprayed on specific plants within the cluster, whereas in large, evenly distributed, grid plantations spraying must be done systematically over the entire area, which is more costly and less specific from an application standpoint. Planting and thinning costs can be reduced by operations being limited to smaller specific areas within a stand instead of being conducted over the entire stand. Natural thinning also begins more quickly in cluster plantings than in grid plantations because of the tighter spacing. This hastens the emergence of dominance in better crop trees and the natural pruning process (Emmington and Entry 1991). Deer browse risk is decreased for seedlings planted in cluster patterns as compared to grid patterns (Carlson 1987). The possibility of natural regeneration and greater species diversity within (if the spacing is wide enough) and especially among clusters is more likely than in traditional grid style plantings and is often encouraged (Saha 2012). In addition, cluster planting may be more suited to conifers because of their stronger epinastic control than hardwoods which have a decurrent growth pattern (Emmington and Entry 1991, Pallardy 2008).

Cluster plantings can be established in cutover or disturbed stands as well as on cleared sites. Few studies in North America have investigated cluster planting in either situation. A study in Ontario by

Sutton (1974) reported satisfactory survival after a decade with white spruce (*Picea glauca)* cluster plantings in a high-graded mixed-woods stand. Planted species should have some shade tolerance to survive in these environments. Shortleaf pine is less intolerant during the seedling and sapling stages, becoming more intolerant with growth (Baker et al. 1996, Shelton 1995). In these situations, future survival and growth will depend primarily on the shading created by residual overstory trees adjacent to the cluster. Cluster plantings in areas without a residual overstory, such as a large clearcut have not been investigated in North America, but in Europe when crop tree species have been planted with trainer tree species these planting configurations have been successful with a variety of species (Anderson 1951).

***Literature Summary***

Mixed shortleaf pine-hardwood forests once covered vast acreages on upland sites throughout eastern North America, yet these forest types have been declining in area across most of their native range for the last 50 plus years because of unsuitable conditions for natural shortleaf pine regeneration. Stands that once had a mature shortleaf pine component now lack one necessitating the use of artificial regeneration to restore mixed stand compositions in areas presently occupied by mixed hardwoods. Unique characteristics of shortleaf pine such as its tolerance of periodic disturbance (e.g. sprouting ability), longevity, and tolerance of many soil types and environmental conditions permit a range of silvicultural practices and pathways to re-establish mixed shortleaf pine-hardwood forests. These potential practices have not been explored.

## Chapter 2: Objectives

The research objectives are to evaluate establishment and early development of mixed shortleaf pine-hardwood stands. Two approaches are investigated: (1) even-aged pine-hardwood establishment after a complete harvest with natural hardwood regeneration and systematic shortleaf pine planting at two wide spacings (12 x 12' and 18 x 18') at the University of Tennessee (UT) Highland Rim Forest near Tullahoma, TN, and (2) cluster planting of shortleaf pine in partially harvested hardwood stands with sparse stocking creating a two-age stand with the older residual hardwoods, regenerating hardwoods, and the planted pine clusters at the UT Cumberland Forest in Morgan County, Tennessee.

Hardwoods were prevalent and little to no shortleaf pine was present at either site prior to planting: this required planting of shortleaf pine. Five site preparation and release treatments were conducted at each study site. Burn treatments completed after planting were designed to determine if planted shortleaf pine sprouts could compete with natural hardwoods. At the Highland Rim Forest, even-aged study, the release treatments conducted were:

1. Post-planting broadcast burn only
2. Post-planting foliar herbicide release only
3. Post-planting broadcast burn and foliar herbicide release combination
4. Post-planting burn in cleared, linear strips between existing wooded areas
5. No treatment (control)

At the Cumberland Forest two–aged site, the treatments evaluated were:

1. Post-planting burn only

2. Pre-planting residual stump herbicide and post-planting spot foliar herbicide release only

3. Pre-planting residual stump herbicide treatment, post-planting burn and spot foliar herbicide release combination

4. Pre-planting scarification

5. No treatment (control)

Two distinct studies with two different approaches for creating mixed shortleaf pine-hardwood stands were examined in this research. The first approach investigated the effects of five site preparation and release treatments on shortleaf pine survival and growth three years post seedling planting at the UT Highland Rim Forest. At this site, even-aged cohorts of planted shortleaf pine and natural hardwood and pine regeneration were established. Natural regeneration composition, growth, and density response in association with planted shortleaf pine seedlings were considered as well.

The second approach studied five site preparation and release treatments and their effects on shortleaf pine survival and growth two years post planting at the UT Cumberland Forest. Four of the five release treatments were the same at this site, and a scarification treatment was substituted for the strip-burn treatment investigated at the Highland Rim Forest. At the Cumberland Forest site, some residual trees were left following a partial harvest creating a multi-age stand with the residual stems, the planted shortleaf pine within clusters, and natural hardwood regeneration. To address impacts of introducing planted shortleaf pine in these residual hardwood areas, the following aspects were examined:

1. Shortleaf pine survival and growth response to landform and environmental factors,
2. Hardwood regeneration composition, growth, and density response in association with planted shortleaf pine seedlings, and
3. Evaluation and comparison of hardwood composition and growth by location within cleared clusters and outside of clusters within the residual forest.

## Chapter 3: Methods-University of Tennessee Highland Rim Forest Site

### *Site Description*

The University of Tennessee Highland Rim Forest is a unit of the University of Tennessee Forest Resources Research and Education Center (FRREC) and is located in Estill Springs, Tennessee in northern Franklin County (35.31062° N -86.15089° W). The study area is on the Eastern Highland Rim physiographic province, which is characterized as weakly dissected plateau with red soils and by broad, nearly level to undulating ridges with some depressions and sinkholes. A dendritic drainage system is present, and many intermittent streams drain into sinkholes (Smalley 1983). Precipitation in the area averages 48-58 in. annually, and the mean air temperature is 57-59 degrees Fahrenheit (National Oceanic and Atmospheric Administration 2017).

Soils are silty and cherty and range from well-drained to poorly drained. They typically are 2-6 feet (ft.) deep overlying limestone residuum (Smalley 1983). The four soil types on the study site are Dickson silt loam 2 to 5 percent slopes; Dickson silt loam 2 to 5 percent slopes, eroded; Baxter cherty silt loam, rolling phase and undulating phase; and Greendale silt loam. The Dickson soils are classified as fine-silty, siliceous, semiactive, thermic, Glossic Fragiudults. Dickson soils are notable for the presence of a fragipan at a depth of 18-36 in. that limits water infiltration. Greendale soils are fine-loamy, siliceous, semiactive, mesic, Fluventic Dystrudepts. This soil type does not contain a fragipan or limiting feature for at least 80 inches. Baxter soils are classified as fine, mixed, semiactive, mesic Typic Paleudalfs (Web Soil Survey 2015). Site indexes for shortleaf pine, white oak, southern red oak, black oak, and northern red oak range from 70 to 76 feet on these four soil types at base age 50 years (Coile and Schumacher 1953, Olson 1959, Web Soil Survey 2015).

The study site at the Highland Rim Forest consists of four separate areas with little difference in vegetation productivity in terms of site index for upland oaks and yellow-pines (USDA NRCS 2016). The largest area that contains 17 of the 24 non-strip experimental unit treatments is approximately 35 acres with level topography except for an intermittent stream that flows from southwest to northeast separating experimental units 1-5 from 6-17 (Figure 1). The next largest area contains experimental units 18-24 and

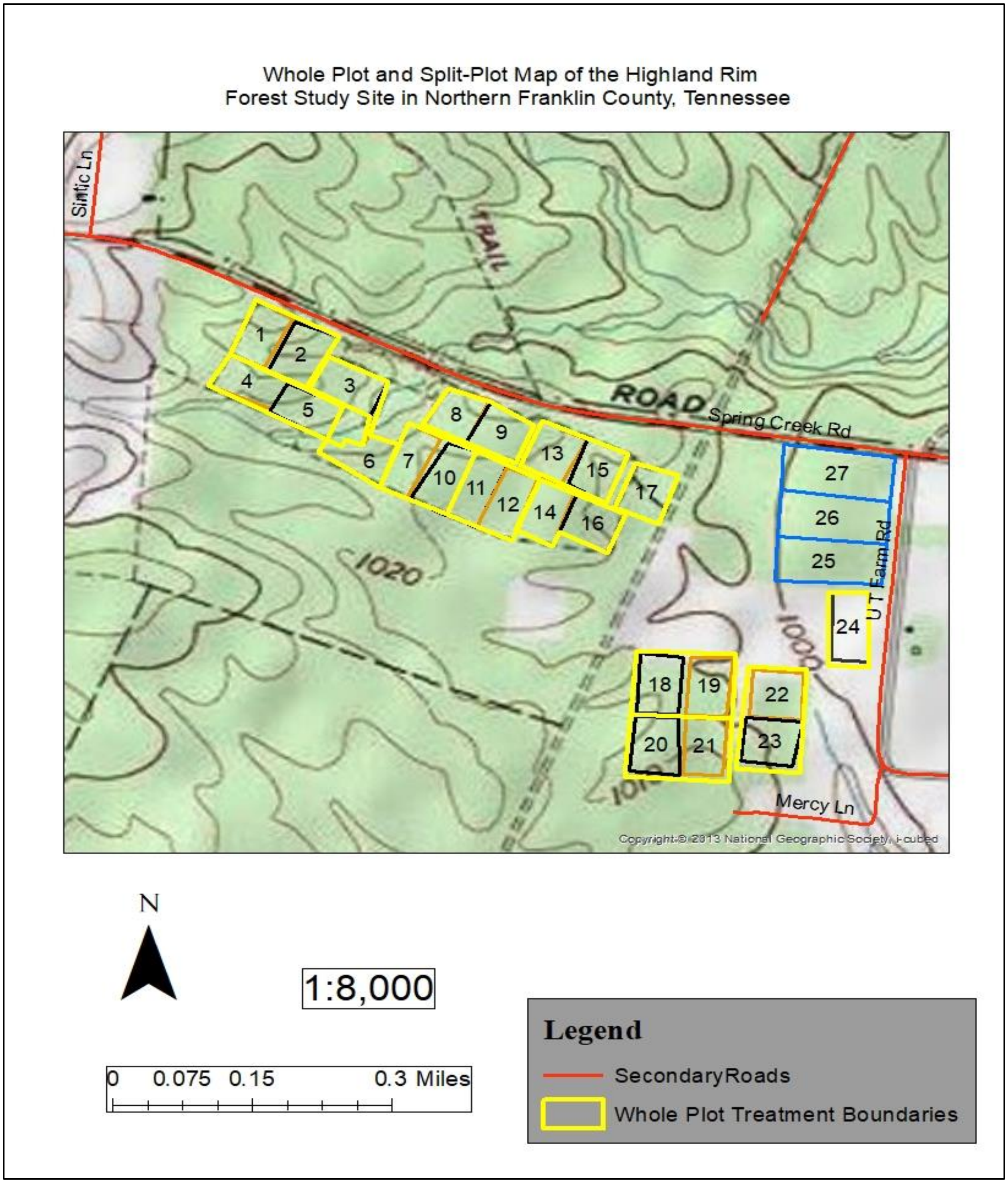


Figure 1. Map depicting the experimental unit layout of the Highland Rim Forest study site in northern Franklin County, Tennessee. Experimental units with an orange outline denote the 12x12 ft. spacing. The black outline denotes the 18x18 ft. spacing and the blue outline the strip-burn treatment, which has both tree spacings in an experimental unit.

is approximately 15 acres, excluding a strip of planted loblolly pine that separates units 18-21 from units 22-24 (Figure 1). This area does not include any of the strip treatment experimental units, and topography is homogenous across this area. The last area contains all five of the strip treatment experimental units and is approximately 10.2 acres. Topography was homogenous across this area.

In 1965, a planted pine spacing and species growth and yield study was established on the area of the study where experimental units 1-17 are located (Figure 1). Prior to study establishment, the area consisted of hardwoods, which were clearcut followed by injection of cull hardwoods with 2,4-D and mist-blowing of herbaceous vegetation with 2,4,5-T . The objectives of this prior study were to examine and compare basal area per acre, volume production per acre, and value per acre among four pine species planted at four spacings. Loblolly pine, shortleaf pine, Virginia pine (*Pinus virginiana* Mill.), and eastern white pine (*Pinus strobus* L.) were planted at 6 x 6, 9 x 9, 12 x 12, and 15 x 15 ft. spacings (Schubert 2001). The southern pine (*Dendroctonus frontalis*) beetle outbreak that occurred from 1999 to 2001 in Tennessee (Cassidy 2004) caused significant mortality to all species and the site was salvage harvested in 2005-2006. Vegetation on all three sites prior to the present study establishment was 8 to 12-year-old thickets primarily comprised of loblolly pine, Chinese privet (*Ligustrum sinense* Lour.), callery pear (*Pyrus calleryana* Decne.), black cherry (*Prunus serotina* Ehrh.), white poplar (*Populus alba* L.), red maple, *Rubus* spp., devil's walking stick (*Aralia spinosa* L.), and upland white and red oaks that ranged from 10 to 25 ft. tall. No management had occurred on these sites for at least eight years before the present study was initiated.

***Study Establishment and Treatment Implementation***

The first site preparation burn of each area was conducted on November 14, 2013 in an attempt to topkill the existing vegetation for drum chopping mechanical treatments. All areas of the study were ignited in a ring pattern. This burn was most effective in the east end of the large block containing experimental units 1-17 (Figure 1). The five strips in the strip-plot area were surveyed and flagged in early December 2013. Each planted strip was approximately 80 ft. wide and 840 ft. long with 30 to 40 ft.

wide residual vegetation buffers between the cleared strips. All planting areas were drum-chopped with at least one pass during January, February, or March of 2014 with a drum chopper obtained from Arnold Air Force Base and pulled with a bulldozer provided by the Tennessee Department of Agriculture, Division of Forestry (TDF). After drum-chopping was completed, site preparation burns ignited as spot burns were completed on March 31, 2014 and April 1, 2014 on all five areas as needed to facilitate planting. Pin flags were used to mark the tree spacing around the perimeter of each block from April 2, 2014 to April 9, 2014. Bareroot 1-0 stock shortleaf pine seedlings purchased from the Tennessee Division of Forestry state nursery (Arkansas seed provenance) were planted on April 8$^{th}$ and 9$^{th}$ 2014 at 12x12 feet and 18x18 ft. spacings. Randomly located individual seedling survival checks were completed on June 11, 12, 17, and 18$^{th}$ 2014. Initial survival checks ranged from 65 to 84% for all treatments.

Herbicide treatments for the herbicide and herbicide and burn treatments were completed on July 31st and August 7$^{th}$ 2014. Herbicide solutions were applied using Stihl® SR 450 and SR 200 mist-blowers with the nozzle output setting on medium flow. The SR 450 mistblower was used to provide the most coverage in each block due to its greater brake horsepower (3.9 bhp versus 1.1 bhp), tank capacity (3.7 versus 2.1 gallons), and maximum horizontal spray distance (48 ft. versus 29.5 ft.) as compared to the SR 200 mistblower. Herbicide mixtures in the SR 450 mistblower applied to all herbicide and herbicide and burn experimental units consisted of 7.5 ounces isopropylamine salt of imazapyr (Arsenal®), 2/3 ounce of granular metsulfuron methyl (Escort®), 1 ounce non-ionic surfactant, and 3.17 gallons (12 liters) of water. Herbicide mixtures in the SR 200 mistblower used on all herbicide and herbicide and burn experimental units consisted of 6 ounces isopropylamine salt of imazapyr (Arsenal®), 1/2 ounce of granular metsulfuron methyl (Escort®), 1 ounce non-ionic surfactant, and 2.1 gallons (8 liters) of water. Experimental units 1 and 2 (herbicide treatment) had high densities of white poplar (*Populus alba*), thus the rate of Arsenal® used was increased 1.5 ounces per tank (Figure 1). In addition, experimental unit 22 (herbicide treatment) received a backpack sprayer application only on the northern ¼ of the unit due to mistblower malfunctions. Two 3 gallon tanks were used in this section of unit 22. The remainder of the unit received mistblower application (Figure 1 and Table 2). Solution amounts for each experimental treatment are given in Table 2.

Herbicides used for release treatments were selected based on recommendations from Yeiser (2012) and loblolly and shortleaf pine herbicide release methods used by the U.S. Forest Service on the Poor and Good Farm Forties at the Crossett Experimental Forest in Crossett, Arkansas (Guldin and Bragg 2016). In addition, this herbicide mixture has proven to be the least detrimental to planted pine seedlings compared to other herbicides tested for pine release from woody and herbaceous vegetation (Miller 1990).

Table 2. Herbicide solution amounts applied in 2014 and 2015 for each herbicide and brown-and-burn experimental unit for the University of Tennessee Highland Rim Forest. Arsenal® amounts per tank were increased in 2015. Deviations from these mixtures are noted in the footnotes.

| Treatment | Spacing (ft.) | Number of Seedlings | Figure 1 Map Unit(s) | Number of Passes SR 450 | Number of Passes SR 200 | Total Herbicide solution Used SR 450 (L) | Total Herbicide Solution Used SR 200 (L) | Total Herbicide Solution used (L) |
|---|---|---|---|---|---|---|---|---|
| Herbicide[a] | 12x12 and 18x18 | 630+315=945 | 1 and 2 | 3 | 3 | 33 | 24 | 57 |
| Herbicide and Burn | 18x18 | 308 | 3 | 2 | 1 | 22 | 8 | 30 |
| Herbicide and Burn | 12x12 | 600 | 6 | 4 | 3 | 22 | 8 | 30 |
| Herbicide and Burn | 12x12 and 18x18 | 630+275=905 | 7 and 10 | 4 | 3 | 36 | 24 | 60 |
| Herbicide and Burn | 12x12 and 18x18 | 648+270=918 | 14 and 16 | 4 | 3 | 36 | 24 | 60 |
| Herbicide | 12x12 | 624 | 17 | 3 | 1 | 18 | 8 | 26 |
| Herbicide | 18x18 | 300 | 24 | 3 | 3 | 12 | 16 | 28 |
| Herbicide[b] | 12x12 and 18x18 | 650+306=956 | 22 and 23 | 4 | 3 | 24 | 16 | 40 |

[a]-The Arsenal® amount used per tank was increased by 1.5 ounces for both mistblowers.

[b]-The northern ¼ of experimental unit 22 (12x12 ft spacing) was treated with backpack sprayers in 2014. A three gallon backpack sprayer was used to disperse six gallons of herbicide solution. The backpack sprayer used the same herbicide mixture that was used in the SR 450 mistblower.

Another herbicide release application was applied the next year on August 10, 2015. This application was completed because of inadequate suppression of woody vegetation. Conservative herbicide rates were applied per acre the previous year to avoid reductions in height growth. The Arsenal® herbicide label does not recommend a conifer release application before the end of the second growing season (BASF Corporation 2010). The same mistblowers were used with the same number of passes in each experimental unit(s), but Arsenal® herbicide rates were increased from 7.5 ounces the previous year to 10 ounces per 3.17 gallons in the SR 450 mistblower, and from 6 ounces to 8 ounces per 2.1 gallons of solution in the SR 200 mistblower. Amounts of Escort® and non-ionic surfactant were kept constant.

The three treatments that were scheduled to receive burns were inventoried for woody fuel loads during March 2015 and February 2016 to compare before and after burn fuel loads and obtain an indication of burn intensity and coverage. The burn, brown-and-burn, and strip-burn treatments were inventoried using the planar intersect method outlined in Brown (1974). Two 35 ft. transects per experimental unit, one per tree spacing, were taken. Transects were established on a random azimuth from a point that was two chains from the southeast corner of each experimental unit. This point was permanently marked with rebar and a point was taken with a GPS unit so that post-burn transects could be established. One hour (0-0.25 in.) and 10-hour fuel (0.25-1 in.) intersections along the transect were extended six feet. One-hundred hour fuels (1-3 in.) were recorded to ten feet, and sound and rotten 1000-hour fuels (greater than or equal to 3 in.) were extended to 35 feet. Specific gravities for woody material in the South region were acquired from Anderson (1978), while all other formula constants were obtained for one-year-old slash in Brown (1974).

Burn treatments at the Highland Rim Forest were completed on November 13 and 15th 2015. Weather conditions for these days are presented in Table 3. Contiguous areas that required a burn were initiated in a ring pattern around the experimental unit perimeter. If the fire did not carry throughout the unit, then strips were ignited as needed within the interior of the area. Strip-firing was also conducted in both the cleared strips and the residual vegetation of the strip-burn treatment to ensure burn coverage where needed. The larger size of the strip block area compared to the other burn experimental units (10.2

acres versus 1.6 to 2.1 acres) and the older, larger vegetation in the leave strips provided more shade resulting in less fuel drying and greater relative humidity than burned units in the open (units 1-17).

Table 3. Weather conditions are presented for the two days that treatment burns were applied at the University of Tennessee Highland Rim Forest.

| | | | |
|---|---|---|---|
| Date: 11/13/2015 | Time: 1:15-5:00 PM | | |
| Temperature Range (°F) | Relative Humidity Range (%) | Wind Speed Range (mph) | Wind Direction Range |
| 55-57 | 20-25 | 8.1-13.8 | N-NNW |
| Date: 11/15/2015 | Time: 1:15-5:00 PM | | |
| Temperature Range (°F) | Relative Humidity Range (%) | Wind Speed Range (mph) | Wind Direction Range |
| 57-60 | 20-31 | 2.0-12.0 | S-SE |

***Measurements and Sampling Procedures***

Global positioning system (GPS) points were collected with a Garmin handheld unit on November 21st and 22nd 2015 at all plot corners of the 24 area based plots in the study site. Numbers of planted seedling rows and columns were also counted on each plot to create the sampling grid. Data were entered into Microsoft Excel, and converted to UTM coordinates before importing the points into ArcGIS. Once the points were entered into ArcGIS, polygons were drawn around each of the 24 non-strip-plot experimental units. The fishnet tool in ArcGIS was then used to create grids based on the number of seedlings in a row and a column, and the area of each experimental unit was determined using the calculate geometry tool. A random number generator in Microsoft Excel was used to pick grid intersections in each experimental unit where a circular 1/300th (6.8 ft. plot radius) acre natural regeneration plot (ideally centered on a shortleaf pine seedling) and planted shortleaf pine were sampled using a different protocol based on plot spacing. The 12x12 ft. spacing was sampled at the center shortleaf pine seedling (if present) and at 24' ± 6' in. each cardinal direction so that if all planted shortleaf pine seedlings were alive on a plot, nine trees would be measured. The six foot sampling error for the location of each seedling was used to allow for variation in planting spacing during study establishment. The 18x18 ft. spacing was sampled at the center seedling (if present) and at 18 ft. ± 6 ft. in each cardinal direction so that if all planted shortleaf pine seedlings were alive on a plot, five trees would be measured. All shortleaf pine seedlings were measured to the nearest quarter inch for height to the tip of the central leeder and basal diameter to the nearest hundredth of an inch. Plots were centered at a piece of rebar used to permanently mark the plot for future measurements, and then a GPS unit was used to note the plot's coordinates. The number of sampling plots in each experimental unit depended on the acreage of the experimental unit with the smallest of the non-strip-plot units being 1.76 acres (9 plots of each type) and the largest 2.06 acres (11 plots of each type). The sampling intensity for natural regeneration in each experimental unit was approximately 5% and the shortleaf pine sampling intensity was roughly 25%. Figures 2-5 display the locations of sample plots and the natural regeneration and planted shortleaf pine plot radii within these experimental units.

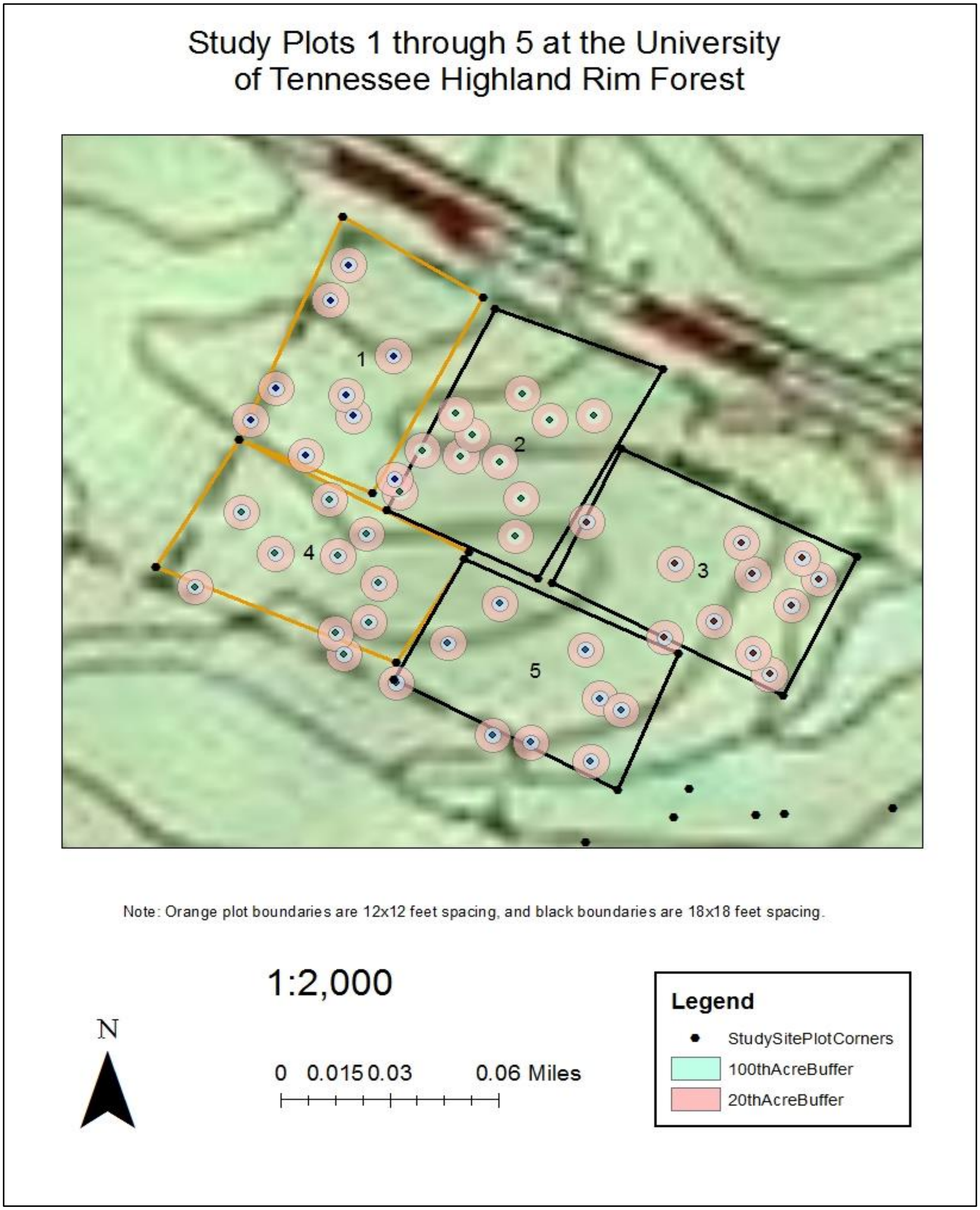


Figure 2. Sampling plot layout for experimental units 1 through 5 at the University of Tennessee Highland Rim Forest.

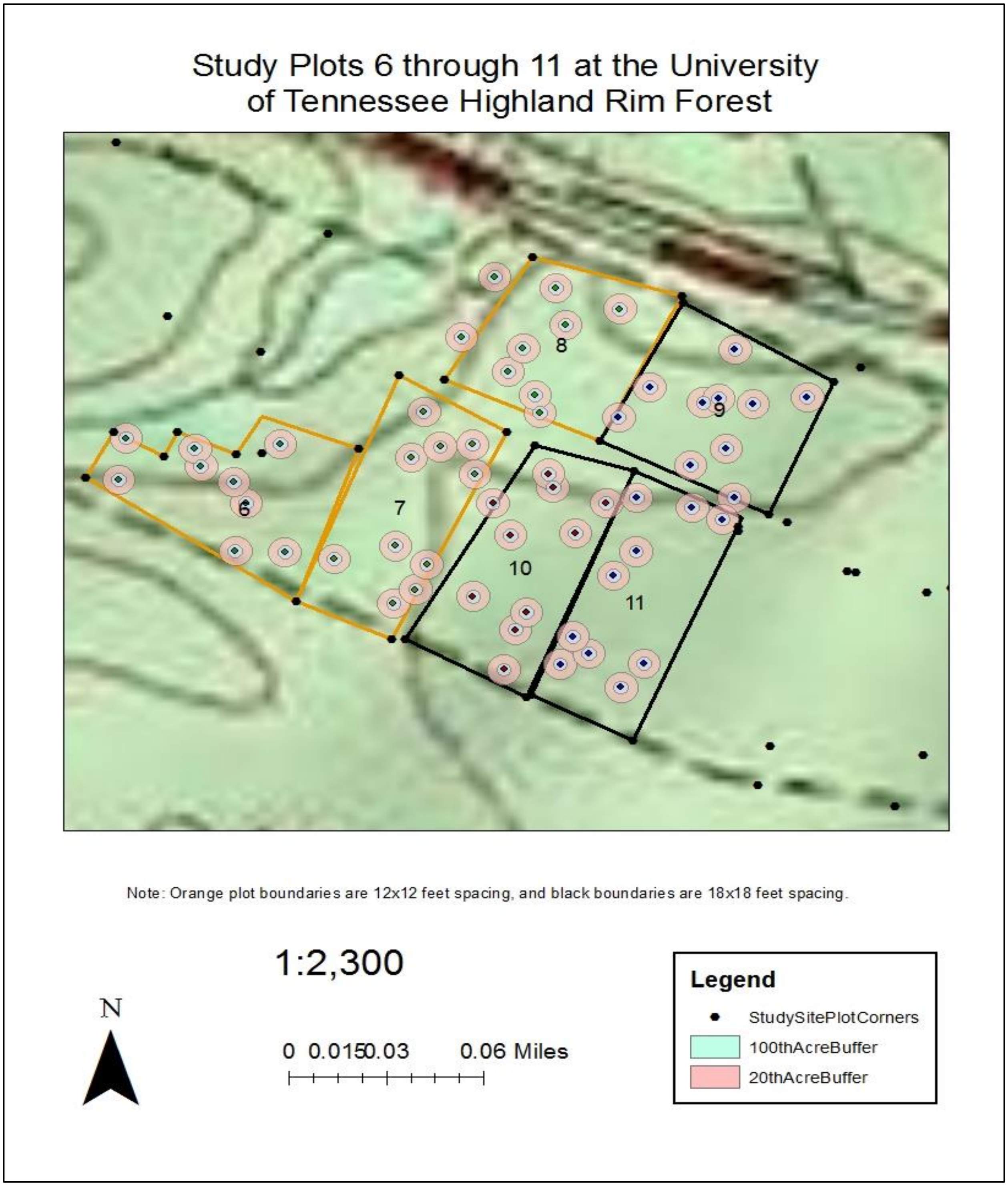


Figure 3. Sampling plot layout for experimental units 6 through 11 at the University of Tennessee Highland Rim Forest. Experimental unit 8 GPS corners were incorrect on the southwest and northwest corners resulting in plots appearing beyond the boundary line of the unit.


Figure 4. Sampling plot layout for experimental units 12 through 17 at the University of Tennessee Highland Rim Forest.

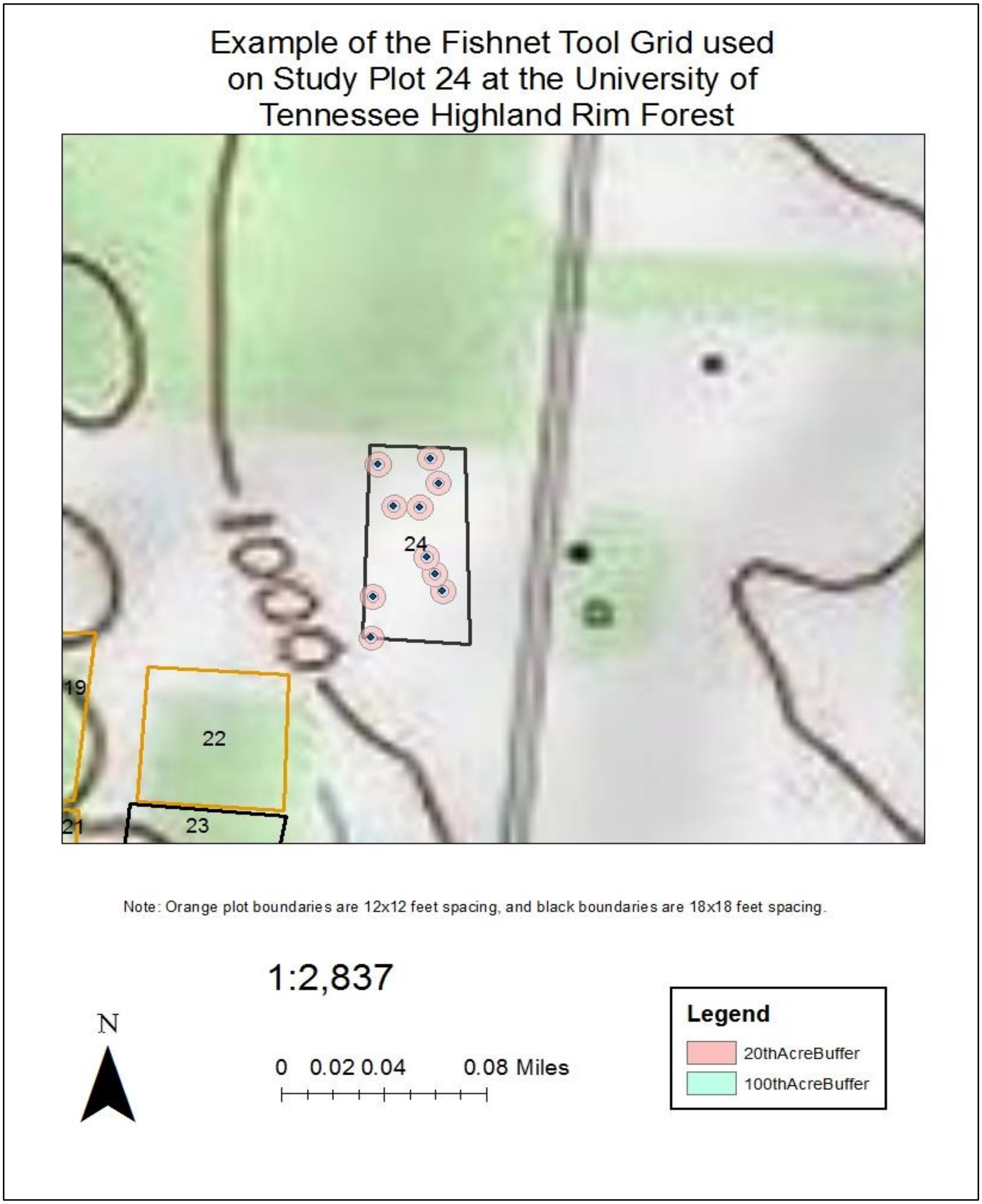


Figure 5. Sampling plot layout for experimental unit 24 at the University of Tennessee Highland Rim Forest.

Measured shortleaf pine seedling variables included: survival (assuming 100% survival, there should be five seedlings per sampling plot in 18x18 ft. experimental units and nine seedlings per sampling plot in 12x12 ft. experimental units with 9 to 11 sampling plots per experimental unit), height, and basal diameter. All stems in n the 1/300$^{th}$ acre natural regeneration plots were identified to species, and tallied to one of eight specific six inch height classes (6-12", 12.1-18", 18.1-24", 24.1-30", 30.1-36", 36.1-42", 42.1-48", and 48+").

The strip-plots were sampled differently because their layout was different than the other experimental units in the study (Figure 6). One planted shortleaf pine column within each of the ten subplots (five at 18x18 ft. spacing and five at 12x12 ft. spacing) subplots within a block were sampled for the same variables as the other treatments. For an 18x18 ft. spacing transect, if all seedlings survived, seven trees could be assessed, whereas on a 12x12 ft. planting spacing, ten trees could potentially be assessed. At each planted shortleaf pine tree, a circular 1/300$^{th}$ acre natural regeneration sampling plot was established. The same woody regeneration variables were then measured as in the other treatments in the study.

***Statistical Analyses***

Measurements of planted seedlings and natural hardwoods were completed during the winter and early spring of 2017 three growing seasons after planting. Analysis of variance (ANOVA) was used to test for treatment and planting spacing differences using mixed models (Proc Mixed, SAS 9.4) (Littell et. al 1996) as a completely random design with sampling and a split-plot treatment design (18x18 ft. and 12x12 ft. spacing) for shortleaf pine basal diameter and height. A completely random design with sampling was used to test for treatment differences in natural regeneration density and height. Two pine planting spacings (18x18 ft. and 12x12 ft.) were not compared for natural regeneration due to an expected lack of statistical differences in the young stand. Shortleaf pine seedling survival treatment and spacing effects were tested with Proc Glimmix using the binomial distribution. Height and basal diamteter data were tested for normality using the Shapiro-Wilk test (Littell et al. 1996). Least squares means were separated using Fisher's least significant difference and an alpha level of p=0.05. The basal diameter

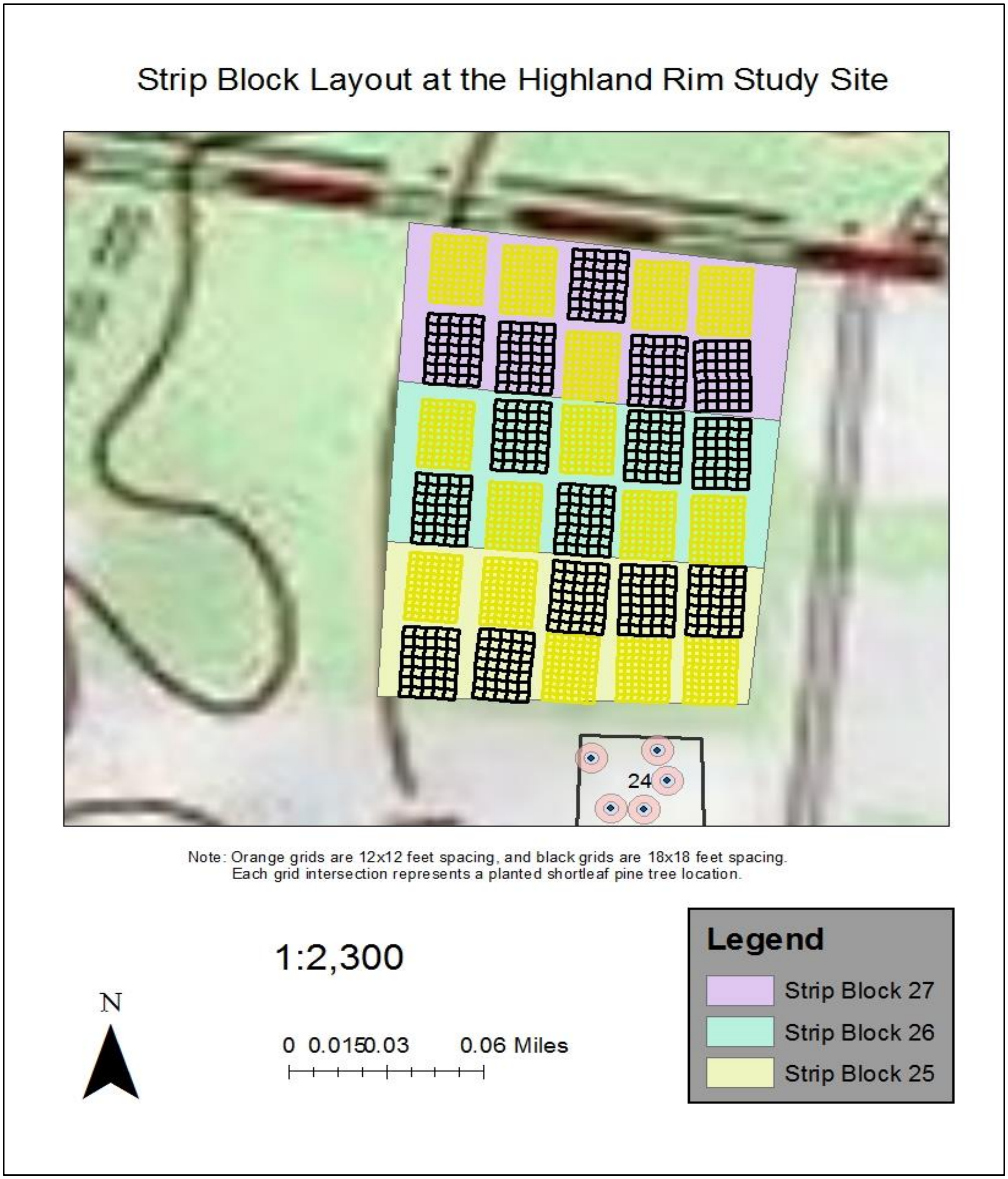


Figure 6. Layout of the strip-burn treatment blocks at the Highland Rim study site is presented. The 18x18 ft. sub-plots contain 7 rows and 5 columns. The 12x12 ft. sub-plots contain 10 rows and 7 columns.

variable was transformed using the log transformation to correct skewness. The natural regeneration density variable was transformed using a square root transformation to correct skewness. Untransformed means and standard errors are reported. Natural regeneration percent composition was reported by treatment. All woody fuel sizes were combined for a tons per acre fuel load for data analysis using analysis of variance as a completely random design with a split-plot treatment design in SAS version 9.4 (SAS Institute 2012). Least squares means were separated using Fisher's least significant difference and an alpha level of $p=0.05$.

## Chapter 4: Methods-University of Tennessee Cumberland Forest Site

### *Site Description*

The south unit of the University of Tennessee Cumberland Forest, a unit of the FRREC, is in Morgan County, Tennessee at the southern terminus of the Cumberland Mountains. The study site is located on Little Brushy Mountain at 36.05376° N -84.43563° W. This area is characterized by Smalley (1984) as the Thrust Block Interior, Wartburg Basin, and Jellico Mountains region of the Cumberland Mountains. Little Brushy Mountain is a smaller extension of Big Brushy Mountain to the North and the Wartburg Basin to the northwest. The Wartburg Basin is delineated by the Jacksboro Fault to the northeast, the Cumberland Plateau to the west and northwest, and Walden's Ridge on the southeast. Bedrock in this area consists of strata that contain shales, siltstones, and coal (Wilson et al. 1956). Relief in the Wartburg Basin averages 1,800 ft., and slopes range from 20 to 60 percent (Smalley 1984).

Three soil types dominate the site in this area: Gilpin-Boulin-Petros Complex, 25 to 80 percent slopes, very stony; Shelocta silt loam, 12-20 percent slopes; and Lily-Gilpin Complex, 20 to 35 percent slopes. The Gilpin component of the complex is a silt loam, is well-drained, and occurs at the center-third of the mountain slope. The Bouldin component is a very bouldery, fine, sandy loam, is well-drained, and occurs on the lower third of the mountain slope. The Petros component is a channery silt loam, is well-drained, and occurs on the upper third of the mountain slope. The Shelocta silt loam, 12-20 percent slopes, is well-drained and typically is more than 80 in. to a restrictive feature. The Lily-Gilpan complex, 20-35 percent slopes is a loam or clay loam, is well-drained, and is anywhere from 20 to 40 in. to lithic bedrock (Web Soil Survey 2015). Site indices for these soils differ by species. Black oak has a site index of 60 ft. at base age 50 years, whereas white oak has a site index of 75 ft. at base age 50 years as reported by Olson (1959). Yellow-poplar has the highest site index on these sites at 90 ft. for base age 50 years (Beck 1962).

The study site consists of all aspects with west and northwest slopes the most prevalent. Slopes on the mountain range from 1-86%. Four intermittent streams develop on the middle third of the mountain and flow westward towards Tennessee Highway 62 and into the Middle fork of the Little

Emory River, which is a tributary of the Emory River. Rainfall in the area averages from 48-61 in. annually, while the mean temperature ranges from 41-67 degrees Fahrenheit (National Oceanic and Atmospheric Administration 2017).

The vegetation pre-harvest consisted of a two-aged mixed hardwood stand. The older age cohort was 150-190 years, whereas the younger age cohort was 60-80 years. The primary dominant and codominant trees on west and northwest aspects and the lower two-thirds of the mountain consisted primarily of chestnut oak, red maple, and white oak. Dominant and codominant species composition shifted on the upper third of the mountain where many different aspects were present. Chestnut oak was still common, while white oak, black oak, hickories, and northern red oak became more prevalent. Throughout most of the study site, midstory and regenerating species consisted primarily of red maple, eastern white pine, sourwood (*Oxydendrum arboreum* L.), and mountain laurel (*Kalmia latifolia* L.). A few, large shortleaf pine trees were present at all different aspects and slope positions throughout the site. In total, there were 12 mature shortleaf pines spread throughout the 76 acre study site. Many identifiable stumps, logs, and snags, as well as small pockets of advanced shortleaf pine regeneration were evident across the site. Most mature shortleaf pine stems throughout the region and most of Tennessee (55 of 95 counties) experienced a severe southern pine beetle outbreak from 1999-2001 (Cassidy 2004). The forests on the study site reflect the major shift from softwood and softwood-hardwood dominated stands to stands with higher proportions of oaks, maples, and poplars as has been observed throughout the state by Oswalt et al. (2016).

***Study Establishment and Treatment Implementation***

Blocks were mapped and marked during the winter of 2014. Experimental units (denoted as a number i.e. 1, 2, 3, 4, or 5) were laid out in three blocks (denoted as a letter, i.e. A, B, or C) that were divided based on slope position with the experimental unit areas oriented perpendicular to the slope (Figure 7). Block A was located on lower slopes from approximately 1,280 to 1,380 ft. elevation, block

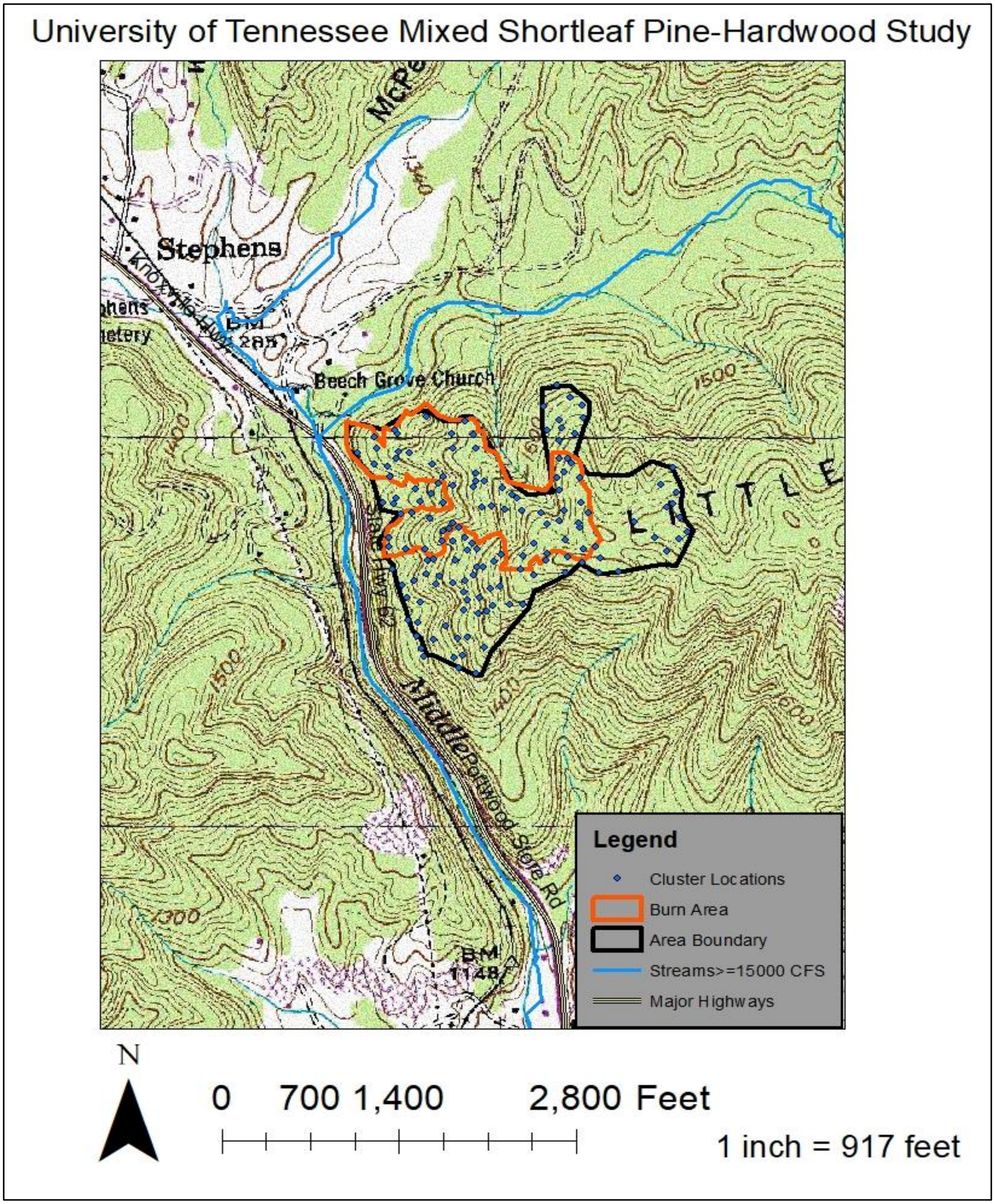


Figure 7. Cluster locations by repetition, block, and plot number at the University of Tennessee Cumberland Forest. The burn treatments area is added for reference. The background map is a 20 ft. contour topographic map.

B was located along the middle elevations of the mountain from 1,280 to 1,670 ft. elevation, and block C was located at the highest elevations of the mountain from 1,670 to 1,840 ft. elevation. On the lower slopes, the five experimental units (each with 10 clusters each in an area of approximately four acres) were established with drainages as natural boundaries. For the upper two blocks, blocks were oriented so that they would fit within the timber sale boundary and to avoid possible streamside management areas. Pre-harvest retention tree marking began on June 3, 2014 and was finished by June 10, 2014. Retention trees were kept as the older age class to maintain two age classes with gaps for regeneration. Across the entire 76-acre study area, retention trees were selected based on size and species. The amount of marked overstory retention tree basal area ranged from 14 to 25 $ft^2$ $ac^{-1}$ across blocks. In most blocks, if retention trees were plentiful enough to achieve the desired 15 to 20 $ft^2$ $ac^{-1}$ of basal area, only oaks, hickories, and sourwood were selected as retention trees. On blocks with fewer desirable species retention tree candidates, downy serviceberry (*Amelanchier arborea*.), eastern hemlock (*Tsuga candensis*), eastern white pine, and in rare instances, red maple were selected and marked as overstory retention trees. All retention trees that were marked, unless they were large, non-merchantable wolf trees in difficult to access areas, were less than 14 in. diameter at breast height (dbh) and greater than or equal to two in. dbh.

Logging commenced on the site on October 1, 2014. All logging was completed by Broughton Logging Company from Harlan, Kentucky. Operations were completed by April 6, 2015. The timber was sold to R&R Lumber in nearby Coalfield, Tennessee. Prior to harvest, the site averaged 7,100 board feet/acre of sawtimber (Doyle form class 78 and 80). This inventory was based on a combination of a complete tally cruise and a variable radius plot cruise conducted at two different times. After harvest, the area averaged 1,550 ± 359 SE board feet per acre of sawtimber (Doyle form class 78 and 80). This estimate was based on a variable radius plot cruise. Post-harvest pulpwood tallies included all trees 4 to 14 in. dbh and residual cull trees larger than 14 in. dbh. Green tree weight equations to a four inch diameter outside bark upper height were acquired from Clark III et al. (1986) and McNab and Clark III (1982). There was an average of 20.6 tons of pulpwood size stems per acre after harvest.

One-hundred fifty shortleaf pine clusters were established on the site following the conclusion of logging activities (Figure 7). Clusters were square grids measuring 28 x 28 ft. with shortleaf pine seedlings planted at a 4x4 ft. spacing (64 trees per cluster). Ten clusters were established within each experimental unit (50 per block) from January 12 to April 6, 2015 (150 total). A GPS point of each cluster was taken, and a piece of rebar was used to mark the most southwestern corner of each cluster. All trees or shrubs within a cluster greater than 3 ft. tall were identified to species and diameter was measured to the nearest one-inch class. These stems were then cut using a chainsaw and most woody debris was removed from a cluster to facilitate planting. The number of stems after harvest but before cluster establishment by species and treatment are presented in Table 4. Red maple was the most frequently occurring species within clusters across all treatments. The number of felled stems that were not harvested by the loggers are presented by DBH class and treatment in Table 5. The number of stems that were harvested by the loggers are presented by stump diameter and treatment in Table 6. In addition, large stems outside of but near a cluster boundary that blocked or partially blocked overstory light from southerly directions were felled or girdled. The amount of residual overstory basal area around clusters was assessed in the summer following harvest. A 10-factor prism was used to determine basal area and the number of stems 2 in. dbh and greater at a point 35 feet from two opposite corners of each cluster. These data were analyzed as a randomized complete block design with sampling. The control treatment had the greatest residual basal area around clusters at 80.8 $ft^2\ ac^{-1}$ whereas the scarification treatment had the lowest at 52.1 $ft^2\ ac^{-1}$ (Figure 8).

Table 4. Number of stems by species and treatment surveyed within clusters after harvest but before cluster establishment at the University of Tennessee Cumberland Forest. Tallies includes all stems greater than three ft. tall.

| | Treatment | | | | |
|---|---|---|---|---|---|
| Species | Brown-and-Burn | Burn | Brown | Control | Scarify |
| American Chestnut | 0 | 1 | 0 | 0 | 0 |
| American Holly | 6 | 3 | 2 | 3 | 3 |
| American Beech | 14 | 10 | 1 | 4 | 2 |
| Buffalo Nut | 8 | 2 | 0 | 12 | 12 |
| Blackgum | 63 | 25 | 17 | 5 | 8 |
| Black Oak | 7 | 2 | 2 | 2 | 8 |
| Black Cherry | 5 | 18 | 27 | 22 | 5 |
| Chestnut Oak | 25 | 26 | 79 | 165 | 44 |
| Cucumber Magnolia | 3 | 12 | 4 | 11 | 5 |
| Deerberry | 62 | 52 | 70 | 32 | 34 |
| Downy Serviceberry | 0 | 3 | 3 | 2 | 0 |
| Eastern Hemlock | 0 | 1 | 0 | 2 | 2 |
| Eastern White Pine | 72 | 49 | 65 | 75 | 52 |
| Hickory spp. | 5 | 8 | 10 | 2 | 6 |
| Mapleleaf Viburnum | 3 | 55 | 0 | 1 | 2 |
| Miscellaneous spp. | 2 | 13 | 0 | 0 | 0 |
| Mountain Laurel | 38 | 107 | 9 | 134 | 32 |
| Northern Red Oak | 0 | 2 | 0 | 3 | 0 |
| Red Maple | 256 | 246 | 350 | 267 | 89 |
| Sassafras | 135 | 76 | 121 | 91 | 18 |
| Scarlet Oak | 1 | 1 | 0 | 0 | 0 |
| Shortleaf Pine | 2 | 0 | 10 | 9 | 0 |
| Sourwood | 12 | 27 | 17 | 47 | 4 |
| Southern Red Oak | 7 | 3 | 2 | 0 | 0 |
| Striped Maple | 3 | 6 | 0 | 5 | 2 |
| Sweetgum | 1 | 2 | 1 | 5 | 2 |
| White Oak | 13 | 3 | 11 | 1 | 3 |
| Yellow-Poplar | 20 | 12 | 52 | 25 | 11 |
| Totals | 782 | 803 | 947 | 1097 | 395 |

Table 5. Number of stems by diameter class and treatment felled within clusters after logging operations were completed at the University of Tennessee Cumberland Forest. The smallest size class includes stems shorter than dbh height (4.5 feet).

| | Treatment | | | | |
|---|---|---|---|---|---|
| Size Class (in.) | Brown-and-Burn | Burn | Brown | Control | Scarify |
| <1 | 451 | 555 | 646 | 828 | 200 |
| 1 | 93 | 59 | 132 | 87 | 47 |
| 2 | 64 | 51 | 42 | 41 | 15 |
| 3 | 39 | 38 | 26 | 27 | 5 |
| 4 | 33 | 25 | 20 | 23 | 11 |
| 5 | 15 | 17 | 18 | 13 | 9 |
| 6 | 14 | 13 | 12 | 14 | 7 |
| 7 | 5 | 9 | 9 | 7 | 3 |
| 8 | 5 | 9 | 9 | 7 | 3 |
| 9 | 3 | 0 | 2 | 6 | 2 |
| 10 | 4 | 1 | 1 | 2 | 1 |
| 11 | 3 | 4 | 4 | 4 | 1 |
| 12 | 7 | 0 | 1 | 3 | 2 |
| 13 | 1 | 1 | 3 | 2 | 0 |
| 14 | 4 | 2 | 1 | 0 | 2 |
| 15 | 0 | 0 | 0 | 0 | 1 |
| 17 | 0 | 1 | 0 | 0 | 0 |
| 22 | 1 | 0 | 0 | 0 | 0 |
| Totals | 742 | 785 | 926 | 1064 | 309 |

Table 6. Number of harvested stems within clusters by stump diameter class and treatment at the University of Tennessee Cumberland Forest.

| | Treatment | | | | |
|---|---|---|---|---|---|
| Size Class (in.) | Brown-and-Burn | Burn | Brown | Control | Scarify |
| 1 | 0 | 0 | 1 | 0 | 3 |
| 2 | 0 | 1 | 3 | 0 | 3 |
| 3 | 3 | 1 | 2 | 1 | 2 |
| 4 | 3 | 0 | 0 | 3 | 2 |
| 5 | 0 | 1 | 1 | 2 | 2 |
| 6 | 0 | 1 | 1 | 1 | 0 |
| 8 | 2 | 0 | 0 | 5 | 1 |
| 9 | 3 | 0 | 2 | 1 | 2 |
| 11 | 1 | 0 | 0 | 1 | 0 |
| 12 | 1 | 0 | 0 | 1 | 0 |
| 13 | 0 | 0 | 0 | 1 | 0 |
| 14 | 0 | 0 | 1 | 0 | 0 |
| 15 | 2 | 0 | 0 | 0 | 0 |
| 18 | 1 | 0 | 0 | 0 | 0 |
| 20 | 1 | 0 | 0 | 0 | 0 |
| 21 | 2 | 0 | 1 | 0 | 0 |
| 23 | 5 | 2 | 0 | 1 | 2 |
| 24 | 1 | 3 | 1 | 3 | 0 |
| 25 | 0 | 2 | 1 | 2 | 4 |
| 26 | 1 | 1 | 2 | 1 | 3 |
| 27 | 2 | 3 | 0 | 3 | 0 |
| 28 | 3 | 1 | 3 | 0 | 2 |
| 29 | 0 | 1 | 3 | 1 | 1 |
| 30 | 3 | 0 | 1 | 1 | 2 |
| 31 | 1 | 0 | 1 | 1 | 0 |
| 32 | 1 | 1 | 1 | 0 | 0 |
| 33 | 1 | 0 | 0 | 0 | 1 |
| 34 | 1 | 1 | 1 | 1 | 1 |
| 35 | 0 | 1 | 0 | 0 | 1 |
| 36 | 1 | 2 | 0 | 0 | 2 |
| 37 | 0 | 2 | 0 | 0 | 2 |
| 38 | 0 | 0 | 1 | 0 | 0 |
| Totals | 39 | 24 | 27 | 31 | 37 |

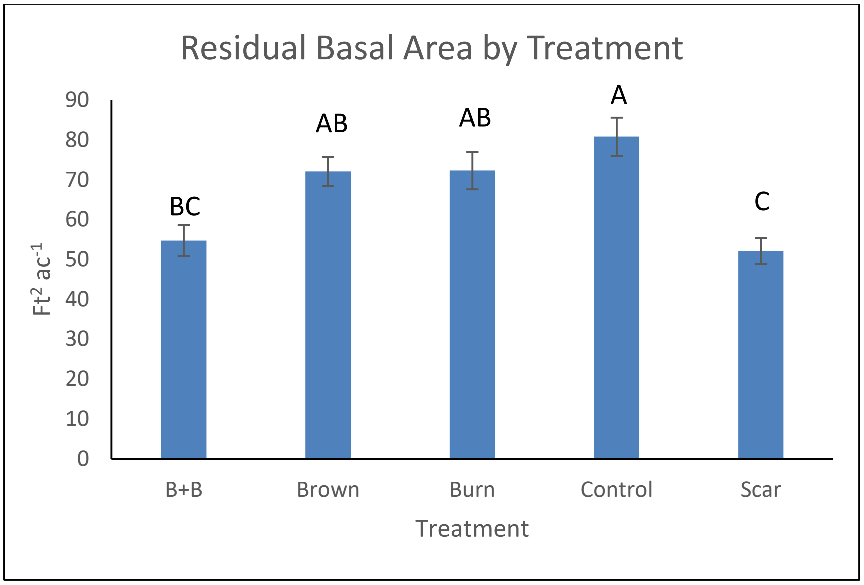


Figure 8. Mean residual basal areas surrounding clusters by treatment (n=30) are presented. Significant differences were found among treatments (p=0.04). Columns without the same letter are statistically different.

All ten clusters within an experimental unit were assigned one of five site preparation or release treatments that included: a no treatment control, herbicide only, brown-and-burn, burn only, and scarification by logging equipment and/or hand equipment. Experimental units were subjectively placed within each block without a preconceived impression of how planted shortleaf pine and natural regeneration would respond, which is known as the "subjective without preconceived bias" method of selecting areas on a landscape for experimental unit or plot placement (Mueller-Dombois and Ellenburg 1974). In blocks B and C, brown-and-burn and burn treatments were placed adjacent to one another to make burn operations more contiguous and reduce the amount of necessary hand fire break construction. In addition, the scarify treatment was assigned to experimental units in each block where logging machinery had exposed the most mineral soil. In clusters that had not or only partially been scarified by logging machinery, undisturbed areas were scarified using a fire rake to remove the litter layer and remove minimal amounts of the duff layer. All stumps of stems that were cut in herbicide and herbicide and burn treatments were treated with a 9.3% solution of Arsenal® AC (salt of imazapyr) herbicide and water following felling. Herbicide application totals by treatment are presented in Figure 9. Trees within the cluster that were felled previously by the loggers were also treated with herbicide solution.

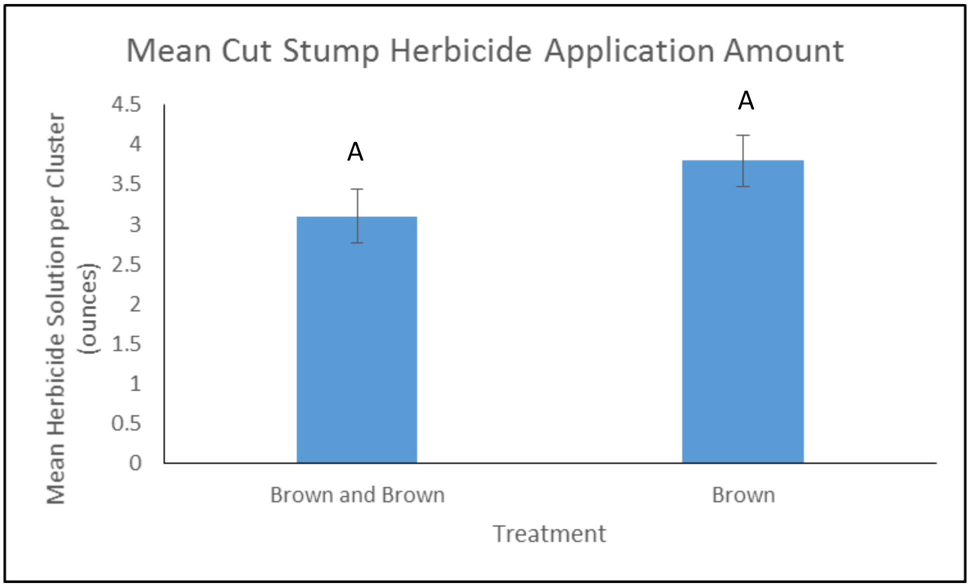


Figure 9. Arsenal® herbicide solution rates (9.3%) applied as a cut stump treatment to herbicide only and brown-and-burn treatments (n=30 clusters per treatment). A two-sided t-test indicated there was no statistical difference between herbicide solution amounts used (p=0.81).

The most readily available shortleaf pine seedlings in the state were obtained from the Tennessee Department of Agriculture Division of Forestry. Seedlings from this nursery have an Arkansas seed provenance. Bareroot, 1-0 stock seedlings were planted on April 7 and 8, 2015 by hand planting crews. Exactly 9,548 seedlings were planted on the study site with an average of 63.7 seedlings per cluster, just under the 64 seedlings per cluster target.

The brown-and-burn and herbicide only treatments received a foliar herbicide release applications using backpack sprayers on August 12, 2015. A 2.5% solution of Arsenal® AC was used with a 0.16% solution of Escort® (metsulfuron methyl) per tank mix. Herbicide was applied as needed to all non-shortleaf pine plants within a cluster. No difference was detected between herbicide amounts used on the two treatments according to a two-sided t-test (p=0.56) (Figure 10). Arsenal® AC and Escort® applications used as release herbicides were based on recommendations from Miller (1990), Yeiser (2012), and loblolly and shortleaf pine herbicide release methods used by the U.S. Forest Service on the

Poor and Good Farm Forties at the Crossett Experimental Forest in Crossett, Arkansas (Guldin and Bragg 2016).

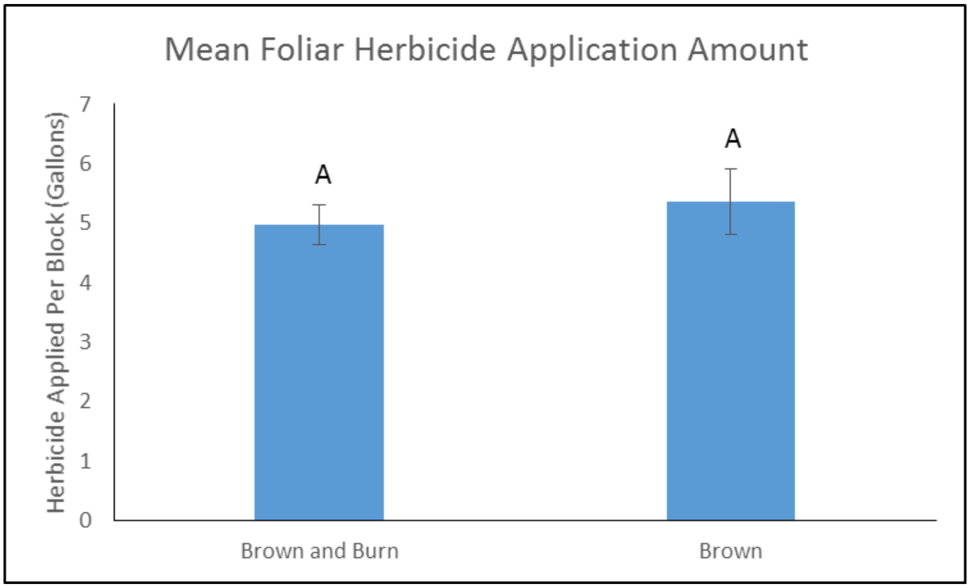


Figure 10. Foliar herbicide application solution averages and standard error for the herbicide and brown-and-burn treatments (n=30 clusters per treatment). A two-sided t-test indicated no difference between herbicide amounts used between treatments (p=0.56).

The brown-and-burn and burn only treatment units were burned on March 17, 18, and 30, 2016. Weather conditions are provided in Table 7. Experimental unit C2 and portions of C3 and B2 were burned on March 17th 2016. Units were ignited in a ring pattern. When skid trails entered a unit, flames were initiated along the edges of the skid trail and allowed to spread into the interior of the experimental unit(s). In interior portions of experimental units where coverage was poor, strip head burn ignition patterns were used to improve coverage. On March 18th, 2016, units C3, B2, and portions of B1, A1, and A3 were burned. Due to the steepness of the topography and the rapid spread of the fire in these areas, strip-heading fires were not needed for coverage, but in these areas where skid trails entered a unit, flames were initiated on both sides of the skid trails and allowed to spread into the interior of the experimental unit(s). Coverage was 100% in all experimental units.

Table 7. Burn treatment weather conditions recorded at the University of Tennessee Cumberland Forest.

| | | | | |
|---|---|---|---|---|
| Date: 3/17/2016 | Time: 5:00-7:00 PM | | | |
| Temperature Range (°F) | Relative Humidity Range (%) | Wind Speed Range (mph) | Wind Direction Range | Reps and Blocks Burned |
| 65-70 | 14-18 | 6.9-8.1 | W | C2, B2, and C3 |
| Date: 3/18/2016 | Time: 12:00-7:00 PM | | | |
| Temperature Range (°F) | Relative Humidity Range (%) | Wind Speed Range (mph) | Wind Direction Range | Reps and Blocks Burned |
| 64-70 | 18-23 | Calm to 8.1 | Variable | B2, C3, B1, A1,and A3 |
| Date:3/30/2016 | Time: 1:30-5:30 | | | |
| Temperature Range (°F) | Relative Humidity Range (%) | Wind Speed Range (mph) | Wind Direction Range | Reps and Blocks Burned |
| 71-76 | 22-29 | 5.8-11.5 | SSE-SSW | A1 and A3 |

### *Measurements and Sampling Procedures*

Measurements at this site involve vegetation sampling within individual clusters and directly outside of them. Shortleaf pine seedling survival, height growth, and basal diameter were assessed in each cluster. Natural hardwood regeneration was assessed inside and outside of three randomly selected clusters out of ten in each experimental unit. Natural regeneration within a circular 1/300$^{th}$ acre plot at the center of the cluster and one 1/300$^{th}$ acre circular plot located 26.4 ft from the center of the cluster perpendicular to the slope were used for natural regeneration assessment inside and outside of clusters, respectively. All natural regeneration greater than six in. tall and less than one in. dbh was tallied by species and placed into one of eight 6-inch height classes (6-12", 12.1-18", 18.1-24", 24.1-30", 30.1-36", 36.1-42", 42.1-48", and 48+"). Measurements were completed during fall and winter of 2016/2017.

Natural regeneration was assessed spatially at five points spaced 6.6 feet apart on two 33 ft. transects within each cluster that natural regeneration was sampled. Transects were established perpendicular to the slope. The points at 6.6 and 13.2 ft. were within the cluster, whereas the 19.8, 26.4 and 33 ft. transect points were located outside of the clusters. The closest naturally regenerating stem to each transect was assessed. At each point along the transect, the distance to the nearest regenerating stem greater than six in. tall but less than one in. dbh was measured. In addition, the species, height, and basal diameter was noted. These measurements were completed at the same time as the cluster interior and exterior 1/300$^{th}$ acre natural regeneration plots were assessed.

Soil compaction was measured using a DICKEY-john® soil penetrometer with a ¾" tip, which measured compaction on a pounds per square inch (PSI) scale from 0-350 in increments of 25 PSI. All compaction measures were recorded following suitable rainfall events that had begun within 24-72 hours and had completed within the past 24 hours (Duiker 2002). Rainfall amounts for each assessment day are presented in Table 8. Compaction measurements were taken from the soil surface to a depth of 12 inches. The penetrometer was pushed into the ground at a rate of one inch per second until a 12 inch depth was reached. Every other seedling (n=32) in a cluster had a measurement taken at six in. to the south of an individual seedling or as close to this point as possible (rockiness of the substrate forced movement of the penetrometer at times but usually no more than six inches). The greatest pounds per square inch (PSI) reading to the nearest 25 PSI interval was recorded.

A small area around half of the planted shortleaf pine seedlings in each cluster of the scarification treatment were assigned a scarification rating and the soil compaction near these seedlings was assessed. The square foot around a seedling (the seedling as the center point) was visually assessed prior to the end of the first growing season, and one of four levels (greater rating was indicative of more scarification by logging equipment) of scarification was assigned to this area similar to the scale devised by Dryness (1965). Scarification levels are defined as follows: Level one was characterized by only leaf litter removal and some organic material (O horizon) may have been disturbed (<20%). None of the A horizon or deeper horizons in the soil profile were exposed. Level two was characterized by leaf litter removal and the organic and A horizons were incorporated into one another. Incorporation of these horizons was due to machinery traffic. This level was characteristic of areas where only 1-3 stems were skidded from the site. Level three was defined by removal or incorporation of the organic and A horizons, and the Bt horizon(s) (clay) was exposed. Machinery compaction was not severe (PSI<250). Level four was defined by incorporation or removal of the organic and A horizons and exposure of the Bt horizon(s) (clay). These areas were more severely compacted by machinery than the level 3 classification (PSI≥250).

Table 8. Rainfall amounts recorded by NOAA in nearby Oliver Springs, Tennessee prior to or the day penetrometer readings were taken on the thirty scarification clusters in the shortleaf pine-hardwood establishment study.

| Assessment Date | Rainfall Date(s) | Rainfall Amount (in.) |
|---|---|---|
| 8/19/2015 | 8/18-8/19/15 | 0.63 |
| 7/23/2015 | 7/21-7/23/15 | 0.58 |
| 7/21/2015 | 7/21/2015 | 0.36 |
| 6/19/2015 | 6/17 and 6/19/15 | 1.68 |
| 6/18/2015 | 6/17/2015 | 0.54 |
| 6/4/2015 | 6/1-6/3/15 | 1.21 |

The overstory hardwoods effect on shading and infiltrating sunlight to the shortleaf pine seedlings and natural regeneration was quantified during July and August 2016 when leaves were casting shadows on the understory and forest floor. The brown-and-burn and burn treatments conducted in March 2016 killed 13.9 and 14.3 $ft^2 ac^{-1}$ of the overstory tree basal area, respectively, making summer 2016 the optimal time to complete this assessment. Sunlight within each cluster was quantified during July and August 2016 using a ceptometer to measure photosynthetically active radiation (PAR) levels at each corner and the center point of each cluster and in the middle of an open area on or near each specific cluster at the same time. Photosynthetic photon flux density levels ($\mu mol\ s^{-1} m^{-2}$) were recorded using an Accupar Linear PAR/LAI Model PAR-80 ceptometer (Decagon Devices, Pullman, WA) at a fixed height (four feet) at each point and divided by values taken at nearly the same time (within five minutes) in areas unshaded by vegetation for a percent sunlight value. All readings were taken during 1045 to 1430 hours on days with suitable weather conditions (Parent and Messier 1996, Messier and Parent 1997). An average value was computed from the five measures taken in each cluster.

***Statistical Analyses***

Analysis of variance (ANOVA) as a randomized complete block design with sampling using mixed models (Proc Mixed, SAS 9.4) (Littell et al. 1996) was used to test for differences among treatments for shortleaf pine height and basal diameter as well as natural regeneration stem density (per acre) and height at this site. Blocking was used because of the elevation and soil differences from the bottom to the top of the mountain. Shortleaf pine survival rate differences across treatments were evaluated using Proc Glimmix and the binomial distribution. Data were tested for normality using the Shapiro-Wilk test. Least squares means were separated using the Fisher’s least significant difference and an alpha level of $p=0.05$. The shortleaf pine basal diameter and height variables were transformed with a square root transformation due to slight skewness. The natural regeneration density variable was transformed with a log transformation due to strong skewness. Untransformed means and standard errors are reported. Natural regeneration average stem density and height outside and inside of clusters were compared using a two sample t-test with an alpha level of p=0.05. Natural regeneration percent composition by species or genera was reported by treatment.

The effects of abiotic factors on shortleaf pine seedling survival, height, and basal diameter were tested at the tree level using backwards variable selection using mixed models and multiple regression in SAS 9.4. Eighty percent of the observations were randomly selected for use in a training sample and twenty percent were randomly selected for use in a holdout sample. An alpha level of p=0.05 was used to test for variable significance. Independent variables that were tested in the model included: elevation, slope, percent full sunlight, and aspect (categorical variable with eight levels) for all treatments other than the scarification treatment. The scarification treatment also included the visual scarification rating and soil compaction (PSI) level measurements. Twenty-five validation runs were used during the holdout sample tests for each dependent variable. A model with an R-square of 0.7 or higher and a p-value less than or equal to 0.05 was considered a strong predictor for a shortleaf pine dependent variable at this site. If a majority (13 or greater) of the twenty-five holdout sample runs fit these criteria the model could be used for prediction and was reported in the results.

Natural regeneration basal diameter, height, and distance differences at individual transect points leading from the cluster center into the surrounding residual forest were evaluated using ANOVA tests. The five sample locations along the 33 foot transects were treated as independent variables. The 6.6 and 13.2 ft. points were inside the cluster and the 19.8, 26.4, and 33 ft. points were outside the cluster in the residual forest. Transects were not averaged for the same cluster in the analysis. The cluster transects were analyzed using a randomized block design with repeated measures and sampling (two transects on each cluster) using SAS Proc Mixed (SAS Institute 2012) to account for a lack of independence among values from one transect location to another due to spatial autocorrelation. The autoregressive correlation method with sampling in the whole plot was used in the repeated measures analysis (Littell et al. 1996). Least squares means were separated using Fisher’s least significant difference and an alpha level of p=0.05. Square root transformations were used to account for normality concerns with each of the three variables and back transfomed means and standard errors are reported.

Species data were analyzed using a contingency table chi-square test and a likelihood ratio chi-square test with a significance level of p=0.05. The five transect locations were used as one factor, and to help increase the interpretability of the table, individual species were classified into three levels of shade tolerance (intolerant, intermediate, and tolerant) for the other factor to produce a 5x3 table. Intolerant species included: sumac spp. (*Rhus* spp.), sassafras (*Sassafras albidum* Nutt.), yellow-poplar, scarlet oak, royal paulownia (*Paulownia tomentosa* Thunb.), black locust, black cherry, black birch (*Betula lenta* L.), shortleaf pine, and Virginia pine. Intermediate tolerance species included: chestnut oak, deerberry (*Vaccinium stamineum* L.), northern red oak, white oak, black oak, white pine, arrowwood (*Viburnum dentatum* L.), hickory *spp.*, cucumbertree, azalea spp. (*Rhododendron* spp.), and white ash (*Fraxinus americana* L.). Shade tolerant species included: sourwood, red maple, blackgum, mountain laurel, buffalo nut (*Pyrularia pubera* Michx.), mapleleaf viburnum (*Viburnum acerifolium* L.), and American beech (*Fagus grandifolia* Ehrh.).

## Chapter 5: Results-University of Tennessee Highland Rim Forest Site

### *Planted Shortleaf Pine*

Treatment was a significant factor explaining shortleaf pine seedling survival (p<0.001), whereas the spacing factor (p=0.135) and the treatment x spacing interaction (p=0.314) were not (Table 9). Survival was greatest in the herbicide treatment (51.2% ± 4.7 SE) followed closely by the control (49.2% ± 4.8 SE). The brown-and-burn had the next lowest survival rate (41.4% ± 4.6 SE) followed by the burn only (30.1% ± 4.1 SE) and finally the strip-burn treatment (12.9% ± 3.7 SE). The shortleaf pine survival rate for the 12x12 ft. (n=1,139) spacing was 38.4% ± 2.9 SE, whereas the 18x18 ft. (n=694) spacing survival rate was slightly lower at 32.1% ± 3.2 SE.

Treatment (p<0.001) and spacing (p=0.02) were both significant factors explaining stem basal diameter, yet the treatment x spacing interaction was not statistically significant (p=0.28) (Table 9). Basal diameter was greatest in the brown-and-burn treatment (1.18 in ± 0.24 SE), followed closely by the strip burn treatment (1.10 in ± 0.50 SE). The herbicide (0.79 in ± 0.23 SE) and control (0.65 in ± 0.23 SE) treatments were statistically similar to one another, while the burn treatment had the smallest average basal diameter of any treatment (0.56 in ± 0.26 SE). The average stem basal diameter for the 12x12 ft spacing was 1.10 in ± 0.16 SE and was statistically different from the 18x18 ft spacing, which had a mean basal diameter of 0.61 in ± 0.22 SE.

Differences in mean height were significant among treatments (p=0.009), yet no differences were detected for the spacing factor (p=0.53) or the spacing x treatment interaction (p=0.63) (Table 9). Stems in the brown-and-burn treatment had the greatest average height (49.2 in ± 3.0 SE). The control and herbicide treatment were statistically the same and averaged 45.8 in ± 2.9 SE and 45.4 in ± 2.9 SE, respectively. The burn treatment had the second shortest stems on average (37.7 in ± 3.1 SE). The strip burn treatment had the shortest stems but the highest variation of all treatments (25.8 in ± 5.6 SE). Average stem height in the 12x12 ft spacing averaged 41.7 in ± 1.9 SE, and the 18x18 ft spacing averaged 39.9 in ± 2.4 SE.

Table 9. Planted shortleaf pine seedling mean survival, basal diameter, and height following three growing seasons for five site preparation and release treatments and two planting spacings at the University of Tennessee Highland Rim Forest near Tullahoma, Tennessee. Means, standard errors, and letter groupings are presented.

| | Survival (%) P<0.001 | Basal Diameter (in.) P<0.001 | Height (in.) P=0.009 |
|---|---|---|---|
| Treatment | Mean ± S.E | Mean ± S.E. | Mean ± S.E. |
| Brown-and-Burn | 41.4 ± 4.6 ab* | 1.18 ± 0.24 a | 49.2 ± 3.0 a |
| Burn | 30.1 ± 4.1 b | 0.56 ± 0.26 c | 37.7 ± 3.1 bc |
| Control | 49.2 ± 4.8 a | 0.65 ± 0.23 b | 45.8 ± 2.9 ab |
| Herbicide | 51.2 ± 4.7 a | 0.79 ± 0.23 ab | 45.4 ± 2.9 ab |
| Strip-Burn | 12.9 ± 3.7 c | 1.10 ± 0.50 d | 25.8 ± 5.6 c |
| Spacing | P=0.13 | P=0.02 | P=0.53 |
| 12x12 Feet | 38.4 ± 2.9 a | 1.10 ± 0.16 a | 41.7 ± 1.9 a |
| 18x18 Feet | 32.1 ± 3.2 a | 0.61 ± 0.22 b | 39.9 ± 2.4 a |

*Treatments followed by the same letter in a column are not statistically different at the p=0.05 level.

***Natural Regeneration***

Treatments differed (p=0.016) in natural pine and hardwood regeneration density (Table 10). The brown-and-burn treatment had the fewest regenerating stems per acre of any treatment and was significantly different from all others (2,401 $ac^{-1}$ ± 805 SE). The herbicide treatment had the next fewest stems and had nearly double the stem density as the brown-and-burn treatment (5,089 $ac^{-1}$ ± 2,325 SE).The burn and control treatments were statistically the same and were similar in mean number of stems per acre (7,586 $ac^{-1}$ ± 555 SE and 8,714 $ac^{-1}$ ± 1,827 SE, respectively). The strip burn treatment had the most stems per acre (13,382 $ac^{-1}$ ± 1,163 SE).

Treatment effects on natural regeneration height were not significant (p=0.21) (Table 10). Height ranged from 24.2 in ± 1.2 SE the brown-and-burn treatment to 28.1 in ± 1.1 SE in the control treatment.

Table 10. Natural pine and hardwood regeneration density expressed as stems per acre and mean height for five site preparation and release treatments are presented three growing seasons after establishment for the shortleaf pine-hardwood establishment study at the University of Tennessee Highland Rim Forest near Tullahoma, Tennessee. Means, standard errors, and letter groupings are presented.

| | Mean (stems per acre) P=0.016 | Mean Height (in.) P=0.21 |
|---|---|---|
| Treatment | Mean ± S.E. | Mean ± S.E. |
| Brown-and-Burn | 2,401 ± 805 c* | 24.5 ± 1.2 a |
| Burn | 7,586 ± 555 ab | 27.5 ± 1.1 a |
| Control | 8,714 ± 1,827 ab | 28.1 ± 1.1 a |
| Herbicide | 5,089 ± 2,325 bc | 27.2 ± 1.4 a |
| Strip-Burn | 13,382 ± 1,163 a | 28.0 ± 1.3 a |

*Treatments followed by the same letter within a column are not statistically different at the p=0.05 level.

Natural regeneration species composition percentages varied by treatment. The brown-and-burn treatment had black cherry (15%) and sassafras (15%) as the two most common species (Figure 11). The next most prevalent species included southern red oak (8%), sumac spp. (8%), callery pear (5%), red maple (8%) scarlet oak (6%), and post oak (5%). Species in the red and white oak families were more abundant in this treatment than any other and comprised 23% of the regenerating stems.

The burn treatment had Chinese privet (44%), and sumac spp. (42%) as the two most dominant species (Figure 12). The next most prevalent species included blackgum (3%) and red maple (2%). Species in the red and white oak families only comprised 2% of the regenerating stems.

The control treatment was dominated by Chinese privet (42%) and sumac spp. (34%) as the two most common species (Figure 13). The next most prevalent species were black cherry (5%), devil's walkingstick (4%), red maple (3%), and southern red oak (3%). Species in the red and white oak families comprised only 4% of the species composition.

Species composition in the herbicide treatment was dominated once again by Chinese privet (82%) (Figure 14). The next most prevalent species were sumac spp. (5%) and red maple (2%). Species in the red and white oak families made up only one percent of the regenerating stems.

The strip burn treatment was co-dominated by sumac spp. (47%) and Chinese privet (38%) (Figure 15). Other minor species in this treatment included callery pear (6%), red maple (4%), and devil's walkingstick (3%). Species in the red and white oak families comprised less than 0.5% of the species composition.

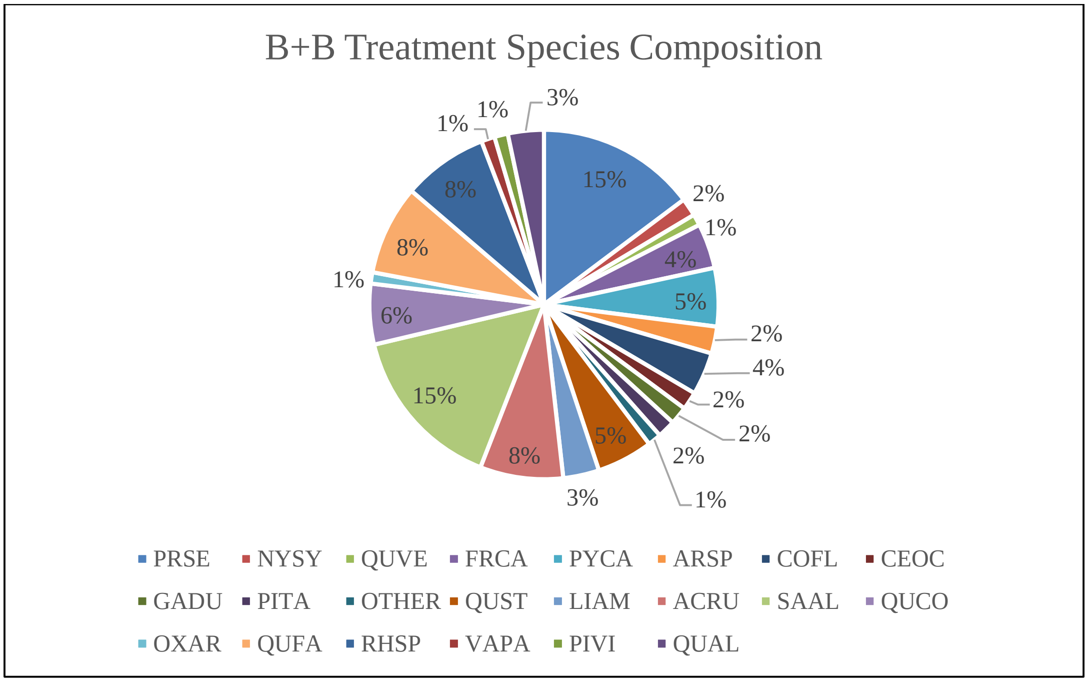


Figure 11. Natural regeneration by species or species group for the brown-and-burn treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Highland Rim Forest near Tullahoma, Tennessee. The "OTHER" species category includes ash spp., hickory spp., winged elm, and willow oak. Species abbreviations given in the legend are explained in Appendix 1.

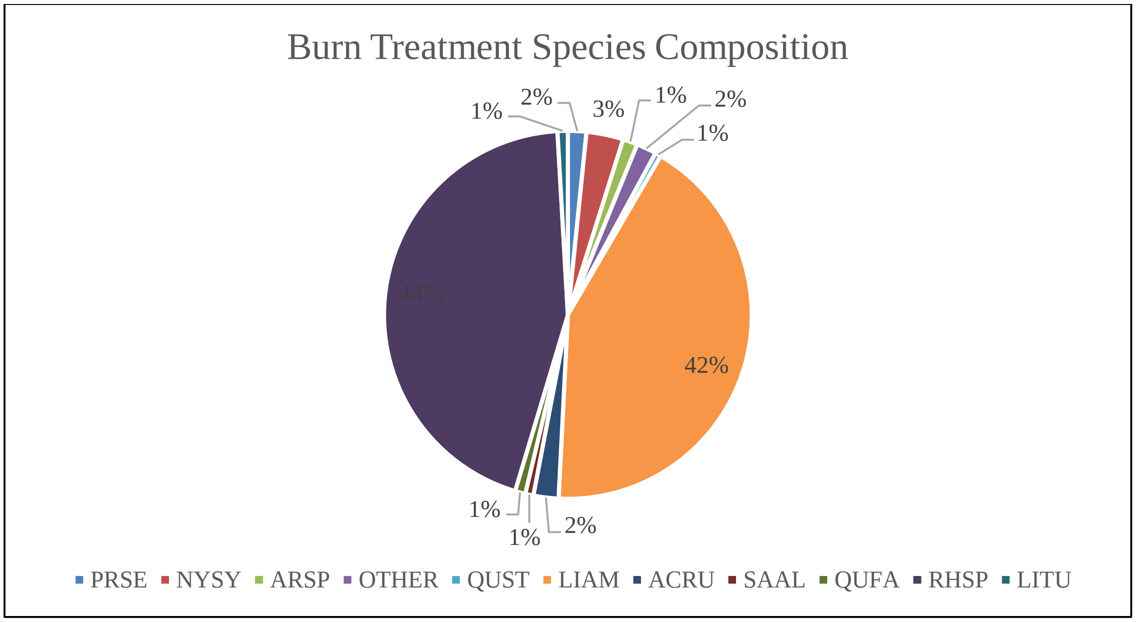


Figure 12. Natural regeneration by species or species group for the burn treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Highland Rim Forest near Tullahoma, Tennessee. The “OTHER” species category includes: callery pear, dogwood, scarlet oak, sourwood, *Vaccinium* spp., eastern white pine, and willow oak. Species abbreviations given in the legend are explained in Appendix 1.

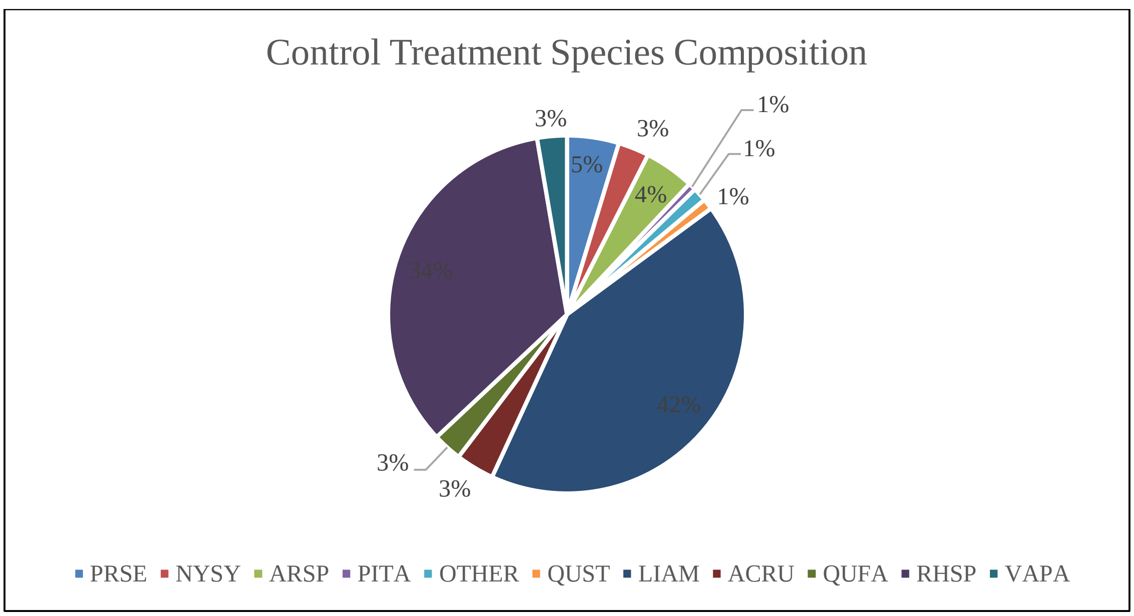


Figure 13. Natural regeneration by species or species group for the control treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Highland Rim Forest near Tullahoma, Tennessee. The “OTHER” species category includes callery pear, hickory spp., sassafras, and Virginia pine. Species abbreviations given in the legend are explained in Appendix 1.

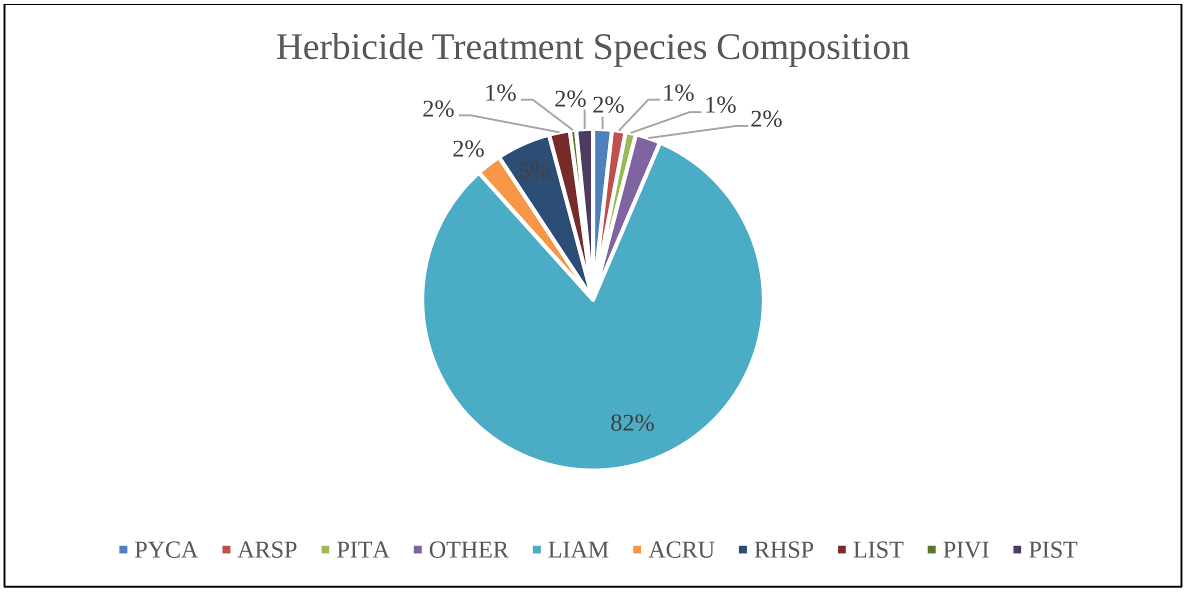


Figure 14. Natural regeneration by species or species group for the herbicide treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Highland Rim Forest near 4 Tullahoma, Tennessee. The “OTHER” species category includes: black cherry, blackgum, black oak, hickory spp., scarlet oak, shortleaf pine, southern red oak, white oak, and willow oak. Species abbreviations given in the legend are explained in Appendix 1.

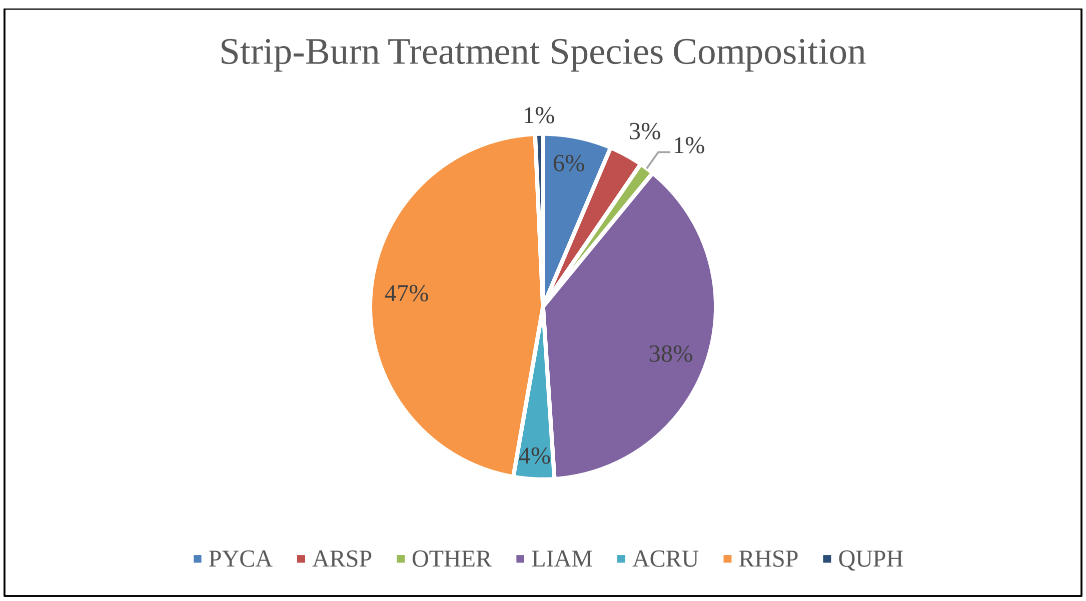


Figure 15. Natural regeneration by species or species group for the strip-burn treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Highland Rim Forest near Tullahoma, Tennessee. The “OTHER” species category includes: American holly, black cherry, and boxelder. Species abbreviations given in the legend are explained in Appendix 1.

### *Woody Fuel Loads*

Pre-burn sound and rotten woody fuel loads at the University of Tennessee Highland Rim Forest did not differ by treatment and spacing (p=0.67). Fuel loads ranged from a low of 8.4 tons/acre ± 3.3 SE in the 18x18 ft. spacing in the strip-burn treatment to 21.8 tons/acre ± 8.2 SE in the 12x12 ft spacing in the burn treatment (Table 11). Post-burn sound and rotten woody fuel loads did not differ by treatment and spacing for the three treatments that received burns (p=0.92). Fuel loads ranged from 6.7 tons/acre ± 2.8 SE in the 18x18 ft. spacing of the brown-and-burn treatment to 11.9 tons/acre ± 3.4 SE and 11.9 tons/acre ± 4.1 SE in the 12x12 ft. burn and 12x12 ft. brown-and-burn treatments, respectively.

Table 11. Pre-burn treatment x spacing mean fuel loads (tons/acre) for the three burn treatments at the University of Tennessee Highland Rim Forest near Tullahoma, Tennessee (p=0.67).

| Treatment | Spacing (ft.) | Mean Fuel Load (tons/acre) | Standard Error (+/- tons/acre) | Letter Grouping |
|---|---|---|---|---|
| Burn | 12x12 | 21.8 | 8.2 | a* |
| | 18x18 | 9.7 | 2.8 | a |
| Brown and Burn | 12x12 | 16.3 | 5.6 | a |
| | 18x18 | 8.5 | 4.2 | a |
| Strip-Burn | 12x12 | 10.8 | 5.2 | a |
| | 18x18 | 8.4 | 3.3 | a |

*Treatments followed by the same letter within a column are not statistically different at the p=0.05 level.

Table 12. Post-burn treatment x spacing mean fuel loads (tons/acre) for the three burn treatments at the University of Tennessee Highland Rim Forest near Tullahoma, Tennessee (p=0.92).

| Treatment | Spacing (ft.) | Mean Fuel Load (tons/acre) | Standard Error (+/- tons/acre) | Letter Grouping |
|---|---|---|---|---|
| Burn | 12x12 | 11.9 | 3.4 | a* |
| | 18x18 | 8.4 | 2.3 | a |
| Brown and Burn | 12x12 | 11.9 | 4.1 | a |
| | 18x18 | 6.7 | 2.8 | a |
| Strip-Burn | 12x12 | 10.0 | 4.3 | a |
| | 18x18 | 7.5 | 1.9 | a |

*Treatments followed by the same letter within a column are not statistically different at the p=0.05 level.

## Chapter 6: Results-University of Tennessee Cumberland Forest Site

### *Planted Shortleaf Pine*

Treatment was not a significant factor in explaining planted shortleaf pine seedling survival (p=0.38) (Table 13). Survival was numerically greatest in the scarification treatment (56.1% ± 5.8 SE), while the brown-and-burn (39.8% ± 5.8 SE) and burn (37.8% ± 5.7 SE) treatments had the lowest survival rates. The control (44.6% ± 5.8 SE) and herbicide (45.7% ± 6.0 SE) treatments had similar survival rates.

Treatment differences were not found for shortleaf pine basal diameter (p=0.12) (Table 13). Basal diameter ranged from 0.4 in ± 0.04 SE in the scarification treatment to 0.18 in ± 0.04 SE in the burn treatment.

Treatment was a significant factor (p=0.05) for explaining differences in shortleaf pine seedling height (Table 13). This finding was due to the greater growth rate of seedlings in the scarification treatment (29.2 in ± 2.1 SE) compared to all other treatments, which were statistically the same (16.0 ± 2.1 SE to 20.9 ± 2.1 SE inches).

Table 13. Planted shortleaf pine seedling mean survival, basal diameter, and height following two growing seasons for the five site preparation and release treatments at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. Means, standard errors, and letter groupings are presented.

| | Survival (%) P=0.38 | Basal Diameter (in.) P=0.12 | Height (in.) P=0.05 |
|---|---|---|---|
| Treatment | Mean ± S.E. | Mean ± S.E. | Mean ± S.E. |
| Brown-and-Burn | 39.8 ± 5.8 a* | 0.29 ± 0.04 a | 19.7 ± 2.3 b |
| Burn | 37.8 ± 5.7 a | 0.18 ± 0.04 a | 16.0 ± 2.1 b |
| Control | 44.6 ± 5.8 a | 0.26 ± 0.04 a | 20.9 ± 2.1 b |
| Herbicide | 45.7 ± 6.0 a | 0.31 ± 0.04 a | 20.9 ± 2.3 b |
| Scarification | 56.1 ± 5.8 a | 0.4 ± 0.04 a | 29.2 ± 2.1 a |

*Treatments followed by the same letter within a column are not statistically different at the p=0.05 level.

### *Natural Regeneration*

Within clusters, treatment was a significant factor in explaining the number of naturally regenerating stems per acre (p=0.001) (Table 14). The control treatment had the most regenerating stems per acre on average (37,500 $ac^{-1}$ ± 5,532 SE), and it was followed by the scarification (19,267 $ac^{-1}$ ± 4,557 SE) and burn treatments (12,000 $ac^{-1}$ ± 3,810 SE), which were statistically similar. The herbicide (6,000 $ac^{-1}$ ± 1,410 SE) and the brown-and-burn (3,993 $ac^{-1}$ ± 1,467 SE) treatments had the fewest stems per acre and were statistically the same.

No significant differences among treatments were found for the number of regenerating stems outside of the clusters (p=0.493) (Table 14). The average number of stems per acre ranged from 13,267 $ac^{-1}$ ± 3,083 SE in the burn treatment to 22,133 $ac^{-1}$ ± 6,272 SE in the scarification treatment. A two sample t-test found no difference (p=0.47) in the overall average number of stems outside of clusters (18,726 $ac^{-1}$ ± 2,077 SE) versus the number of regenerating stems inside of clusters (15,740 $ac^{-1}$ ± 3,534 SE).

No treatment differences were found for average cluster interior regenerating stem height (p=0.361) (Table 14). Heights ranged from 11.7 in ± 3.0 SE in the brown-and-burn treatment to 20.3 in ± 2.9 SE for the scarification treatment. In addition, no treatment differences were found for average cluster exterior regenerating stem height (p=0.333) (Table 14). Heights ranged from 17.5 in ± 1.5 SE for the brown-and-burn treatment to 22.0 in ± 1.4 SE for the scarification treatment, which was the same as the minimum and maximum treatment height trend seen in the cluster interiors. The two sample t-test comparing interior and exterior average height indicated a significant difference (p=0.037) in overall cluster exterior regenerating stem height (19.7 in ± 0.7 SE) and cluster interior regenerating stem height (16.3 in ± 1.3 SE).

***Cluster Interior Natural Regeneration Composition***

Natural regeneration species composition within clusters of the brown-and-burn treatment consisted primarily of deerberry (24%) and serviceberry (23%) as the two most common species (Figure 16). Other species was the next most abundant category (17%), followed by blackgum (8%) and chestnut oak (6%). Species from the red and white oak families comprised 9.6% of the regenerating stems in this treatment.

Table 14. Natural regeneration mean number of stems per acre and height are presented inside and outside of cluster plantings for the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. Means, standard errors, and letter groupings are presented.

| | Number of stems per acre | | Height (in.) | |
|---|---|---|---|---|
| | Interior (p=0.001) | Exterior (p=0.493) | Interior (p=0.361) | Exterior (p=0.333) |
| Treatment | Mean ± S.E. | Mean ± S.E. | Mean ± S.E. | Mean ± S.E. |
| Brown-and-Burn | 3,993 ± 1,467 c* | 21,800 ± 3,034 a | 11.7 ± 3.0 a | 17.5 ± 1.5 a |
| Burn | 12,000 ± 3,810 bc | 13,267 ± 3,038 a | 17.2 ± 2.8 a | 18.2 ± 1.6 a |
| Control | 37,500 ± 5,532 a | 22,000 ± 4,850 a | 18.1 ±2.4 a | 20.3 ± 1.4 a |
| Herbicide | 6,000 ± 1,410 c | 14,433 ± 5,452 a | 16.4 ± 3.2 a | 21.4 ± 1.5 a |
| Scarification | 19,267 ± 4,557 b | 22,133 ± 6,272 a | 20.3 ± 2.9 a | 22.0 ± 1.4 a |

*Treatments with the same letter within a column are not significantly different at the p=0.05 level.

The burn treatment cluster interior natural regeneration consisted primarily of deerberry (36%), mountain laurel (14%), and other species (13%) (Figure 17). Secondary species were sourwood (10%) and blackgum (6%). Species from the red and white oak families constituted 8.1% of the species composition. Control treatment cluster interiors were composed of deerberry (35%), azalea spp. (19%), and other species (14%) (Figure 18). Secondary species consisted of white oak (6%) and chestnut oak (5%). Species composition was 18.3% stems from the red and white oak families in the interior control treatments, the most of any treatment.

The herbicide treatment cluster interior species composition was dominated by deerberry (28%), naturally regenerating shortleaf pine (19%), and red maple (15%) (Figure 19). The next most prominent species were yellow-poplar (7%), northern red oak (6%), and sassafras (4%). Species from the red and white oak families composed 5.5% of the regenerating stems, the lowest percentage of any treatment. The cluster interiors of the scarification treatment were predominately other species (15%) and yellow-poplar (14%) (Figure 20). The next most common species were mountain laurel (11%), chestnut oak (7%), scarlet oak (7%), and blackgum (6%). Species from the red and white oak families composed 15.6% of the regenerating stems.

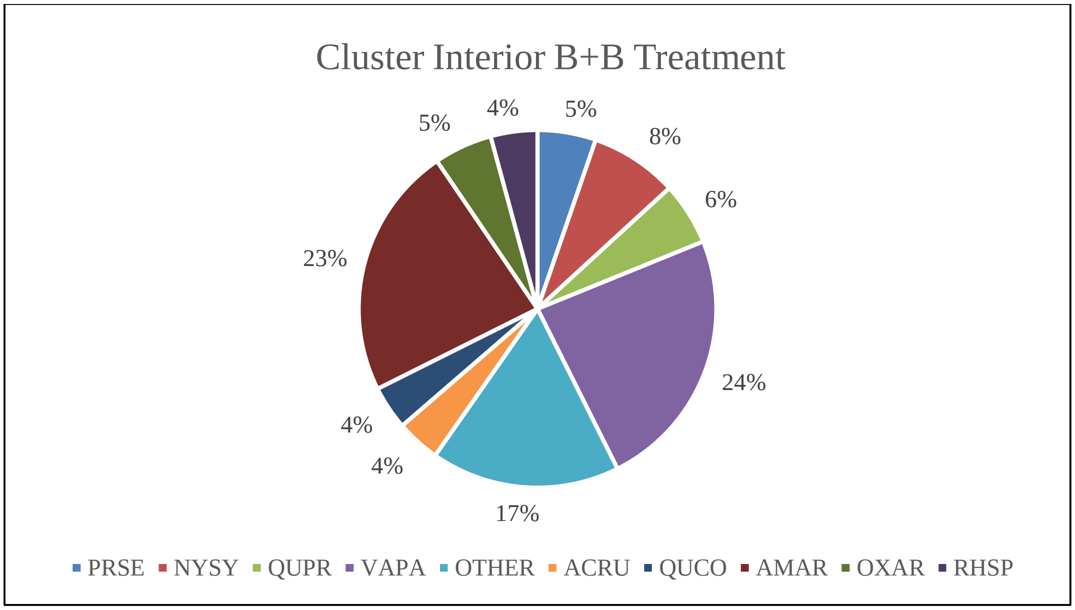


Figure 16. Natural regeneration by species or species group within clusters for the brown-and-burn treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The "OTHER" species category includes: black birch, hawthorn spp., mountain laurel, royal paulownia, sassafras, and yellow-poplar. Species abbreviations given in the legend are explained in Appendix 1.

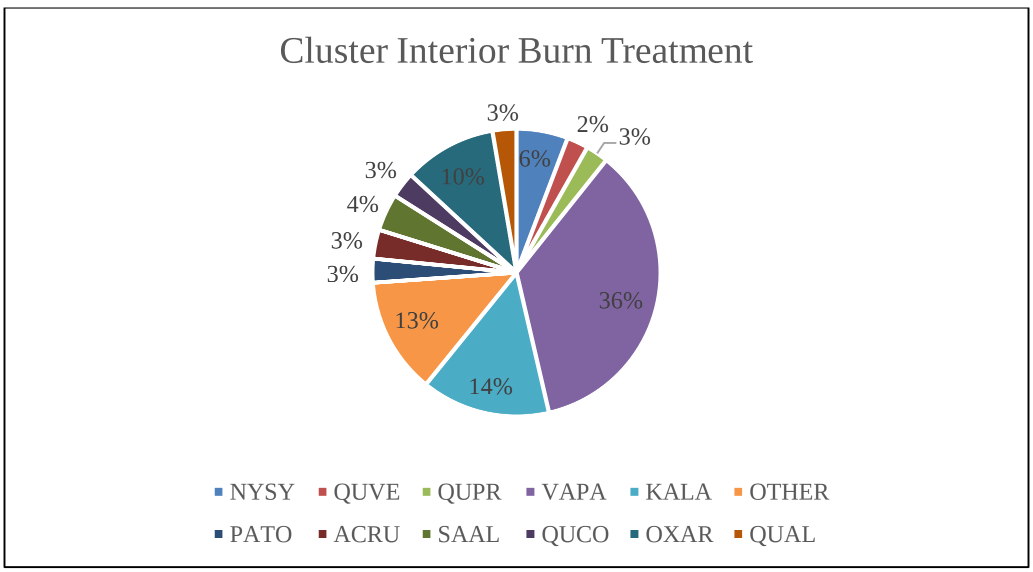


Figure 17. Natural regeneration by species or species group within clusters for the burn treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The "OTHER" species category includes: azalea spp., buffalo nut, hawthorn, hickory spp., northern red oak, sumac spp., eastern white pine, and yellow-poplar. Species abbreviations given in the legend are explained in Appendix 1.

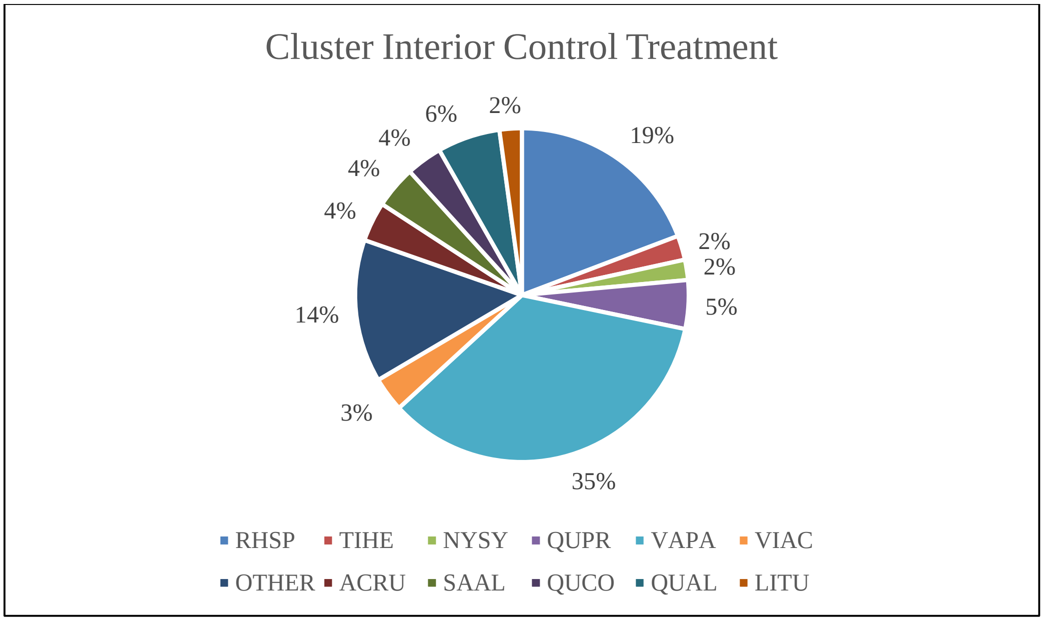


Figure 18. Natural regeneration by species or species group within clusters for the control treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The "OTHER" species category includes: American holly, arrowwood, black birch, black cherry, black oak, northern red oak, royal paulownia, serviceberry, sourwood, sumac spp., and sweetgum. Species abbreviations given in the legend are explained in Appendix 1.

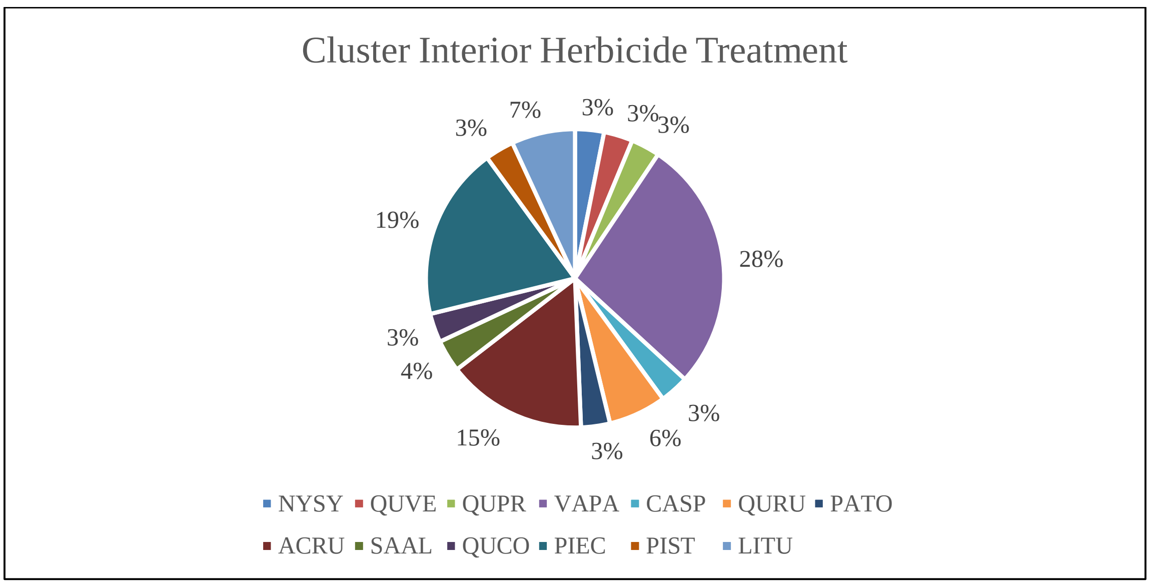


Figure 19. Natural regeneration by species or species group within clusters for the herbicide treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. Species abbreviations are given in the legend and explained in Appendix 1.

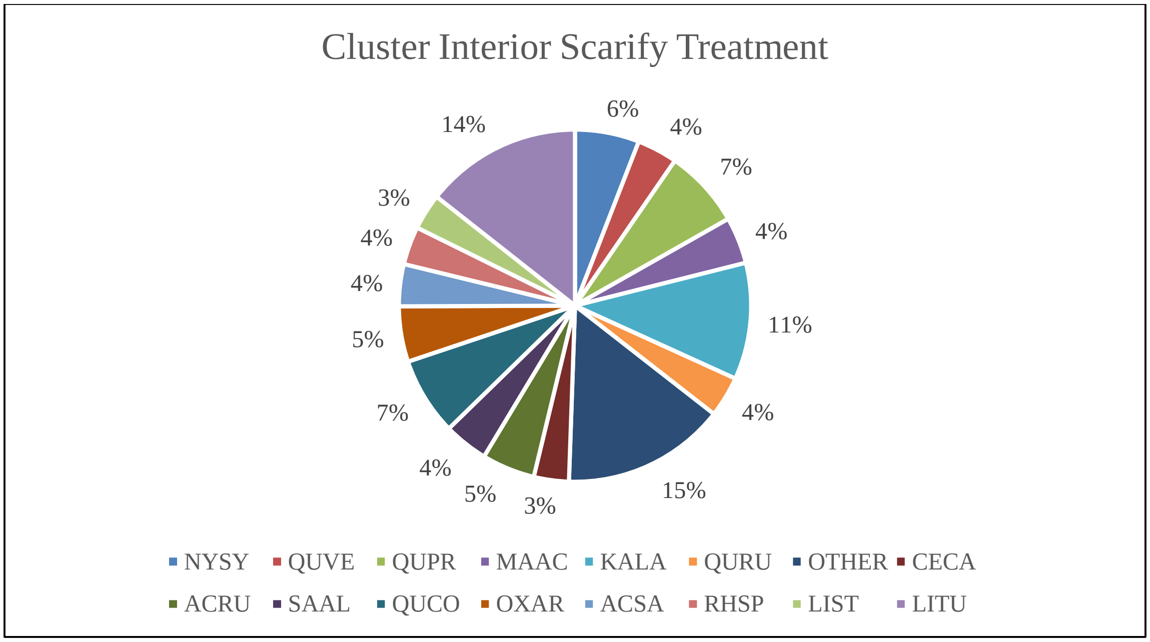


Figure 20. Natural regeneration by species or species group within clusters for the scarification treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The "OTHER" species category includes: white ash, American basswood, black birch, black cherry, hickory spp., royal paulownia, and serviceberry. Species abbreviations given in the legend are explained in Appendix 1.

***Cluster Exterior Natural Regeneration Composition***

Natural regeneration composition exterior to the clusters of the brown-and-burn treatment was predominately comprised of sumac spp. (27%), other species (16%), and azalea spp. (15%) (Figure 21). The next most common species were deerberry (10%), buffalo nut (7%), and sassafras (6%). Species from the red and white oak families composed 7.6% of the regenerating species, the lowest percentage of any treatment.

The burn treatment cluster exterior area was made up mostly of mountain laurel (42%) and other species (11%) (Figure 22). The next most common species were deerberry (9%), red maple (7%), and sassafras (5%). Species from the red and white oak families constituted 16.3 percent of the regenerating stems, the highest percentage of any treatment. The control treatment was dominated by deerberry (26%), azalea spp. (9%), and other species (15%). Secondary species included white oak (7%), scarlet oak (5%), and red maple (5%). Species from the red and white families comprised 11.5% of the regenerating stems.

The herbicide treatment cluster exterior area was led by other species (21%) and deerberry (19%) (Figure 23). Secondary species included: sourwood (9%), red maple (8%), and azalea spp. (7%). Species from the red and white oak families comprised 12.9% of the regenerating stems exterior to the clusters in this treatment. The scarify treatment was dominated by deerberry (29%), yellow-poplar (10%), and other species (9%) (Figure 24). Sourwood (7%), sumac spp. (6%), and chestnut oak (5%) were the next most common species. Species from the red and white oak families comprised 8.9% of the regenerating stems in this treatment.

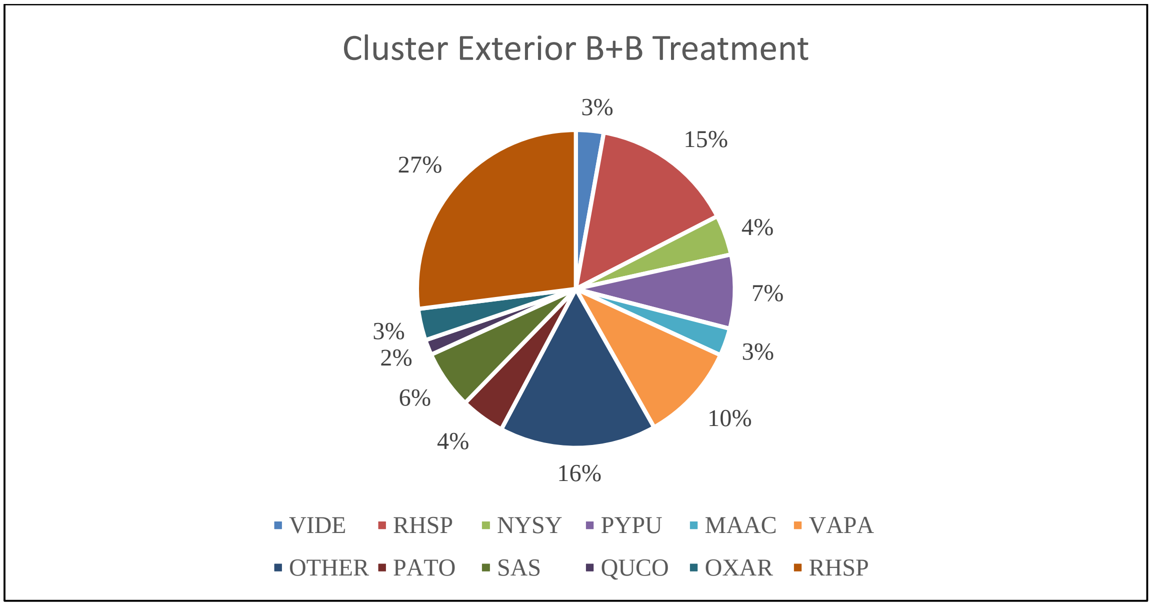


Figure 21. Natural regeneration by species or species group outside of clusters for the brown-and-burn treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The "OTHER" species category includes: black cherry, black oak, chestnut oak, northern red oak, red maple, scarlet oak, serviceberry, white oak, eastern white pine, and yellow-poplar. Species abbreviations given in the legend are explained in Appendix 1.

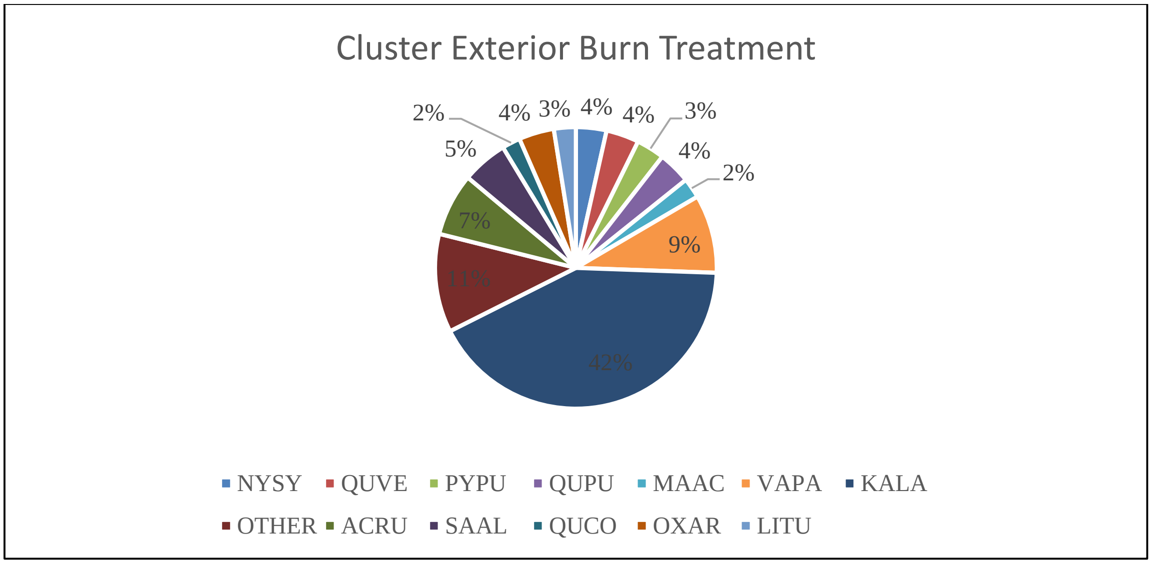


Figure 22. Natural regeneration by species or species group outside of clusters for the burn treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The “OTHER” species category includes: American holly, tree-of-heaven, black cherry, American beech, hickory spp., mapleleaf viburnum, and serviceberry. Species abbreviations given in the legend are explained in Appendix 1.

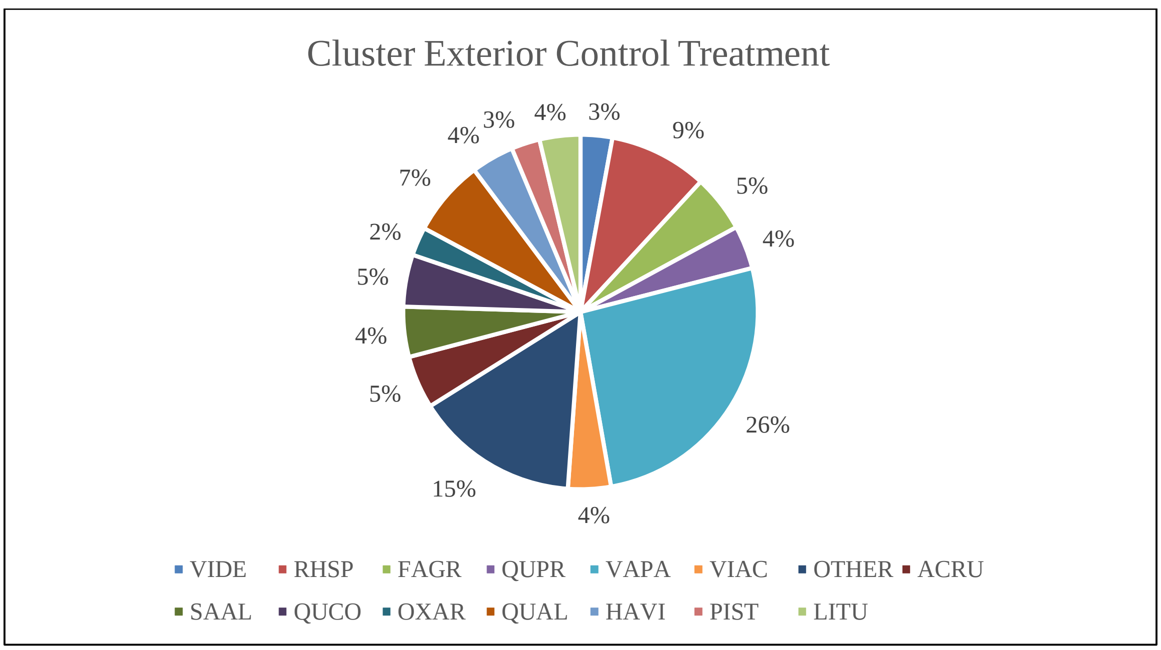


Figure 23. Natural regeneration by species or species group outside of clusters for the control treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The “OTHER” species category includes: white ash, black cherry, black oak, buffalo nut, northern red oak, royal paulownia, and Virginia pine. Species abbreviations given in the legend are explained in Appendix 1.

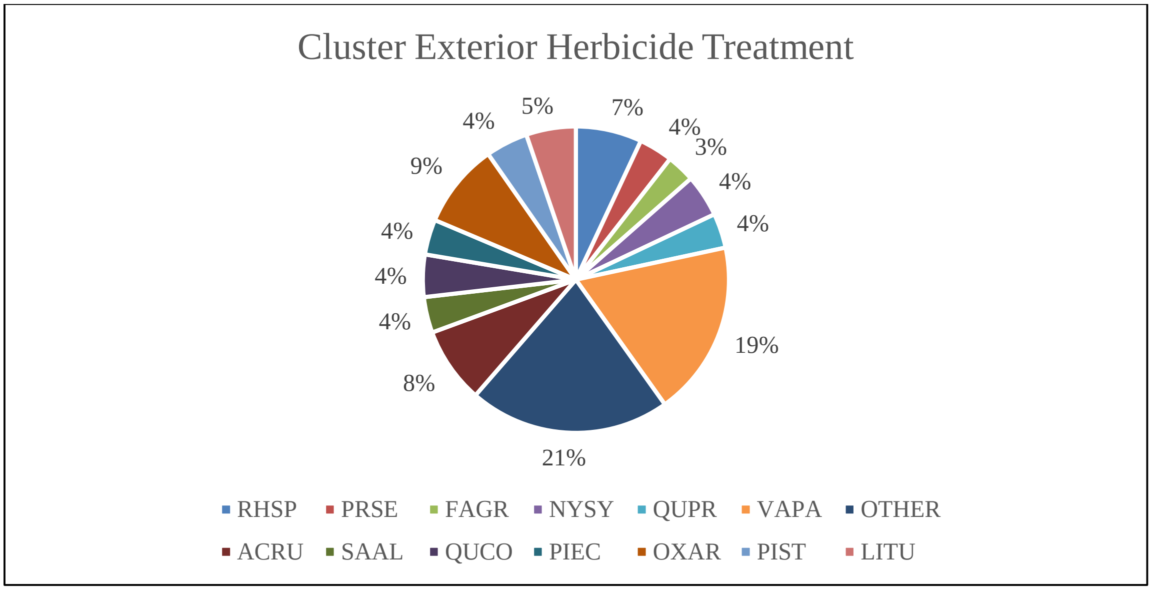


Figure 24. Natural regeneration by species or species group outside of clusters for the herbicide treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The "OTHER" species category includes: white ash, black oak, hickory spp., mapleleaf viburnum, royal paulownia, serviceberry, sumac spp., and white oak. Species abbreviations given in the legend are explained in Appendix 1.

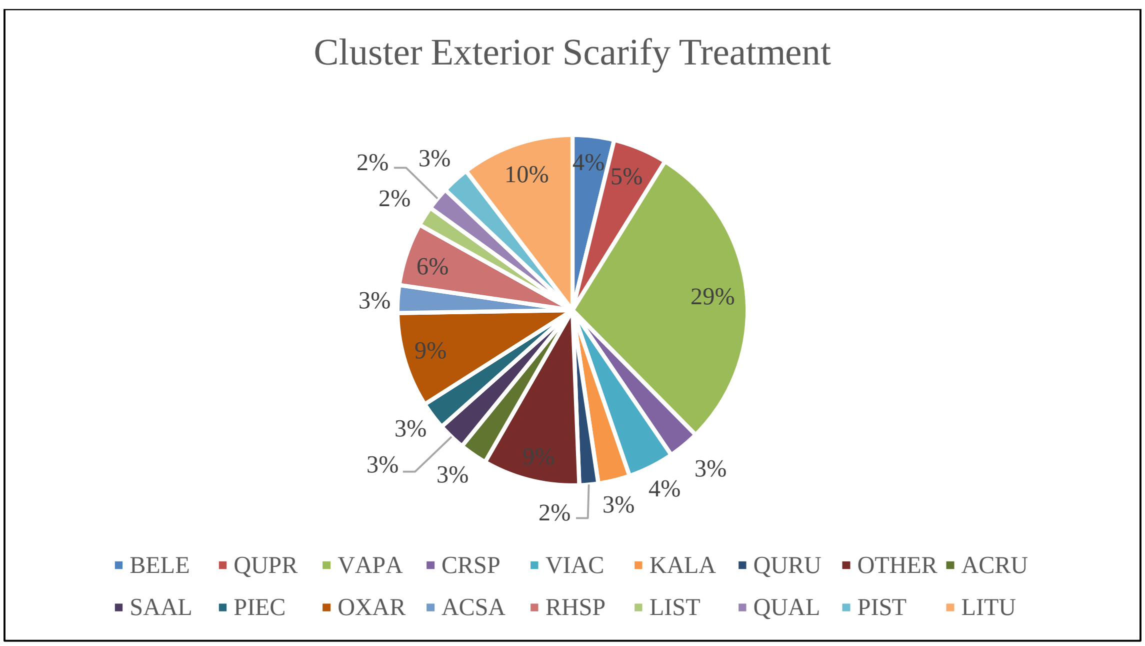


Figure 25. Natural regeneration by species or species group outside of clusters for the scarification treatment in the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. The "OTHER" species category includes: American basswood, blackgum, royal paulownia, scarlet oak, black cherry, and black oak. Species abbreviations given in the legend are explained in Appendix 1.

***Abiotic Factors' Effects on Shortleaf Pine Survival and Growth***

Percent full sunlight varied by treatment across the study site from an average of 39.9% within the control treatment to 74.4% within the brown-and-burn treatment. The most commonly occurring aspects within clusters on the site were southwest and west. Average slope percent by treatment ranged from 16.5% in the scarification treatment to 21.2% in the control treatment. Average cluster elevation by treatment ranged from 1,539.5 ft in the control treatment to 1,601.5 ft in the scarification treatment.

Seedling survival was only significantly affected by slope ($p<0.0001$) in the training sample (Table 15). The 25 holdout sample validation runs did not have any r-square values greater than or equal to 0.7. Thus, slope cannot be used as a predictor variable for shortleaf pine seedling survival. Seedling basal diameter was affected by light, elevation, and slope (Table 15). The holdout sample validation runs indicated that these three abiotic variables could be used for predicting seedling basal diameter on this site. Of these runs, 24/25 (96%) had an r-square of 0.7 or higher. The same three variables significantly affected seedling height (Table 15). The holdout sample validation runs suggested that the model is capable of predicting shortleaf pine growth. In the validation step, 24/25 (96%) of the runs had an r-square value of 0.7 or higher.

***Abiotic Factors' Effects on Shortleaf Pine Survival and Growth in the Scarification Treatment***

The average compaction rating measured across all scarification treatment clusters was 172 PSI ± 68 SD. The average scarification rating was 2.21 ± 1.16 SD. Seedling survival was significantly affected by scarification rating, elevation, and slope ($p<0.05$) (Table 16). The 25 holdout sample validation runs found that 24/25 (96%) runs had R-square values greater than or equal to 0.7. This indicates that these three variables may be able to predict shortleaf pine seedling survival on scarified sites. The regression results suggest that PSI, light, and elevation all significantly affected basal diameter growth ($p\leq0.05$) (Table 16), yet these variables could not be used for prediction purposes because all of the validation runs had R-square values less than 0.7. Seedling height was significantly affected by light and elevation ($p<0.05$), yet could not be used for prediction purposes based on the validation runs as only 1/25 (4%) of the runs could sufficiently predict height (Table 16).

Table 15. Shortleaf pine seedling multiple regression overall predictor variables for survival, basal diameter, and height for all treatments excluding the scarification treatment for the shortleaf pine-hardwood forest establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee.

| Survival | | | | | |
|---|---|---|---|---|---|
| Effect | Estimate | Standard Error | Degrees of Freedom | t-value | P-value |
| Light | -0.0003 | 0.0002 | 9529 | -1.16 | 0.2461 |
| Direction | -0.0009 | 0.002 | 9529 | -0.33 | 0.7392 |
| Elevation | 0.0001 | 0.00008 | 9529 | 1.69 | 0.0915 |
| Slope | -0.0051 | 0.0009 | 9529 | -5.37 | <0.0001 |
| **Basal Diameter** | | | | | |
| Effect | Estimate | Standard Error | Degrees of Freedom | t-value | P-value |
| Light | 0.0014 | 0.0001 | 4271 | 11.06 | <0.0001* |
| Direction | -0.0015 | 0.0016 | 4271 | -0.97 | 0.333 |
| Elevation | 0.0004 | 0.00005 | 4271 | 9.05 | <0.0001 |
| Slope | -0.0018 | 0.00056 | 4271 | 3.2 | 0.0014 |

Table 15. Continued.

| Seedling Height | | | | | |
|---|---|---|---|---|---|
| Effect | Estimate | Standard Error | Degrees of Freedom | t-value | P-value |
| Light | 0.086 | 0.008 | 4271 | 10.96 | <0.0001 |
| Direction | -0.102 | 0.098 | 4271 | -1.04 | 0.2984 |
| Elevation | 0.009 | 0.0024 | 4271 | 3.55 | 0.0004 |
| Slope | -0.171 | 0.0344 | 4271 | -4.98 | <0.0001 |

*Model effects were considered significant at the $p \leq 0.05$ level.

***Natural Regeneration Transects***

Average natural regeneration height did no differ by transect location (p=0.18) (Table 17). Heights ranged from 16.1 in ± 1.7 SE at the 6.6 ft. location inside the clusters to 20.5 in ± 1.9 SE at the 26.4 ft. location outside of the clusters. Natural regeneration basal diameter did not differ by transect location (p=0.25) (Table 17). The 6.6 ft. location (within a cluster) had the smallest average diameter (0.19 in ± 0.02 SE), whereas the 26.4 and 33 ft. locations (outside of clusters) were the same at 0.23 in ± 0.02 SE.

Table 16. Shortleaf pine seedling multiple regression predictor variables for survival, basal diameter, and height in the scarification treatment for the shortleaf pine-hardwood forest establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee.

| Survival | | | | | |
|---|---|---|---|---|---|
| Effect | Estimate | Standard Error | Degrees of Freedom | t-value | Prob-t |
| Rating | 0.05 | 0.018 | 911 | 2.74 | 0.006 |
| PSI | 5.89E-06 | 0.0003 | 911 | 0.02 | 0.9 |
| Light | -0.0008 | 0.0008 | 911 | -0.09 | 0.3 |
| Direction | 0.001 | 0.008 | 911 | 0.1 | 0.9 |
| Elevation | -0.0002 | 0.0001 | 911 | -2.01 | 0.04 |
| Slope | 0.007 | 0.003 | 911 | 2.71 | 0.007 |
| Basal Diameter | | | | | |
| Effect | Estimate | Standard Error | Degrees of Freedom | t-value | Prob-t |
| Rating | 0.01 | 0.01 | 465 | 1.33 | 0.2 |
| PSI | -0.0003 | 0.002 | 465 | -1.97 | 0.05 |
| Light | 0.001 | 0.0004 | 465 | 2.86 | 0.004 |
| Direction | 0.008 | 0.005 | 465 | 1.81 | 0.07 |
| Elevation | 0.0008 | 0.0002 | 465 | 5.31 | <0.0001 |
| Slope | 0.0003 | 0.002 | 465 | 0.21 | 0.8 |
| Seedling Height | | | | | |
| Effect | Estimate | Standard Error | Degrees of Freedom | t-value | Prob-t |
| Rating | 0.008 | 0.63 | 465 | 0.01 | 0.9 |
| PSI | -0.02 | 0.01 | 465 | -1.66 | 0.09 |
| Light | 0.06 | 0.03 | 465 | 2.1 | 0.04 |
| Direction | 0.4 | 0.3 | 465 | 1.48 | 0.14 |
| Elevation | 0.03 | 0.009 | 465 | 3.61 | 0.0003 |
| Slope | -0.02 | 0.1 | 465 | -0.17 | 0.86 |

* Model effects were considered significant at the p≤0.05 level.

Distance to the nearest regenerating stem differed by location along the transects from cluster interiors to exteriors (p=0.009) (Table 17). The 19.8 ft. (15.6 in ± 1.8 SE), 26.4 ft. (14.2 in ± 1.7 SE), and 33 ft. (13.2 in ± 1.6 SE) locations all had significantly shorter distances to naturally regenerating stems than the two positions located within the clusters, which were the 6.6 ft. (21.4 in ± 2.1 SE) and 13.2 ft. (19.6 in ± 2 SE) positions.

Table 17. Natural regeneration average height, basal diameter, and distance by each of five transect locations within and outside of sampled clusters two years post establishment for the shortleaf pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee.

| | Height (in) (p=0.18) | Basal Diameter (in) (p=0.25) | Distance (in) (p=0.009) |
|---|---|---|---|
| Location (ft.) | Mean ± S.E. | Mean ± S.E. | Mean ± S.E. |
| 6.6 | 16.1 ± 1.7 a* | 0.19 ± 0.02 a | 21.4 ± 2.1 a |
| 13.2 | 17.3 ± 1.8 a | 0.2 ± 0.02 a | 19.6 ± 2 a |
| 19.8 | 19.8 ± 1.9 a | 0.22 ± 0.02 a | 15.6 ± 1.8 b |
| 26.4 | 20.5 ± 1.9 a | 0.23 ± 0.02 a | 14.2 ± 1.7 b |
| 33 | 19.9 ± 1.9 a | 0.23 ± 0.02 a | 13.2 ± 1.6 b |

* Locations followed by the same letter within a column are not statistically different at the p=0.05 level.

The chi-square (p=0.82) and the likelihood ratio chi-square (p=0.83) tests both showed no differences in species composition by shade tolerance class for different transect positions. The results did show a weak trend of intolerant species becoming less abundant from the center of the clusters into the residual forest and a weak trend of shade tolerant species becoming less abundant along transect points located in the residual forest to the cluster centers (Table 18). The intermediate shade tolerance species showed no discernable trend from the cluster interiors to the residual forest.

Table 18. Chi-Square results are presented for regenerating species shade tolerance classification by cluster transect locations two years after study establishment for the pine-hardwood establishment study at the University of Tennessee Cumberland Forest near Coalfield, Tennessee. Observed data frequencies, deviations from expected counts, contribution of an individual cell to the overall chi-square test, shade tolerance row percentages, and transect location column percentages are presented for the Chi-Square location by species table.

| Table of Location by Species (p=0.82) | | | | |
|---|---|---|---|---|
| | Species Shade Tolerance | | | |
| Location | Intolerant | Moderate | Tolerant | Total |
| 6.6 ft. | | | | |
| Frequency | 43 | 26 | 21 | 90 |
| Deviation | 3 | -0.6 | -2.4 | |
| Cell Chi-Square | 0.225 | 0.014 | 0.246 | |
| Tolerance Percentage | 47.8 | 28.9 | 23.3 | |

Table 18. Continued.

| Location | Intolerant | Moderate | Tolerant | Total |
|---|---|---|---|---|
| Location Percentage | 21.5 | 19.6 | 18.0 | |
| 13.2 ft. | | | | |
| Frequency | 43 | 25 | 22 | 90 |
| Deviation | 3 | -1.6 | -1.4 | |
| Cell Chi-Square | 0.225 | 0.096 | 0.084 | |
| Tolerance Percentage | 47.8 | 27.8 | 24.4 | |
| Location Percentage | 21.5 | 18.8 | 18.8 | |
| 19.8 ft. | | | | |
| Frequency | 39 | 30 | 21 | 90 |
| Deviation | -1 | 3.4 | -2.4 | |
| Cell Chi-Square | 0.025 | 0.4346 | 0.2462 | |
| Tolerance Percentage | 43.3 | 33.3 | 23.3 | |
| Location Percentage | 19.5 | 22.6 | 18.0 | |
| 26.4 ft. | | | | |
| Frequency | 41 | 26 | 23 | 90 |
| Deviation | 1 | -0.6 | -0.4 | |
| Cell Chi-Square | 0.025 | 0.014 | 0.007 | |
| Tolerance Percentage | 45.6 | 28.9 | 25.5 | |
| Location Percentage | 20.5 | 19.5 | 19.6 | |
| 33 ft. | | | | |
| Frequency | 34 | 26 | 30 | 90 |
| Deviation | -6 | -0.6 | 6.6 | |
| Cell Chi-Square | 0.9 | 0.014 | 1.862 | |
| Tolerance Percentage | 37.8 | 28.9 | 33.3 | |
| Location Percentage | 17.0 | 19.5 | 25.6 | |
| Total | 200 | 133 | 117 | |

## Chapter 7: Discussion-University of Tennessee Highland Rim Forest Site

### *Shortleaf Pine Survival*

Strong trends in survival rates were evident among treatments. Shortleaf pine seedling survival rates appear to have been negatively affected by burn treatments alone (burn treatment and strip burn) more so than the brown-and-burn, herbicide, or the control treatments. Two reasons for this seem likely. First, not all seedlings that were alive prior to the burn treatment re-sprouted as has been reported in other studies (Lilly et al. 2012 Cain and Shelton 2000, Phares and Crosby 1962), and second, seedlings that did not receive topkill or resprouted after topkill following the burns may have been overtopped and outcompeted in their physiologically weakened state by vigorously germinating and resprouting herbaceous and residual broadleaf woody plants.

The seedlings at this site had finished their second growing season when the burn treatments were conducted. Typically 20-50 percent of the stems that are two to three years old die and do not re-sprout following a burn of low to moderate intensity (Clabo 2014, Phares and Crosby 1962). In younger trees, mortality may be greater than for the seedling ages reported in this study (e.g. summer burn in one year-old seedlings with no survival (Cain and Shelton 2000)) and less in older stems that have reached larger sizes (e.g. Ferguson 1957, Lilly et al. 2012). In addition, several other abiotic factors related to burn intensity and severity can alter seedling survival rates such as fuel amounts, types, season of the year, firing technique, fire residence time, weather conditions, and the amount of soil or duff layer surrounding a seedlings' root collar and basal crook (Lilly et al. 2010, Lilly et al. 2012, Waldrop and Goodrick 2012).

Vigorous herbaceous and woody plant growth response following fire in the burn and strip-burn treatments without herbicide control is a possible secondary reason for the reduced seedling survival in those treatments. Competition for mineral nutrients, soil moisture, growing space, and light (if the vegetation is dense and overtops seedlings) can severely damper growth or kill young pine seedlings if unchecked when growing conditions are suitable (Morris et al. 1993, Zutter et al. 1986). Annual and perennial herbaceous plants often become more abundant per unit area through resprouting, stored seed, or wind and/or animal dispersed seed following a fire due to the improved seedbank and growing conditions (DeBano et al. 1998, Miller 2000, Thomas and McAlpine 2010). In addition, abundance and coverage of common woody species that sprout prolifically such as red maple and blackgum can increase following a prescribed fire (Arthur et al. 1998). Herbicide release in young loblolly pine plantations with intense herbaceous and woody vegetation competition has proven successful to increase survival rates (Creighton et al. 1987). Reduced seedling survival due to the burns themselves was likely the primary reason for decreased survival in the two burn treatments, but increased herbaceous and woody competition following burning alone may have also negatively affected seedlings that initially survived the burn treatments through sprouting or non-topkill.

Fuel consumption rates displayed variability across the three burn treatments and likely reflects differences in burn intensity and coverage. Woody fuel amounts did not differ among the three burn treatments before or after the burns, yet there was high variability in the pre-burn woody fuel loads. Large diameter logging slash (100 and 1,000 hour fuels) from the pine species and spacing study that occupied the site prior to the present study was still present in a subset of experimental units and contributed to the high, yet nonsignificant variability in woody fuel loads across treatments and planting spacings. The percent woody fuel amount reduction averaged 26% in the burn and brown-and-burn treatments, whereas the strip-burn treatment only averaged a 9% reduction in woody fuels. This indicates that the strip-burn treatment burns were not as intense, coverage was not as widespread, or a combination of these two factors, leading to this treatment having less woody fuel consumption than the other two treatments. The lack of fire intensity in the strip-burn treatment was likely affected by the density of naturally regenerating woody species such as privet and sumac spp. that were prevalent throughout the experimental units. The dense areas of these shrubs allowed less drying of fine fuels by solar radiation and wind and less probability of ignition (Waldrop and Goodrick 2012).

Chinese privet is an exotic, invasive shrub that was present along the margins of many experimental units and dispersed throughout a few experimental units in the study. The shrub was prominent in regeneration surveys for all treatments except for the brown-and-burn treatment. Privet has serious ecological implications on native plant communities and has been shown to reduce the abundance and species richness of native species (Merriam and Feil 2002, USDA 2002a). Burning can temporarily reduce privet biomass per unit area but it can also result in an explosion of vegetative reproduction the following couple of years after the burn (Faulkner et al. 1989). The site preparation burns conducted prior to the release treatment burns likely resulted in a vigorous vegetative reproduction response of privet, which could then outgrow and overtop the planted pine seedlings with a less developed root system thus reducing survival. Although not quantified, shortleaf pine seemed to be less abundant in areas with privet infestation.

Shortleaf pine seedling survival rates were relatively low compared to other studies with seedlings planted at wide spacings to allow natural regeneration establishment and development among the planted pines. The treatment design of the control treatment in this study was conducted similarly to the fell-and-burn method described and used by Waldrop (1995, 1997) and Phillips and Abercrombie Jr. (1987) to establish mixed loblolly or shortleaf pine-hardwood stands. The fell-and-burn treatment as used in these similar studies involves a winter or spring silvicultural clearcut of all stems greater than 6-feet tall, a mid- or late summer burn, and finally planting of bareroot pine seedlings at wide spacings during late winter or early spring the next year. The primary difference between this study and those past studies other than location and soils (South Carolina Piedmont versus the eastern Highland Rim of Tennessee) is the timing of the burn treatment. The site preparation burn in this study was conducted during late March rather than the period from July-September. Following four growing seasons, loblolly pine survival was 65% in the Waldrop (1995) study compared to 49% for the control treatment in this study. The study by Phillips and Abercrombie (1987) was conducted using planted shortleaf pine and found an average survival rate of 82% following four growing seasons. The pre-harvest vegetation composition and density as well as the timing of the site preparation burn following the winter or early growing season clearcut are likely the primary causes for the discrepancy in survival rates. After the mid- to late summer burn, the regenerating hardwood stems have been killed twice after resprouting, which reduces their height growth capacity the following growing season (Danielovich et al. 1987, Phillips and Abercrombie Jr. 1987). The hardwood stems in this study were topkilled once and this was done during the dormant season with the timing of the clearcut and burn site preparation. The frequency and timing of topkill may have not negatively influenced the hardwoods' root carbohydrate reserves enough to slow height growth during the first growing season.

Shortleaf pine seedlings breaking dormancy prior to planting due to a late lift date, warm and dry weather conditions on planting days, and a severe drought late during the third growing season may have negatively affected survival (Russell 1979, Hallgren 1992). December through March is typically considered the optimal time to lift and plant shortleaf pine throughout the deep and mid-South (Wakely 1954). Unavoidable weather and site delays in the installation of experimental units postponed lifting seedlings at the nursery until March and planting seedlings in early April. Utmost care was used in the field in protecting seedlings during transport and planting seedlings. Past work has shown that slight drops in survival can occur when nursery lift dates occur in March with more pronounced drops in April (Hallgren 1992). The seedlings were planted on April 8 and 9, 2014 on days with high temperatures around 60-65 °F and mostly sunny to partly cloudy conditions. Relative humidity percentages during the late afternoon on both days planting occurred (but after planting during the morning hours) reached the upper 20s. Seedling water absorption through the roots is minimal within the first five days after planting due to the fine roots (if present) attempting to re-establish in the new soil medium, and new root regeneration is critical to survival during this time (Mexal 1992). Dry and sunny conditions on the day of planting can stress seedlings due to increased transpirational demand and minimal water uptake by the roots (Hallgren 1992). In addition, a severe drought occurred throughout the region during the third growing season from August to November 2016 (National Oceanic and Atmospheric Administration 2016). All of these factors together likely contributed to poorer than desirable survival rates.

***Shortleaf Pine Growth***

Shortleaf pine height and diameter growth displayed treatment differences, and means mirrored the degree of treatment intensity. The brown-and-burn and herbicide treatment seedlings tended to have larger basal diameters and heights than the other treatments. The burn treatments had shorter average heights and basal diameters (excluding the strip-burn treatment) than the other treatments. This trend was likely due to a portion of the planted seedlings being topkilled and re-sprouting one growing season after the burn treatment. The seedling resprouts would have reduced the mean height. In addition, the influx of new herbaceous and woody germinants and sprouts following burning can negatively affect planted pine growth without herbicide release (Creighton et al. 1987, Yeiser 1991). The intense competition for soil water and growing space from privet likely also contributed to reduced growth of the shortleaf pine seedlings in some areas of the experimental units.

The annual height growth rate for the control treatment seedlings was lower than expected for shortleaf pine growth in the mid-South and averaged approximately 12 in. per year (adjusting for an average seedling height of approximately 11 in. at planting) and was on the low end of the 1-3 ft. per year range reported by Williston (1972). Shortleaf pine is known to grow slowly during its first couple of years due to the formation of a taproot if soil conditions allow (Guldin 1986). The Dickson soil series that occurs on most of the study site has a hardpan at about 18-36 in. in the profile (National Cooperative Soil Survey 2001). This hardpan would prevent a large taproot from forming and require the seedling roots to grow horizontally for water and nutrient absorption to a greater extent. Past work has reported that planted bareroot seedlings with more numerous horizontally oriented lateral roots concentrated near the soil surface have poorer height growth than seedlings with more vertically oriented root systems (Harrington et al. 1987). The Dickson soil series on the study site could have partially affected shorter than expected heights after three growing seasons.

Basal diameter growth trends tended to mirror those revealed in the height analysis except for the strip-burn treatment, which had seedlings with the second largest average basal diameter. This treatment did have the largest basal diameter standard error, indicating substantial variability in the measured seedlings. The strip-burn treatment had areas of dense competing vegetation (greatest average density per acre by treatment in the study) as well as areas with virtually no competing vegetation, which may have contributed to this result. The areas of the experimental units that were free of competing vegetation had larger basal diameters than areas with dense competing vegetation and surviving shortleaf pine seedlings. Annual average basal diameter growth rate was lower for all treatments in this study than reported by

Phillips and Abercrombie Jr. (1987) in a similarly designed study conducted in upstate South Carolina. The site preparation method used in the control treatment for this study and the procedures used in the study by Phillips and Abercrombie Jr. (1987) were virtually identical except for the timing of the burn treatment. Average annual basal diameter growth in the South Carolina study averaged 0.46 in. per year across each of their three study sites, whereas average annual growth ranged from 0.18 in. in the burn treatment to 0.39 inches in the brown-and-burn treatment in this study. Similar to height growth response, shortleaf pine basal diameter growth is correlated to root development and orientation, which is different in bareroot seedlings than seeded or naturally regenerated seedlings (Carlson and Harrington 1987, Harrington et al. 1987). Vigorous woody vegetation competition and physical soil characteristics probably affected basal diameter growth negatively.

A statistically significant difference in the two planting spacings was present for basal diameter. The regenerating woody species and the planted shortleaf pine in this study had not differentiated in height yet, but growing space for new germinants was limited by high woody stem densities throughout most of the treatments. This structural condition would be considered the beginning of the stem exclusion phase or brushy stage of stand development as described by Oliver and Larson (1996). With the lack of height differentiation and the aboveground portions of the stems all being roughly the same age with similar competitive pressures at this early stage of development, shortleaf pine basal diameter differences in the two planting spacings are most likely not a result of competitive influences. The difference in sample size between the two spacings may have contributed to this difference

***Natural Regeneration***

Natural regeneration stem densities also reflected the intensity of the site preparation and release treatments imposed on an experimental unit. The two herbicide treatments resulted in the fewest stems per acre with the brown-and-burn treatment having significantly fewer stems per acre than the herbicide only treatment. The average number of natural regeneration saplings (4.5 ft or taller) per acre in the herbicide only treatment (626) were virtually identical to the number (≈600) reported after five years for herbicide control using the same herbicides on 7-year-old woody vegetation at Crossett Experimental Forest in

Arkansas (Cain 2000). The control treatment used nearly the same site preparation and timing of these methods as the upstate South Carolina study reported by Waldrop (1995), but had fewer stems per acre on average (8,714 versus 11,037 stems per acre), but other factors such as, existing rootstocks, soil conditions, and climate differences could significantly influence regeneration response. The strip-burn treatment had the most regenerating stems per acre of any treatment, likely due to the amount of pole size privet and callery pear present on the strip-burn site prior to study establishment and the drum chopping and burn treatments causing vigorous root and stump sprouting of the privet and callery pear in the growing seasons following treatment (Faulkner et al. 1989, Culley and Hardiman 2007). The stem density pattern presented in this study shows a trend of more stems in less disturbed treatments (control) and fewer stems in more disturbed treatments which has been reported in other pine-hardwood site preparation studies (e.g. Mullins et al. 1998).

Natural regeneration height did not differ by treatment. Regeneration height in the control treatment was tallest of any treatment, yet it was not statistically different. Proper timing of fell-and-burn site preparation (late summer burn) can reduce the height growth of natural regeneration following the harvest and burn compared to clearcut only treatments (Waldrop 1995). Only one full growing season had passed since the burn and final herbicide treatments were conducted, which likely was not enough time for differentiation in height to occur due to treatment effects.

Natural regeneration composition was most diverse (in terms of number of species present) and favorable from a mixed stand perspective in the brown-and-burn treatment. Nonnative and invasive woody species only comprised about 12% of the species composition and species from the red and white oak families totaled 23% of the regenerating stems. The more favorable regeneration composition in this treatment may be due to a combination of three reasons. The first, and probably most important reason, is the dearth of invasive species such as privet, callery pear, white poplar, etc. in the brown-and-burn experimental units prior to study establishment. The second reason is the possible control provided by the combination of the site preparation and release burns coupled with the herbicide treatment. The first burn treatment and drum chopping would have reduced the biomass of any invasive species (assuming complete coverage by the site preparation burn). Then the herbicide treatment would have killed most resprouts. Finally, the hotter and more widespread release burn would have topkilled any surviving invasive species a second or possibly third time. The third possible reason for this result is that oak and hickory species along with red maple tend to have better root recovery following an imazapyr and metsulfuron methyl herbicide treatment than many other species typical of upland mixed hardwood forests (Miller 1990). This last reason may explain why these three species are some of the more common species present even though two herbicide release treatments were conducted.

Although the brown-and-burn treatment had satisfactory woody regeneration composition, the herbicide treatment was almost completely occupied by privet (82%) according to regeneration surveys. The imazapyr rates used were at the lower end of the range listed on the Arsenal AC® label for shortleaf pine release, but the amount applied per acre was much less than is listed for privet control (BASF Corporation 2010). This information indicates that privet control after seedling establishment using imazapyr may not be possible. Privet is not listed on the label for Escort® (Bayer Environmental Science 2017), so privet control was not likely through the use of metsulfuron methyl. The two herbicide applications alone without burning were likely not intensive enough to control the plethora of privet stems in some locations. In addition, privet was likely more common on these experimental units than the brown-and-burn treatment units prior to study establishment.

The burn, control, and strip-burn treatments all had similar regeneration compositions. Sumac *spp.* and privet were the two primary species in each treatment, while species such as red maple and devil's walkingstick were minor species components common to all three treatments. Species from the red and white oak families comprised 4% or less of the regenerating stems in each treatment. The use of fire either as a site preparation treatment only (control treatment) or combined with a release burn (burn and strip-burn treatment) likely contributed to the dominance of sumac and privet (USDA 2002b, Faulkner et al. 1989). Both species are considered pioneer species with their abundant seed crops and can reproduce by clonal root growth (Faulkner et al. 1989, Werner and Harbeck 1982). In addition, the past land use of the site (pine plantation species and spacing study) may have caused poor regeneration potential of heavy seeded regeneration sources such as oaks and hickories. Oaks on moderate to poorer sites are more likely to reproduce successfully after a disturbance through advance regeneration or stump sprouting from established root stocks than by seed (Johnson et al. 2009). The herbicide site preparation used to establish the original pine spacing study that was present on the site in the mid-1960s likely reduced the number of oak and other hardwood species' root stocks. When this study was terminated and harvested, the bare soil conditions on the site likely allowed privet and sumac spp. to invade and dominate the regenerating species composition.

***Shortleaf Pine and Natural Regeneration Dynamics***

Growth of surviving shortleaf pine seedlings established adjacent to hardwood stems with established root stocks will likely be suppressed by stump or root sprouts from intact root systems already in place, soil moisture limitations, reduced growing space, and shading imposed on the planted seedlings by these sources of regeneration (Oliver and Larson 1996). Microsites containing shortleaf pine and available growing space are more likely to grow and survive to stand maturity than sites with dense woody competition (Creighton et al. 1987). Free growing space will likely be more available in the two herbicide treatments, which have the lowest densities of woody stems per acre. Cain (1997) has shown that woody vegetation control using herbicides for five successive years (this study used herbicides for two years) can improve shortleaf pine growth for more than one year following treatment. Excluding the control treatment, the other two treatments have lower survival rates than the two herbicide treatments as of year three, indicating that natural regeneration may partially (along with the burns topkilling some seedlings) be reducing the shortleaf pine survival rates. Use of herbicides as site preparation alone or combined with burning or mechanical methods would have shifted the long term species composition towards pines more due to their improved growth rates during the first few years following planting (Mexal 1992, Yeiser and Barnett 1991). Overall, the two treatments that included herbicide applications will likely have more and larger shortleaf pine stems once these stands reach crown closure.

Treatments with less intensive release methods such as the control, burn, and strip-burn treatments will likely have greater stem densities per acre of hardwood or naturally regenerating pine stems and fewer and smaller planted shortleaf pine stems per acre than the more intensive herbicide treatments once these experimental units reach crown closure. Similar results were reported by Clabo and Clatterbuck (2015) in Tennessee with loblolly pine and eastern white pine planted at wide spacings following application of varying intensity site preparation treatments. The more intense treatments that included burning such as the fell-and-burn treatment and herbicide (e.g. brown-and-burn treatment) resulted in stands dominated more by the planted pine after 22 years than less intensive treatments such as a silvicultural clearcut and commercial clearcut, which resulted in greater abundance of hardwoods and poor planted pine survival rates and growth (Clabo and Clatterbuck 2015). Site productivity can also affect how well planted pine does in association with natural regeneration. Thirty-four year results of another fell-and-burn study with shortleaf pine planted at wide spacings in upstate South Carolina noted that basal area of shortleaf pine was greatest on the better sites of the study, whereas hardwoods constituted more of the basal area on poorer sites (Pile and Waldrop 2016). Soils and site productivity at the Highland Rim Forest do not differ greatly among experimental units besides slight changes in elevation, which could affect soil water holding capacity especially in soils containing hardpans. Any evident differences in shortleaf pine dominance as the study ages may be attributable to these slight changes in topography. Steinbeck and Kuers (1996) indicated that less intensive treatments to establish mixed pine-hardwood stands at wide pine spacings following a silvicultural clearcut in Georgia can also produce high densities and stocking of planted loblolly pines at older ages (age 10). The results of this Georgia study may not be applicable to shortleaf pine-hardwood management because loblolly pine survival after three years was greater in the Georgia study (70%) than any treatment implemented at the Highland Rim Forest.  Overall, the less intensive release methods will likely have a species composition that has greater hardwood stocking than shortleaf pine.

The average height results after three growing seasons for shortleaf pine and the natural regeneration indicate that the shortleaf pine is still not overtopped except for in the strip-burn treatment. Similar results were found after four years by Phillips and Abercrombie (1987) where the number of free to grow seedlings ranged from 71 to 91% across three separate study sites. Seedlings that survive planting, the burn treatments, and natural regeneration competition seem to be persistent enough to reach later stages of development. Past research and field trials have shown that planted shortleaf pine that survives the first couple of years after planting is very likely to reach crown closure (Wakely 1954). Although shortleaf pine is reported to have slow initial growth rates during its first couple of years, the surviving trees in this study are at the point where their height growth rate should begin to increase until crown closure is reached, which could reduce the chances of the trees being overtopped in the next few years (Guldin 1986). As these stands develop and the stem exclusion stage of stand development progresses, growth and shade tolerance differences in species will become more pronounced (Oliver and Larson 1996). If shortleaf pine maintains its height advantage, most of the currently surviving shortleaf pine stems will likely be a part of the stand at maturity assuming no major additional disturbances occur.

## **Chapter 8: Discussion-University of Tennessee Cumberland Forest Site**

### ***Shortleaf Pine Survival***

Shortleaf pine survival rates displayed no differences among treatments. The short duration between when seedlings were planted, treatments were completed, and measurements were taken are attributable to no differences being apparent. At the time of measurements, the seedlings had completed two growing seasons. In addition, the burn and herbicide treatments were completed only one full growing season before measurements were taken during winter of 2016/2017. The full effects of the treatments and inter- or intraspecific competition likely have not fully been realized yet. Conversely, Wakely (1954) reported that shortleaf pine seedlings that survived their first growing season tended to have fairly constant survival rates after this critical period until stand crown closure occurred. The actual effect of time since planting and treatment implementation most likely is between these two extremes.

The planting date for the seedlings in this study was later than the period when most seedlings are planted in the South and mid-South (December through mid-March) (Hallgren 1992). Most seedlings reach a physiological peak in mid-March before they break dormancy, and survival and growth is greater when planting occurs just before this period because of stored carbohydrates in the roots and greater potential for root growth after transplanting (Barnett et al. 1986, Hallgren 1992). Mineral nutrition, carbohydrate reserves, electrical impedance, and bud dormancy tests can all be used on a subset of seedlings to quickly test the physiological state of conifer seedlings for new root growth after transplanting (Carlson 1985, Hallgren 1992, Richie 1982, van den Driessche and Cheung 1979, Wakeley 1954). Planting seedlings at later dates may be a viable strategy to improve survival on exposed, high elevation sites prone to late season frosts or freezes. The Cumberland Mountains of Tennessee often experience harsh freezes and ice storms well into February or March. The later planting date likely improved seedling survival due to the milder weather conditions in April. The region around Little Brushy Mountain received above average rainfall during the summer months of 2015, and rainfall occurred on the day of planting making drought an unlikely causal factor of low survival (National Oceanic and Atmospheric Administration 2017, Wakely 1954).

Several factors synergistically combined for the low survival rates incurred in this study and include: later than normal seedling lifting date from the nursery; lack of culling of small trees by the planting crew; thin, rocky soils on most of the site; a third year drought and concomitant redheaded pine sawfly defoliation; high shade from the older, residual cohort; and burn treatments killing some seedlings. The lifting date for the seedlings planted at the Cumberland Forest was March 9, 2015 (Conn 2017). Past research has demonstrated that cold storage shortleaf pine seedlings produce fewer new roots and less root volume the growing season after planting. Slightly lower survival rates with March lifting than January or February lifting have been reported (Hallgren 1992).

The planting crew contracted to complete the planting did not cull morphologically inferior seedlings at this site due to a limited number of available seedlings and the time restraints moving the crew from cluster to cluster across the site. Research has demonstrated that bareroot seedlings should be at least 7-11 in. tall at planting and have diameters greater than 0.2 in. at one inch above ground level to improve survival and long term growth (Barnett et al. 1986, Clark and Phares 1961). If more seedlings had been available to plant and time had been available to teach the planting crew to grade seedling stock for morphological traits, seedling survival probably would have been improved across all treatments.

The Gilpin-Boulin-Petros complex soil type that covers most of the study area is very rocky. Stones that are 10-23 inches in diameter are present throughout the profile and comprise 35-60 percent of the soil by volume (Web Soil Survey 2015). The presence of these stones and the thinness of the soil to bedrock could have contributed to low seedling survival rates. Survival and growth of planted seedlings in rocky soils can be improved by a type of mechanical site preparation known as ripping, which loosens the soil by moving a large blade through the soil to provide free drainage and surface runoff. Ripping also creates channels to collect surface runoff and improve soil moisture content. The method has been shown to improve short term survival and growth of southern pine species by 10-30% when applied in rocky soils, yet can negatively affect diameter and volume growth over the long term (Guldin 2007, Gwaze et al. 2007, Wittwer et al. 1986).

A severe drought occurred throughout the mid-South during the late summer and fall months of 2016 at the end of study's second growing season (National Oceanic and Atmospheric Administration 2016). Drought causes reduced survival in tree seedlings, and it can increase the abundance of forest insect pests which are more likely to damage or kill trees in their weakened state (Barnes et al. 1998). Redheaded pine sawfly (*Neodiprion lecontei*) was identified on seedlings during the winter 2016/2017 measurements. Outbreaks of this insect occur most commonly in young pine stands less than 15 feet tall and in pines growing near hardwoods with heavy vegetation competition and on poor productivity sites (Wilson and Averill 1997). These characteristics were all present at this site. The insect defoliates pine seedlings and saplings, which stresses them, and coupled with severe drought, death can easily occur. The combination of redheaded pine sawfly and drought seedling mortality was about 3% across all treatments and likely increased during the months after seedling assessment due to some seedlings still being classified as alive at the time of assessment, yet having ongoing defoliation.

Partial overstory shade is considered beneficial to many artificially regenerated temperate deciduous tree species due to the protection offered from wind, frost, and other stressors as well as reduced understory competition. However, most of the time, the species that are planted in these scenarios are considered at least partially tolerant of shaded conditions (Paquette et al. 2006). Shortleaf pine is classified as a shade intolerant species (Lawson 1990). Percent overstory shade by treatment in this study ranged from a high of 60% in the control treatment to a low of 21% in the brown-and-burn treatment. Investigations in the Missouri Ozarks with underplanted shortleaf pine seedlings have examined the effects of varying overstory stocking or shade levels (with no midstory stratum present) on seedling survival and growth over five growing seasons. They reported that survival decreases slightly with greater shading but the relationship was not statistically significant (Kabrick et al. 2011, Kabrick et al. 2015). Another study in the Ouachita Mountains region of Arkansas had similar results (Guldin and Heath 2001). Shortleaf pine seedlings were planted under varying levels of residual hardwood overstory after the midstory had been killed by herbicide injection. Seedlings were assessed at three, five, and seven years and minor to no changes in planted seedling density were discovered by level of overstory stocking

(Guldin and Heath 2001). Evidence from these and other studies (e.g. Becton 1936, Shelton 1995, Shelton and Cain 2000) suggests that underplanted shortleaf pine survival is not significantly affected by overstory shade. Direct overhead sunlight in the clusters of this study was not affected by a midstory because of the removal of all stems more than three feet tall within and on the boundary of the clusters. Midstory hardwoods adjacent to the clusters likely affected light infiltration from the side of the clusters. The possible effects of the surrounding midstory on shortleaf pine survival may merit more investigation.

The two burn treatments in this study experienced slightly lower, albeit non-significant, survival rates than the other three treatments. These slightly lower survival rates are probably a result of some seedlings not surviving and resprouting following topkill by the burn treatment. A 20-50% reduction in survival has often been reported in topkilled two to three-year-old shortleaf pine seedlings (Clabo 2014, Phares and Crosby 1962). Often a seedlings' ability to resprout is a function of burn intensity and residence time, the physiological state of the seedling, the seedlings' size, and the location of the basal crook (where dormant buds are located) in the duff or upper soil layer (Lilly et al. 2010, Lilly 2011). The seedlings in the burn treatments actually fared well after one full growing season following burns. Survival rates of seedlings in the burn treatments were not statistically different from the other treatments. The removal of most of the larger logging slash (100, 1,000, and 10,000 hour fuels) from within the clusters during establishment probably reduced the residence time and intensity of the burns (Brown 1974).

Abiotic site factors were evaluated for their effectiveness in predicting shortleaf pine survival due to the diversity of topographic positions, light regimes, and certain soil physical characteristics (scarification treatment only). Similar site evaluation methods have been formulated for oak forests and cove hardwood forests (Gysel and Arend 1953, Johnson et al. 2009, McNab 1993). The four variables used for prediction (elevation, percent light, aspect, and percent slope) of shortleaf pine survival for the non-scarification treatments were not successful. The effects of the treatments applied to the seedlings, possible homogeneity of these variables across the site, a different underlying cause affecting seedling survival, or a combination of these factors likely attributed to the poor prediction. The model devised for seedlings growing in scarified conditions following logging was capable of prediction. Elevation, visual scarification rating, and slope percentage could be used to predict shortleaf pine survival. A greater scarification rating and percent slope tended to have a positive impact on seedling survival, whereas survival tended to decrease with increasing elevation. Greater scarification and percent slope values and positive survival trends likely stem from less competing herbaceous vegetation induced from the disturbed (skid trails) soil conditions. The lower elevation values and greater survival likely are correlated to less extreme climate stressors such as drying winds and frost at lower elevations. Further field testing of this model should be completed to determine its capabilities in predicting shortleaf pine seedling survival.

Seedling survival differences by treatment were not apparent two years after establishment, but differences may become more evident as seedlings develop. Underplanted shortleaf pine seedling survival can possibly be affected by many different biotic and abiotic factors. The effects of these factors on survival rates can range from the obvious as in the case with redheaded pine sawfly defoliation to more indirect effects such as slightly later than normal seedling lifting and planting dates from the nursery. Shortleaf pine survival in underplanting situations could be improved upon by understanding these factors more thoroughly and managing for those issues that can be influenced to reduce their negative effects on seedling survival.

***Shortleaf Pine Growth***

Basal diameter displayed no differences in treatment means when the trees were assessed. The short time period since treatments were applied and young seedlings' growth strategies after planting probably contributed to the lack of treatment response. Trees tend to allocate photosynthate to fine root production and height growth before diameter growth, which are more vital in ensuring survival during their early years (Oliver and Larson 1996, Wakely 1954). In addition, basal diameter growth of shortleaf pine is directly related to the level of root system development (Carlson and Harrington 1987). Prolific fine root production enables the seedling to obtain water from the soil more efficiently to avoid the stress of drought. Consistent height growth allows seedlings to avoid shading from adjacent, competing vegetation (Hallgren 1992). Trends, though not statistically significant, were evident in basal diameter growth. The most obvious trend was the larger average diameters of the scarification treatment seedlings. Artificially regenerated seedlings growing in scarified soils often grow more quickly with less vegetation competition (Löf et al. 2012). Another trend was the slightly greater average basal diameter growth of the two herbicide treatments as compared to the control or burn treatment, which is probably a function of less competing vegetation in these clusters (Cain 1991, Creighton et al. 1987, Yeiser and Barnett 1991). Other southern pine species have shown improved first year diameter growth following woody and herbaceous plant control with herbicides (Zutter et al. 1986). The burn treatment seedlings had the smallest average diameters. Many of these seedlings were resprouts and had to contend with herbaceous and woody vegetation sprouts and new seedlings following the burns (DeBano et al. 1998, Miller 2000). Seedling basal diameter trends by treatment will likely become more pronounced as they age and reach larger size classes.

Seedlings in this study were shorter in height than expected after finishing their second growing season as compared to the annual average range reported for shortleaf pine seedlings (1-3 ft/year) by Williston (1972) and the two feet per year average under a mixed pine-hardwood overstory in southeastern Arkansas reported by Reynolds (1950). One possibility for this trend is poor root development of the seedlings due to the rocky soil conditions on the site. Harrington et al. (1987) demonstrated that planted shortleaf pines which develop lateral roots that spread outwards instead of downward typically have poorer height growth than those with roots that grow vertically. On this site, the rocky soil conditions may have resulted in some seedlings being planted on locations where the root system could not grow sufficiently in the vertical orientation and were forced to grow horizontally, thus reducing height growth rates.

Shading of planted and naturally regenerated shortleaf pine seedlings has been proven to reduce growth rates in a number of studies and may be one of the primary factors behind the lower than average height growth rates observed. Kabrick et al. (2015) stated that level of overstory stocking explained 47% of the variation in height for two-year-old underplanted shortleaf pine seedlings in Missouri. In an

Arkansas study with artificially regenerated seedlings, Guldin and Heath (2001) reported greater average heights for seedlings and saplings at age five and seven growing with no residual overstory with incremental decreases in mean height as residual stocking increased by levels of ten percent. Overstory retention levels were investigated in Missouri using different regeneration harvest methods (including the shelterwood method with differing amounts of overstory stocking retained), with results suggesting that all regeneration methods besides the clearcut and group selection (if group openings are large enough) caused planted shortleaf pine seedling growth reductions (Jensen et al. 2007). In summary, shortleaf pine seedlings that receive partial overhead shade apparently do not grow as well as those in full sunlight reflecting the shade intolerance of shortleaf pine.

The seedlings in the scarification treatment were significantly taller than the other four treatments in this study. Clusters with greater scarification levels based on the visual assessment (levels three and four) had very few competing herbaceous and woody plants after two growing seasons. Scarification benefits planted seedlings in two ways. The first is the removal of competing vegetation, which will depend on the degree of scarification (Nyland 2007, Prevost 1997). Levels three and four had enough soil disturbance to remove some roots of established vegetation and dormant seed in the seed bed. Competing vegetation pressure will be limited following that amount of scarification until new plant propagules colonize the site. The second possible benefit of scarification to planted seedlings is the possible physical changes of the soil that modify soil moisture and temperature that are favorable to seedling growth and the removal of existing vegetation from the site (Löf et al. 2012). Soil compaction and even some soil textures such as heavy clay soils reduce the ability for plant roots to penetrate the soil and uptake nutrients (Pallardy 2008). Even though increased soil compaction, bulk density, and erosion rates are well-founded drawbacks to scarification treatments on some sites (e.g. Dickerson 1976), shortleaf pine does not tend to be negatively affected by moderate to severe compaction as was typical of scarification levels three and four. Research by Ponder (2007 and 2011) has shown increased growth rates for shortleaf pine on compacted sites after nine years compared to non-compacted sites. In addition, root growth and biomass were not adversely affected by compacted soil conditions in those studies. The results in this study suggest that scarification and moderate soil compaction due to logging equipment may significantly enhance shortleaf pine growth for at least two years.

The influence of competing vegetation for soil water, nutrients, growing space, and sunlight does not appear to have affected shortleaf pine growth rates after two years. Natural regeneration density within cluster interiors of the two herbicide treatments was significantly lower than in other treatments, yet these lower densities do not appear to have significantly improved shortleaf pine growth in these treatments after two growing seasons. Bower and Ferguson (1968) stated that understory hardwood removal in fully-stocked stands using only herbicides can significantly increase shortleaf pine regeneration growth rates. Blizzard et al. (2007) reported that an individual shortleaf pine seedling's chances of growing to reach a dominant or codominant crown position when a residual hardwood overstory was present improved with lower natural regeneration densities per unit area. These two studies suggest that shortleaf pine seedling growth will improve given constant overstory stocking percentages when less interspecific competition is present. Further monitoring is warranted to determine if the herbicide treatment improves seedling growth compared to other treatments.

Shortleaf pine seedling basal diameter and height could be predicted by cluster light levels, elevation, and percent slope for all treatments excluding the scarification treatment. Light levels or percent stocking are important determinants of shortleaf pine growth in other studies, and predictable decreases in growth will occur as light levels decrease (Guldin and Heath 2001, Jensen et al. 2007, Kabrick et al. 2011, Kabrick et al. 2015). Elevation and slope are direct indicators of site quality and climate conditions. Increasing percent slope had a negative effect on basal diameter and height growth. Soil water holding potential deficits on steeper terrain likely decreased the rate of basal diameter and height growth. In addition, site index changes with varying slope steepness depending on aspect (Barnes et al. 1998, Carmean 1967). Increasing elevation resulted in greater shortleaf pine growth. The Lily-Gilpin soil complex located at the top of Little Brushy Mountain is more productive in terms of site index and less rocky than the Gilpin-Boulin-Petros complex soil type located on most of the lower slope positions throughout the site. Though elevation differences between the bottom and top of Little Brushy

Mountain were only 600 feet, elevation changes result in micro-site and micro-climate differences in temperature and precipitation. Elevation of a site at a known latitude can be an indicator of plant performance (Barnes et al. 1998). More research should be performed to determine if elevation, slope, and light levels can be used to predict planted shortleaf pine growth on other sites in the region.

No suite of variables was able to predict growth of seedlings in the scarification treatment. The reasons for this are unclear, but this finding could be a result of a variety of factors. Factors include measurements of soil physical or chemical properties that were not completed or a possible micro-climatic effect caused by the scarification that was not accounted for in the model.

***Natural Regeneration***

Stem densities during the seedling or stem initiation stage are greatest when the competition for light, water, and nutrients among stems is intense (Barnes et al. 1998). Treatments that have comparatively few stems (and desirable species present) per unit area during this developmental stage following site preparation or release could grow stems at faster rates due to less competition for resources and greater amounts of growing space. Natural regeneration densities within clusters reflected the intensity of the treatment imposed upon them, and stem densities in this study varied by treatment compared to studies with analogous treatments conducted in similar upland forest types. The control treatment, which only received felling of stems greater than three feet tall at the time of cluster establishment, had the most regenerating stems per acre. The number of regenerating one foot tall to one inch dbh stems per acre for the control treatment in this study was much greater both inside and outside of clusters (19,833 and 14,500 per acre) than the average per acre (9,100 per acre) reported by Miller and Schuler (1995) two years after a similarly conducted two-age regeneration harvests in West Virginia hardwood stands. The herbicide treatments had less than 20% of the stems than the control treatment, whereas the burn treatment had about a third as many stems. The herbicide mixture used in this study was very effective with more suppression of woody plants (as compared to the control treatment) than other similar studies (Cain 1991, Cain 2000), yet overstory shade differences existed that would likely confound results when comparing this study with others that have completed herbicide release treatments in young, previously clearcut stands. The burn treatment cluster interiors in this study had fewer regenerating woody stems per acre on average than reported after two to three years in hardwood and oak/pine stands after one prescribed fire (Arthur et al. 1998, Elliot and Vose 2005). The burns in all three studies were conducted during March. Discrepancies in burn intensities and fuel loads are hypothesized for differing results between these studies. The brown-and-and-burn treatment, though implemented as a release treatment in this study rather than a site preparation treatment, had the fewest stems per acre. Mullins et al. (1998) reported a similar finding for a site preparation brown-and-burn treatment when used to establish either loblolly pine-hardwood or white pine-hardwood stands.

No differences by treatment in the number of stems per acre were apparent outside of the clusters, indicating that the burn treatments had not altered regenerating stem densities in the residual forest around clusters. The average number of stems per acre (18,726 per acre) across all treatments outside of clusters was similar to the average stem density reported for the control (21,821 per acre) treatment by Arthur et al. (1998).

Natural regeneration height growth likely did not display any treatment differences. This result is likely more a function of similar light levels and regeneration sources across treatments rather than treatments altering competitive effects and micro-climates within clusters at this early age of the study. New stems originated from a variety of regeneration sources such as stumps sprouts, seed, and seedling sprouts, which all grow at different rates depending on size, species, and environmental conditions (Loftis 1990, Sander 1971). The partially shaded conditions within all treatments of the study probably reduced height growth rates for some species and forms of regeneration sources while increasing growth rates in others. For instance, hardwood sprouts in a southern Appalachian study displayed greater growth rates one year after harvest following 30 and 40 percent overstory reduction compared to 10 and 20 percent overstory reduction (Keyser and Zarnoch 2014). This result was likely a result of more shade intolerant species utilizing the increased light levels, while shade tolerant species grew at similar rates under all light conditions (Yanai et al. 1998). Nevertheless, natural regeneration cumulative growth averaged across all treatments and regeneration sources two years after harvest were very similar to at least one other study that was conducted in upland hardwood stands where a portion of the overstory was removed (≈60 $ft^2$ $ac^{-1}$ basal area left as residual) (Brose and Van Lear 1997). Natural regeneration growth rates will likely increase as regeneration reaches larger size classes, mortality rates of regenerating woody stems increase, and as subcanopy recruitment fills the cluster gaps (Barnes et al. 1998, Weber et al. 2014). This pattern may not occur if residual overstory trees expand and fill the gaps where the clusters are located (Hibbs 1982).

Regeneration composition did not display noteworthy differences from cluster interiors to exteriors across treatments. Deerberry was common in all treatments except the scarification treatment. Most *Vaccinium* species, including deerberry, can form extensive colonies and reproduce prolifically by runners that can occur either above or belowground (Miller and Miller 2005). *Vaccinium* species have been noted as being serious competitors in young southern pine stands in at least one other study (Cain and Mann Jr. 1980), but because deerberry does not reach heights of more than six feet tall it is not considered a sunlight competitor but more of a soil water and nutrients competitor (Miller and Miller 2005). In the scarification treatment, where deerberry was uncommon, scarification likely removed most or all of the runners from the soil, thus removing the species from this treatment. Perhaps not coincidentally, planted shortleaf pine height growth was greatest in this treatment.

Mountain laurel was the only other species that was prevalent in more than one treatment. Mountain laurel is considered a major competitor of regenerating woody stems and herbaceous vegetation due to its vigorous sprouting ability when the stem is damaged, especially after burning (Miller and Miller 2005, Swift et al. 1993). The species can form dense thickets that create heavy shade that kills or limits the growth of new regeneration (Clinton et al. 1997, Clinton et al. 1993, Swift et al. 1993). Oak regeneration ranged from a low of 5.5% of the regenerating stem composition in the herbicide treatment to 18.3% in the control treatment. Oaks tended to be to be most prevalent in the two treatments that lacked fire or herbicide. This trend is likely a result of less oak seedling mortality in the non-herbicide treatments. In addition, oaks tended to be more prevalent in cluster interiors than exteriors. Improved light and seedbed conditions, especially in the scarification treatment, may have enhanced oak regeneration densities from seed (Lhotka and Zaczek 2003).

The cluster exteriors had similar regeneration composition as the cluster interiors across treatments. Deerberry, mountain laurel, and azalea spp. were common in most treatments. Red maple was more prevalent across cluster exteriors rather than within clusters. One notable addition was sumac spp. being the most prevalent species in the brown-and-burn treatment. Sumac is considered an intense competitor of planted pine seedlings (Cain and Mann Jr. 1980). However, sumac colonies can be beneficial to natural woody regeneration as they can improve tree colonization following disturbance due to frequent wildlife occupancy and their resultant seed dispersal. In addition, sumac colonies can reduce the abundance of competitive herbaceous vegetation cover (Werner and Harbeck 1982).

Red maple is a vigorous competitor to many desirable tree species and colonizes successfully using multiple regeneration methods (Abrams 1998). Monitoring of red maple movement or influence from the cluster exteriors to interiors for release treatments may be beneficial. Oak regeneration composition ranged from 7.6% in the brown-and-burn treatment to 16.3% in the burn treatment. The burning treatments that were conducted throughout the burn and brown-and-burn treatments, coupled with the reduced overstory stocking, may mimic the shelterwood and burn method that has favored oak sprouting over other species and improved oak height growth when oak regeneration was present on the site prior to the first regeneration harvest (Brose and Van Lear 1997). The oak composition should be monitored in the coming years to determine if this pattern occurs.

No statistical differences were indicated in natural regeneration height or basal diameter occurred along transect locations by distance from cluster center into the residual forest. One of two factors likely explains this finding. First, the canopy openings and soil disturbance caused by the partial logging operation and cluster establishment may not have been intense enough to stimulate new regeneration establishment or greater existing stem growth inside of the clusters (6.6 and 13.2 ft. locations) than outside (19.8, 26.4, and 33 ft.) of the clusters. The second possibility was the regeneration within the cluster openings was able to grow quickly enough (as might be expected with fast growing shade intolerant species such as yellow-poplar) following treatments so that stems inside the clusters roughly equaled the size of any regeneration present within the residual forest at the time of assessment. Past work has demonstrated that shade intolerant species densities are more sensitive and responsive to gradual changes in stocking or overstory shade from open to partial or heavy shade, whereas shade tolerant species have a slower growth response, yet their densities are uniform in all shade conditions (Canham 1988, Yanai et al. 1998). A combination of both of these explanations is likely and is made more complex by the different shade tolerances and growth rates of the many species present as well as by the varied topography and shade conditions on the site.

Statistical differences in the distance to the nearest regenerating stem by transect location were detected. The two transect locations within clusters required longer distances to the nearest regenerating stem as compared to the transect locations outside of the clusters. This finding is probably exclusively a result of the two herbicide treatments significantly reducing the number of woody stems in those treatment clusters, thus causing an increase in mean distance to a regenerating stem at the two transect locations within clusters across all treatments. Establishment and recovery of certain species such as red oaks, white oaks, and hickories in the herbicide treatments will likely occur due to the propensity of these species to recover well after imazapyr and metsulfuron methyl applications. However, species such as yellow-poplar may take longer to establish from sprouts (though establishment from seed is likely) because they are more sensitive to applications of this herbicide mixture (Miller 1990). Regeneration densities may increase over time in these two treatments if shortleaf pine survival is poor due to the open growing conditions.

***Stand Dynamics***

Management methods that favor mixed pine-hardwood stands are complex due to the different silvical characteristics of the many species present and the difficulty of obtaining pine or shade intolerant hardwood regeneration when shade is cast by overstory or understory hardwoods and shrubs (Baker et al. 1996, Clinton et al. 1997). Crown density and canopy structure can vary widely by species' shade tolerances and canopy position in temperate deciduous forests (Ellsworth and Reich 1993). Differences in canopy structure (as well as soil moisture effects on foliage production in a particular climatic zone) influence the amounts of leaf surface area at different canopy levels that is able to capture light energy and prevent it from reaching the forest floor (Barnes et al. 1998). Research in shortleaf pine-hardwood stands in Arkansas has revealed that most hardwoods (except some shade intolerant species) with their crown architecture and leaf characteristics produce about twice as much shade or canopy cover as a pine of equivalent size (Baker et al. 1996, Shelton and Baker 1992). This relationship suggests that a moderate to heavy hardwood mid- or overstory will reduce the survival and growth of desirable shade intolerant species such as shortleaf pine and favor shade tolerant species over time. (Runkle 1998, Tryon et al.1992).

The planted shortleaf pine component after two growing seasons is currently taller and growing at a similar rate as naturally regenerating stems within all treatments except the burn treatment. Similar growth rate patterns between pine and hardwood regeneration under varying residual overstories was reported by Kabrick et al. (2011 and 2015). This trend is likely a result of the residual overstory limiting development of fast growing shade intolerant species, and the shortleaf pine seedlings' height advantage (at least briefly) over natural regeneration due to the cutting of all stems three feet tall or greater when clusters were established (Nyland 2007). One possible concern for the shortleaf pine regeneration is rapid growth of under and midstory hardwood stems that were present prior to study establishment and were either felled or felled and treated with herbicide. Shelton (1997) determined that submerchantable hardwood stems that were chainsaw felled or treated with herbicide (as in this study) quickly outgrew shortleaf pine that was established from seed under shortleaf pine-hardwood shelterwoods. Fewer submerchantable stems were present and treated (cut and/or herbicide treated) in that study, yet hardwood stems were able to overtop the shortleaf pine component after three years. One important difference between the two studies is the shortleaf pine regeneration source. Regeneration from seed that had to establish a root system during its first couple of years was used in the Shelton (1997) study, and seedlings that typically ranged from 6-12 in. tall were planted in this study. The larger root system and stem size of the seedlings in this study along with foliar herbicide and broadcast prescribed burns in some treatments after the first growing season may reduce the chances of complete shortleaf pine suppression.

Nevertheless, if cut or cut and herbicide treated submerchantable hardwood sprouts begin to rapidly grow and overtop pines within the next couple of years, the need for another release treatment (if economically viable) could be justified.

The generally small cluster openings (<0.1 acres) in this study alter some of the abiotic effects that are common in larger forest gaps. Sunlight penetration to the forest floor in small gaps is usually diffuse except at midday, but light levels can vary widely due to differences in aspect, surrounding tree height, crown depth, topographic slope, and latitude (Buffo et al. 1972, Oliver and Larson 1996). South and west facing slopes (most clusters in this study were southwest, west, or northwest facing) receive more sunlight and are generally warmer and dryer during the noon and afternoon hours. The warmer and dryer conditions of these cluster gaps may benefit regeneration of more shade intolerant and xeric species such as the planted shortleaf pine and oak species allowing them to perform better in gaps on these aspects (Oliver and Larson 1996). In addition, steeper slopes often result in more diffuse canopies along gap edges allowing more sunlight penetration from the downhill edge depending on the slope and aspect (Barnes et al. 1998). Microclimate conditions such as temperature, wind speed, and humidity in small gaps (<0.1 acres or the size of many cluster openings in this study) do not vary much from the surrounding residual forest (Oliver and Larson 1996). This results in less vegetation differentiation from the opening edges to the residual forest. Residual overstory or midstory trees can provide serious root competition for soil moisture to new regeneration throughout the entirety of gaps smaller than one acre, and root competition becomes more intense the smaller the opening due to the short distances to the intact forest (Oliver and Larson 1996). In most instances, gaps similar in size to the cluster openings in this study do not vary significantly from the conditions in the surrounding older forest.

Other than the possibility of additional natural disturbances, the rate of lateral crown closure and/or subcanopy recruitment into the cluster openings will determine how these two-aged stands develop over the next couple of decades. Hart and Grissino-Mayer (2009) studied gap characteristics and understory recruitment on the Cumberland Plateau in Fentress County, Tennessee in a mature, mixed hardwood forest similar to the Cumberland Forest study site. Their results suggest that lateral canopy expansion and closure occurs in most single tree gaps that are 700-1,500 $ft^2$ in area, similar to many of the cluster gaps in this study. They also reported that gap closure occurs in 20 years or less within these forest types. Another gap dynamics study in mixed pine-hardwood forests on the Cumberland Plateau of Alabama suggested that lateral canopy closure always occurs in gaps less than 1,750 $ft^2$ in this forest type (Weber et al. 2014). This gap dynamics information for oak-hickory and mixed pine-hardwood forest types in the Cumberland Plateau and Mountains regions suggests that unless overstory trees are killed adjacent to clusters through either natural or anthropogenic means then suppression of desirable shade intolerant species such as yellow-poplar, red oaks, and the planted shortleaf pine will occur. Species composition will then shift to more shade tolerant species such as red and sugar maple, sourwood, and blackgum in more than 95% of gaps this size as reported by Barden (1981) and Runkle (1998).

***Management Implications***

The opportunities for different management options associated with cluster planting established under a residual overstory to form a two-aged stand are numerous for managers and landowners. As the stand grows and matures, several different silvicultural pathways could be taken based on species composition, age, growth rates, and structure of these stands. Intermediate treatments such as precommercial or commercial thinning and planted pine release from surrounding hardwood regeneration would reduce tree density, decrease competition, and alter species composition prior to a midrotation and final harvest in a two-age system. The financial benefits associated with two-age stands compared to practicing even-aged grid plantings with planted pines or managing solely for long-rotation mixed hardwood stands would enable landowners to conduct more tending and intermediate management operations for periodic income based on timber markets.

The brown-and-burn, burn, and herbicide treatments received weeding treatments (release treatments completed during the seedling stage) in this study (Nyland 2007). These treatments, did not significantly improve survival or growth compared to any other treatment after two years, and may have best been applied at an older stand age as a cleaning release treatment if competing vegetation becomes more plentiful and larger. A cleaning treatment (release crop trees not past the sapling stage from competing stems) will better serve landowners and managers when the crowns of natural regeneration (especially undesirable species) begin to differentiate in height and overtop the planted shortleaf pine saplings (Nyland 2007). Fast growing and undesirable species such as mountain laurel, red maple, and sassafras were abundant in some treatments throughout the study site. Desirable, yet fast growing species such as yellow-poplar were also a prominent component of the regeneration in some areas. If these fast growing species become numerous or grow quickly (as with stump or root sprouts) a cleaning treatment to ensure the shortleaf pine is not overtopped is a justifiable intermediate treatment. Clusters with more sunlight are likely to need cleaning treatments before those with greater overhead shade. Increasing amounts of shade results in reduced growth rates of natural regeneration (Kabrick et al. 2015). Cleaning treatments in even-age shortleaf pine-hardwood mixtures on moderate productivity sites in South Carolina did not improve survival or height growth of shortleaf pine as compared to a control treatment, but did increase diameter growth by about 20% (Lloyd et al. 1991). Cleanings may be necessary to ensure continued development of shortleaf pine and improve return on investments (Guldin 1984).

Precommercial thinning may be warranted because of the narrow spacing within clusters if most of the planted shortleaf pine survives to the sapling or pole size. Precommercial thinning will allow greater growth on fewer stems reaching sawtimber size classes (or overstory positions) more quickly (Cain 1996, Lohrey 1977). Based on recommendations for area-wide plantings in southern pines by Lohrey (1977), and converted to the small area and spacings of the individual clusters in this study, the optimum density for planted shortleaf pine to reach sawtimber size classes would correlate to about a 22% (14 trees per cluster) survival rate of well-distributed stems within individual clusters. This estimate also assumes minimal crowding from older, stems in the residual stand adjacent to the clusters. All of the treatments within this study currently have survival rates greater than this threshold, but at the two-year assessment, seedlings had not reached the larger size classes when precommercial thinning might be necessary. More mortality could occur in the interim, negating the need for precommercial thinning. When survival rates within clusters are below this threshold, precommercial thinning is not necessary. The recommendation by Lohrey (1977) does not take into account the shading effects of a residual overstory or the competitive effects of regenerating hardwood species. Target survival rates could likely be lower than 22% if natural regeneration of desirable species is growing within and directly adjacent to the clusters. One concern of precommercial thinning is the costs associated with conducting the operation. A return on these costs is difficult to define given that the planted shortleaf pine was introduced primarily as a future seed source through possibly two or three rotations. Trees that survive two or three rotations could be 80-120 years old before they are harvested, whereas returns from precommercial thinning are usually realized much sooner with typical southern pine plantation silviculture (McMinn 1965). The crowding, growth rates, and crown conditions of the stems in the clusters should be carefully monitored during the next few years to determine if precommercial thinning would be beneficial to the continued growth and development of the shortleaf pine component.

Cleaning and precommercial thinning are practices for altering species composition or increasing growth rates in the short term, but do not account for the long term management of two-aged stands. Usually two-aged stands are initiated after a deferment harvest that leaves similar conditions to a clearcut for regeneration and also retains reserve trees with desirable qualities that are left through two cutting rotations for aesthetic purposes, wildlife, or possibly to grow to large, high value size classes (Stringer 2006, Smith et al. 1997). Approximately 10-20 reserve trees per acre are typically left in eastern hardwoods with this type of silvicultural system (Miller et al. 2004), which was the goal for this study when reserve trees were marked prior to harvest. However the logging crew left many more trees per acre than this target throughout most of the study site. In the two burn treatments, overstory basal areas were reduced by 13-19 $ft^2$ $ac^{-1}$, yet basal areas were still higher than guidelines (<30 $ft^2$ $ac^{-1}$) reported for traditional two-age management in eastern hardwoods (Miller et al. 2004). The concern with the higher than anticipated basal areas is that crown closure of the residual overstory and subsequently the cluster will occur causing growth stagnation of the planted pines and shade intolerant regeneration with light conditions favoring regeneration of more shade tolerant species. Miller and Schuler (1995) discovered that the crowns of residual stems did not increase appreciably in size for two-age stands in West Virginia 10 years after the regeneration harvest, yet by age 20 Miller et al. (2004) observed that crown area of the residual trees had increased by roughly 80%. This resulted in greater densities of shade tolerant species in the midstory, and relegated more shade intolerant species to the gaps among the residual trees. Though the Little Brushy Mountain site was a poorer productivity site than the sites used in the West Virginia study, the greater basal areas of residual trees in this study will likely shade the gaps where clusters were established as well as gaps where desirable species are regenerating at a faster rate.

In order to prevent an undesirable shift in species composition, removal of  midstory trees and some overstory trees in the stand to a threshold below 30 $ft^2$ $ac^{-1}$ basal area threshold is recommended by Miller et al. (2004) probably within the next ten years. The most selective and least costly method for the reduction of the overstory basal area would be herbicide stem injection via the hack-n-squirt method (Smith et al.1997). Burning at regular intervals may kill additional overstory trees and shift natural regeneration to more fire adapted species such as oaks under partially shaded conditions (Hutchinson et al. 2012). Periodic burning could also potentially damage stems reducing bole quality or kill desirable residual stems such as oaks (Regelbrugge and Smith 1994, Wendell and Smith 1986). The topkill of the planted shortleaf pine may occur more often if stems have not yet reached basal diameters of at least four in. as stated by Dey and Hartmann (2005) as a size threshold for assured shortleaf pine survival, except under severe fire conditions. Reduction of the residual overstory will likely be necessary to maintain the structural and species composition characteristics associated with two-age management. Growth and development of the younger age class could affect species composition of the next stand.

Midrotation harvests are completed in most two-aged management scenarios barring a major disturbance (Nyland 2007). In mixed hardwood stands of the Appalachian region, hardwood rotation lengths are typically 80 years, which would allow for a midrotation thinning at about 40 years with two-aged management (Miller and Schuler 1995). Shortleaf pine, due to its longevity, is well-suited to longer rotations and is managed on much longer rotations in some areas of its range (Hedrick et al. 2007). At the midrotation harvest, all of the residual overstory can be removed, or a portion can be retained if those stems meet criteria for residuals (Nyland 2007). At 80 years, both reserve trees (now two rotations old) and the 80-year-old residual trees would be harvested, but a few would then be selected/retained for reserve trees in the next rotation, thus extending the harvest cycle. At the first midrotation harvest, natural regeneration of shortleaf pine could be obtained from dispersed seed from any surviving planted trees in the clusters by retaining most or all of them, negating the need for artificial regeneration. A site preparation burn prior to or following logging coupled with the soil scarification from the logging equipment would make a receptive seedbed for a new shortleaf pine age cohort and other r-strategist hardwood species such as yellow-poplar (Wood 1939). Pines would establish mostly from seed, whereas hardwoods would establish from a variety of regeneration sources after the midrotation harvest. Using this harvest schedule along with intermediate treatments such as thinning or release treatments, two-aged management could be practiced into perpetuity on this site to positively influence natural regeneration composition; restore mature, mixed shortleaf pine-hardwood stands; create an aesthetically pleasing forest; and maintain structurally variable habitat for some wildlife species (Nyland 2007).

## Chapter 9: Conclusions-University of Tennessee Highland Rim Forest Site

The planted shortleaf pine at the University of Tennessee Highland Rim Forest displayed different responses to treatments intended to establish even-aged shortleaf pine-hardwood mixtures. Three years after planting and 1-2 growing seasons after treatment implementation seedlings in non-burn treatments had better survival rates than those that were burned. Survival rates for the burn, brown-and-burn, herbicide, and control treatments only varied by 21.1% across treatments, yet the strip-burn treatment could be considered a failure with a seedling survival rate of only 12.9%. Overtopping exotic, invasive vegetation at this location and mortality of shortleaf pine resprouts following burning contributed to the low survival rate. The two wide planting spacings presented no statistical differences for seedling survival. Three year basal diameter and height growth exhibited different trends than survival. The brown-and-burn treatment seedlings had the greatest basal diameter and height after three growing seasons. The herbicide treatment had the next largest seedlings. Herbaceous and woody competition control likely promoted greater growth of the seedlings in both of these treatments. The burn and strip-burn treatments had the least growth across the two height variables, and this pattern can be attributed to the abundance of herbaceous vegetation following the burns, which likely resulted in less soil water availability and added stress for the shortleaf pine seedlings. Statistical differences by planting spacing for seedling basal diameter were present, yet due to the young age of the study and the open canopies among the shortleaf pine and natural regeneration for both spacings, this difference is of little consequence at this time. No statistical differences in seedling height by treatment were indicated, and the height range across treatments was only 3.6 inches.

Natural regeneration density and composition varied by treatment, but regeneration height did not. Naturally regenerating woody stem densities differed by treatment, and stems per acre tended to mirror the intensity of the treatment except in the strip-burn treatment. The strip-burn treatment had the most stems per acre, whereas the brown-and-burn treatment had the fewest. The strip-burn treatment regenerated quickly with root and stump sprouts of sumac spp. and invasive species such as Chinese privet and callery pear, which dominated in all treatments except the brown-and-burn treatment. These species were present along experimental unit exteriors for the most part and site preparation treatments using herbicides after drum chopping would have likely been the most effective method to reduce their negative influence on the developing stand. Species from the red and white oak families composed from less than 0.5% in the strip-burn treatment to 23% in the brown-and-burn treatment. Natural regeneration height had not differentiated by species yet and future monitoring will be necessary.

After three growing seasons, the brown-and-burn treatment appears to have the largest shortleaf pine seedlings and the most desirable natural regeneration composition per acre even though it has significantly fewer regenerating stems per acre on average (2,401) than the other treatments. Across all treatments, except the strip-burn treatment, artificially regenerated shortleaf pine was not overtopped by naturally regenerating woody stems. If the shortleaf pine continues to grow at the same rate as the natural regeneration with little mortality, a mixed stand will be present at crown closure with 40 to 150 planted shortleaf pine trees per acre depending on spacing and treatment (excluding the strip burn treatment) plus any naturally regenerating pine stems. This situation would present the land manager with several viable silvicultural options and pathways to influence how the stand develops into the future such as: thinnings, harvests that favor the planted shortleaf pine or hardwoods (depending on markets and landowner objectives), and the option to clearcut the stand.

## Chapter 10: Conclusions-University of Tennessee Cumberland Forest Site

Shortleaf pine seedling response varied minimally across treatments designed to establish two-aged, mixed shortleaf pine-hardwood stands. Planted shortleaf pine survival did not display any statistical differences by treatment two growing seasons post-planting and one growing season post-treatment application. Seedling survival ranged from 37.8% in the burn treatment to 56.1% in the scarification treatment. Survival was least in the two treatments that included burning. Seedling survival could not be predicted for the brown-and-burn, burn, herbicide, and control treatments using aspect, percent light, slope percent, or elevation as predictor variables. Shortleaf pine seedling basal diameter did not differ by treatment and height growth was greater in the scarification treatment than any other treatment. Seedlings in the burn treatment tended to be smaller than in other treatments, and were probably still recovering from the burn conducted less than a year earlier. These seedlings were resprouts and were competing with the influx of herbaceous vegetation that was controlled with herbicides in the brown-and-burn treatment. Scarification likely reduces competition for soil water among seedlings, herbaceous vegetation, and woody regeneration. Shortleaf pine growth in the brown-and-burn, burn, herbicide, and control treatments could be predicted using percent light, elevation, and percent slope, and validation runs of the regressions confirmed this finding. Shortleaf pine seedling survival and growth in the scarification treatment were investigated using a visual scarification rating, soil compaction, elevation, percent slope, aspect, and percent light as predictor variables. For seedling survival, the visual scarification rating, elevation and slope could all be used for survival prediction purposes. Seedling basal diameter and height could not be predicted by any of the measured variables for the scarification treatment. Further tests of the utility of these survival and growth prediction models should be conducted on additional sites in the Cumberland Plateau and Mountains physiographic regions.

Woody natural regeneration density, height, and composition varied little across treatments. One variable where statistically significant differences occurred across treatments was the natural regeneration woody stem densities within cluster interiors. The pattern of average stem densities reflected the intensity of a treatment. The brown-and-burn treatment had the fewest regenerating stems per acre, whereas the control had the most. The brown-and-burn and herbicide treatments were statistically the same due to the efficacy of the herbicide application, whereas the burn and scarification treatment were statistically similar and were moderate in stem densities compared to the herbicide treatments and control. No statistical differences were discerned for woody stem density among treatments outside of clusters. In addition, no difference in the average number of stems inside versus outside of clusters was detected across all treatments. Natural regeneration height did not differ among treatments either inside or outside of treatments, yet the brown-and-burn treatment had the shortest stems, whereas the scarification treatment had the tallest stems both inside and outside of clusters. There was a significant difference in height between cluster interiors and exteriors averaged across all treatments. This was expected, as the herbicide treatments were only applied within clusters. The short time span between when treatments were applied and measurements were taken is likely the main reason for the lack of statistical differences observed for many variables at this young age.

Woody natural regeneration composition displayed noticeable trends across treatments. Deerberry was common within and outside of clusters in all treatments and formed the majority of regenerating woody stems in most treatments and cluster locations. Yellow-poplar, red maple, and mountain laurel were common in a subset of treatments and cluster locations yet did not compose a majority of the stems in any treatment or cluster location. Species composition from the red and white oak families was similar across treatments and usually were more numerous within clusters than outside of them. Naturally regenerating stems did not display differences in basal diameter or height growth by spatial location within or outside of clusters, yet the distance to the closest naturally regenerating stem by spatial location within or outside of a cluster was significant. Longer average distances to the nearest regenerating stem within clusters than outside of them were discovered, and this trend is likely due to the herbicide and scarification treatments killing stems within the clusters. Spatial location has not yet resulted in statistical differences in species composition by shade tolerance level from less shaded cluster interiors, edge areas, and often more shaded cluster exteriors, which could change if the crowns of overstory stems expand during the coming years.

The scarification treatment had the greatest survival and growth of planted shortleaf pine seedlings and had more desirable natural regeneration with a considerable red and white oak component compared to most other treatments. Shortleaf pine seedlings tended to be taller than naturally regenerating stems within clusters in all treatments except the burn treatment. This bodes well for the continued survival and growth of the shortleaf pine component. Shading effects from regenerating or midstory stems outside of clusters may impede growth rates along with the high shade from the residual overstory. The shade cast by overstory stems should limit the quick growth of pioneer species such as yellow-poplar within the small clusters, but concurrently slow the growth of the planted shortleaf pine. If the overstory trees respond with crown expansion to the additional growing space provided by the first regeneration harvest, the small cluster gaps may become heavily shaded, necessitating the partial removal of the midstory and overstory. Monitoring of the development of this study will be undertaken in the future to determine when intermediate treatments may be required to maintain desirable species compositions and stand structures.

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**Appendices**

***Appendix 1.***

Species codes, Scientific names, and common names presented for the University of Tennessee Highland Rim and Cumberland Forest natural regeneration results.

| Species Code | Latin Name | Common Name |
|---|---|---|
| ILOP | *Ilex opaca* (Aiton) | American Holly |
| VIDE | *Viburnum dentatum* (L.) | Arrowwood |
| RHSP | *Rhodedendrun spp.* (Michx.) | Azalea |
| TIHE | *Tilia heterophylla* (L.) | American Basswood |
| FAGR | *Fagus grandifolia* (Ehrh.) | American Beech |
| BELE | *Betula lenta* (L.) | Sweet Birch |
| PRSE | *Prunus serotina* (Ehrh.) | Black Cherry |
| NYSY | *Nyssa sylvatica* (Marsh) | Blackgum |
| QUVE | *Quercus velutina* (Lam.) | Black Oak |
| FRCA | *Frangula caroliniana* (Walter) | Carolina Buckthorn |
| PYPU | *Pyrularia pubera* (Michx.) | Buffalo Nut |
| PYCA | *Pyrus calleryana* (Decne.) | Callery Pear |
| QUPR | *Quercus prinus* (L.) | Chestnut Oak |
| MAAC | *Magnolia acuminata* (L.) | Cucumbertree |
| ARSP | *Aralia spinosa* (L.) | Devil's Walking stick |
| COFL | *Cornus florida* (L.) | Flowering Dogwood |
| CEOC | *Celtis occidentalis* (L.) | Hackberry |
| CRSP | *Crataegus spp.* (L.) | Hawthorne |
| CASP | *Carya spp.* (Nutt.) | Hickory |
| GADU | *Gaylussacia dumosa* (Andr.) | Huckleberry |
| PITA | *Pinus taeda* (L.) | Loblolly Pine |
| VIAC | *Viburnum acerifolium* (L.) | Mapleleaf Viburnum |
| KALA | *Kalmia latifolia* (L.) | Mountain Laurel |
| QURU | *Quercus rubra* (L.) | Northern Red Oak |
| PATO | *Paulownia tomentosa* (Thunb.) | Royal Paulownia |
| QUST | *Quercus stellata* (Wangenh.) | Post Oak |
| LIAM | *Ligustrum amurense* (Carriere) | Amur Privet |
| CECA | *Cercis canadensis* (L.) | Eastern Redbud |
| ACRU | *Acer rubrum* (L.) | Red Maple |
| SAAL | *Sassafras albidum* (Nutt.) | Sassafras |
| QUCO | *Quercus coccinea* (Muenchh.) | Scarlet Oak |
| AMAR | *Amelanchier arborea* (Michx.) | Downy Serviceberry |
| PIEC | *Pinus echinata* (Mill.) | Shortleaf Pine |
| OXAR | *Oxydendrum Arboreum* (L.) | Sourwood |
| QUFA | *Quercus falcata* (Michx.) | Southern Red Oak |

| | | |
|---|---|---|
| ACSA | *Acer saccharum* (Marsh.) | Sugar Maple |
| RHSP | *Rhus spp.* (L.) | Sumac |
| LIST | *Liquidambar styraciflua* (L.) | Sweetgum |
| VAPA | *Vacciniun pallidum* (Aiton) | Lowbush Blueberry |
| PIVI | *Pinus virginiana* (Mill.) | Virginia Pine |
| QUAL | *Quercus alba* (L.) | White Oak |
| HAVI | *Hamamelis virginiana* (L.) | Witch Hazel |
| PIST | *Pinus strobus* (L.) | Eastern White Pine |
| QUPH | *Quercus phellos* (L.) | Willow Oak |
| LITU | *Liriodendron tulipifera* (L.) | Yellow-Poplar |

## Vita

David Charles Clabo was born in Maryville, Tennessee in 1988 to Chuck and Martha Clabo. In 2007, he graduated from Gatlinburg-Pittman High School in Gatlinburg, Tennessee. David became interested in forestry during his sophomore year of undergraduate studies at the University of Tennessee. 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. David completed his Master's degree in August 2014.

David began his Doctor of Philosophy degree in August 2014 after being awarded a grant with Dr. Clatterbuck to fund a shortleaf pine-hardwood establishment study from the National Fish and Wildlife Foundation and International Paper during September 2013. While teaching silviculture labs and taking classes at UT, he helped establish and implement treatments at research sites to investigate different site preparation and release techniques for the establishment of mixed shortleaf pine-hardwood stands using even-aged and two-aged silvicultural systems. David's career goals include either establishing and conducting forestry extension programs and research through state and university cooperative programs or becoming a silviculturist for the United States Forest Service.