Shortleaf pine (Pinus echinata, Pinaceae) seedling sprouting responses: Clipping and burning effects at various seedling ages and seasons

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Source: The Journal of the Torrey Botanical Society, 146(2) : 96-110
Published By: Torrey Botanical Society
URL: https://doi.org/10.3159/TORREY-D-18-00004.1
Shortleaf pine (*Pinus echinata* Mill.) can sprout after stem injury or top kill. Currently, evidence regarding the effects of seedling age and disturbance timing on sprouting potential are limited. The objectives of this study were to determine the effects of clipping and season of burning on shortleaf pine seedling survival, number of sprouts, and total seedling height at three different seedling ages. Treatments included: a March clip, an April burn, a July burn, a November burn, and a control. All treatments were applied to 1-, 2-, and 3-yr-old planted shortleaf pine seedlings located in Morgan County, TN. Seedling survival did not differ by season of burning for any age tested. Sprout production of early season disturbances were similar for each age tested. Total heights of sprouts were greater with treatments conducted early in the growing season rather than later for the second and third growing years, but not the first year. Some 2-yr-old seedlings burned in November and most 3-yr-old burn seedlings burned in either burn treatment were large enough that they were not top-killed by the treatment burns. Burning of artificially regenerated shortleaf pine seedlings should be delayed for at least 3 yrs after planting in the Cumberland Plateau and Mountains regions to reduce top-kill rates, growth losses, and mortality experienced by younger seedlings.

**Key words:** disturbance, seedling, season of burn, shortleaf pine, sprouting

Shortleaf pine (*Pinus echinata* Mill.) is a common species across much of the eastern USA, and is a component of many different forest types across a wide range of physiographic regions (Eyre 1980). Forest types dominated by shortleaf pine are defined as having at least 50% of the live tree stocking as shortleaf pine (Moser et al. 2007). An early US Department of Agriculture publication with unsubstantiated inventory methods stated there were 28 to 32 million ha of shortleaf pine and related forest types throughout the eastern USA (Mohr and Roth 1896). In the early 1950s, according to formal US Forest Service forest inventory and analysis (FIA) data, there were 6.5–7 million ha of shortleaf pine-dominated forest types throughout the species’ native range (Boyce and Knight 1979, McWilliams et al. 1986), a reduction of approximately 75% from 1896. Recent FIA inventories for shortleaf pine’s native range indicate that shortleaf pine is dominant on only about 2.2 million hectares (Oswalt 2012), a decrease of 66%. The first FIA inventories conducted in the late 1940s and early 1950s on the Cumberland Plateau region of Tennessee indicated natural southern yellow pine and mixed pine-hardwood forest types (primarily shortleaf pine) occupied 613,000 ha of the 1.2 million forested hectares in the region (Wheeler 1952). Current estimates for the Cumberland Plateau region in Tennessee indicate 134,000 ha are in the same forest cover types, a decline of 78% from 1950 (Oswalt et al. 2012). These statistics indicate shortleaf pine forest types have decreased more acutely in the Cumberland Plateau region of Tennessee than throughout shortleaf pine’s natural range. The abrupt decrease of shortleaf pine has initiated range-wide restoration efforts (Anderson et al. 2016).

The beginning of impactful and successful nationwide fire suppression policies in the early to mid-1940s has likely contributed to the decline in the establishment and maintenance of shortleaf pine (Brose et al. 2001). For instance, the historical fire return interval for the Cumberland and Allegheny Plateau regions in the eastern portion of shortleaf pine’s range was reduced dramatically following the era of fire suppression. From 1875–1936, the fire return interval averaged 1.7–11.1 years, whereas after the early 1940s (national fire suppression initiation) fire is infrequent with much longer return intervals of 13–200+ years throughout the eastern portion of shortleaf pine’s native range (McEwan et al. 2007, Hutchinson et al. 2008, Lafon et al. 2017).
Mesophication and the increased abundance of shade-tolerant and fire-intolerant tree and shrub species caused by reduced fire intervals and lack of disturbance has limited shortleaf pine regeneration potential in many regions throughout its native range (Nowacki and Abrams 2008). Other range-wide causal factors for the decline in shortleaf pine include loblolly-shortleaf pine introgression or hybridization (Stewart et al. 2013) and urbanization (Alig, Kline, and Lichenstein 2004). Synergistic drivers of shortleaf pine decline more specific to the Cumberland Plateau region include increased abundance of eastern white pine (Pinus strobus L.), red maple (Acer rubrum L.), mountain laurel (Kalmia latifolia L.), and other mesophytic hardwood species due to lack of disturbance (Guyette, Muzika, and Dey 2002; Guyette, Spe-tich, and Stambaugh 2006; Oswalt, Oswalt, and Meade 2016), widespread planting of loblolly pine (Pinus taeda L.) on sites where mixed or pure shortleaf pine forests previously existed (Birdsey 1983, May 1991), laws eliminating free-range livestock grazing (Todd 1980), and shortleaf pine mortality caused by repeated southern pine beetle (Dendroctonus frontalis (Zimmerman) epidemics (Mattoon 1915, Guyette, Muzika, and Volker 2007, Masters 2007, Keeley 2012).

Shortleaf pine is well-suited to drought and fire-prone sites. Attributes that make shortleaf pine a good species to retain or promote as part of the residual overstory on suitable sites include tree longevity and resiliency (fire adaptability) with individual trees regularly living to 250–300 years, drought resistance, branch pruning, sprouting ability, rot resistance around fire scars, and its suitability for wildlife species as cover and as a habitat component for some threatened species such red-cockaded woodpeckers (Leuconotopicus borealis) and northern bobwhite (Colinus virginianus) that require very different seral stages (Mattoon 1915, Guyette, Muzika, and Volker 2007, Masters 2007, Keeley 2012).

Although there has been a renewed interest in shortleaf pine promotion and ecosystem restoration west of the Mississippi River, little information is available on shortleaf pine regeneration and management east of the Mississippi River on the Cumberland Plateau, Ridge and Valley, Appalachian Mountains, and Piedmont physiographic provinces (Bukenhofer, Neal, and Montague 1994; Guldin et al. 2004; Hedrick et al. 2007). The Interior Highlands region of Arkansas, Missouri, and Oklahoma has fewer and less abundant. highly competitive tree and shrub species such red maple, white pine, and mountain laurel as compared to areas east of the Mississippi River such as the Cumberland Plateau (Hardin, Leopold, and White 2001; Prasad et al. 2014). Because of these competitive relationships among species, management of shortleaf pine is often less difficult in the Interior Highlands than the Cumberland Plateau. Shortleaf pine in mixed stands with hardwoods was once prevalent throughout the Cumberland Plateau region, but has declined dramatically since the 1980s due to causes such as southern pine beetle epidemics leading to a demise of older shortleaf pine seed trees needed to naturally regenerate the species (Moser et al. 2007; Oswalt 2012; Oswalt, Oswalt, and Meade 2016).

Thus artificial regeneration is necessary for shortleaf pine establishment without a seed source. Hardwood tree and shrub species such as red maple, blackgum (Nyssa sylvatica Marshall), sourwood (Oxydendrum arboreum (L.) DC.), hickories (Carya spp.), and mountain laurel, tend to proliferate on sites throughout the Cumberland Plateau compared to shortleaf pine, unless disturbances that increase sunlight levels and expose bare mineral soil (such as surface fires) occur at regular intervals. Prescribed fire can be more difficult to initiate or control because of historically greater annual precipitation amounts and more mountainous terrain in many of these areas east of the Mississippi River, as compared to the Interior Highlands region of Arkansas, Missouri, and Oklahoma (Baldwin 1973, Pyne 1984).

Shortleaf pine is one of the few southern USA Pinus species that sprout from dormant buds located at the base of the stem at the root collar. Even after planting, burning drought-prone and low to moderate soil productivity sites to promote shortleaf pine sprouting and reduce influence from competing hardwoods might be necessary to give shortleaf pine an initial advantage over other woody species in mixed species stands (Guldin 2007). In addition, burning planted shortleaf pine seedlings before they reach size classes where they are more resistant to top kill could be a useful technique to favor pure shortleaf pine over loblolly-shortleaf pine hybrids due to the greater propensity of shortleaf pine to sprout compared to hybrid seedlings (Stewart et al. 2015). Shortleaf pine sprouts from dormant buds located just above an adaptation known as the basal crook. The basal
crook is a J-shaped root section just below the root collar where the taproot grows horizontally prior to growing vertically again (Mattoon 1915, Lilly 2011). The crook begins to develop 2 to 3 mo after germination in seedlings grown in full sunlight (Little and Mergen 1966). Numerous dormant buds are located just below the soil surface on or near the basal crook and root collar. During a surface fire, these buds are protected from the lethal burn temperatures at or near the soil surface (Lilly et al. 2010). New sprouts can initiate from the basal crook until trees reach about 15 cm to 20 cm diameter at breast height (dbh) (Lawson 1990).

Seedling size and bark thickness, as well as seedling physiological and phenotypic state can all affect sprouting ability (Stone and Stone 1954, Little and Somes 1956, Miller 2000, Lilly et al. 2010). Sprouting ability decreases with increasing age and size, much like other tree species that are capable of sprouting (Mattoon 1915, McGee 1978, Hardin, Leopold, and White 2001). Sprouts that develop just below the ground surface are likely to avoid insect, fungal, and disease problems that can arise if sprouts are entirely aboveground and dependent on the parent stump and root system (Del Tredici 2001).

Knowledge of shortleaf pine seedlings’ sprouting capabilities will aid silviculturists in shortleaf pine management and restoration. Natural regeneration of shortleaf pine is only possible when a seed source is present on site or nearby. Properly timed periodic burning could be used to foster bioaccumulation of shortleaf pine regeneration (Guldin 2007). A percentage of seedlings already on the ground would resprout following top kill, and bare mineral soil would be exposed, which would promote seed germination (Guldin 2007). This process could be repeated to increase stocking of shortleaf pine regeneration in the understory until a disturbance releases the seedlings, allowing new ingrowth into the overstory. In artificial regeneration situations, knowledge of shortleaf pine’s sprouting capabilities following burns at different seedling ages could be useful for shortleaf pine savannah and woodland ecosystem restoration where a shortleaf pine seed source is not present and burning at regular intervals is necessary to maintain vegetation structure and species composition. The number of seedlings planted and fire return intervals could be dictated by survival and resprout percentages of artificially regenerated shortleaf pine seedlings. Currently there are knowledge gaps for regenerating shortleaf pine, including the species’ sprouting capabilities, how many seedlings should be planted to maintain suitable stocking in areas that will receive prescribed burns, and if burning and the species’ sprouting ability can be used in combination to promote the species. Shortleaf pine might more readily endure periodic burning due to its sprouting ability than more mesophytic and less fire-resistant tree and shrub species such as red maple, loblolly pine, eastern white pine, and mountain laurel on moderate to low productivity sites throughout the Cumberland Plateau physiographic region (Abrams 1998, Agee 1998, Dobbs 1998, Williams 1998, Elliott et al. 1999).

A specific understanding of the season to apply the burn could favor the survival and growth of young shortleaf. Fire research with other woody species has suggested that burns coinciding with seasonal carbohydrate reserve fluctuations can affect sprouting ability. For instance, hardwood seedlings and saplings burned annually during the summer were eventually eliminated due to lower carbohydrate reserves, whereas dormant-season burns resulted in an influx of sprouts due to greater carbohydrate root reserves during those months (Waldrop and Lloyd 1991, Miller 2000). In addition, differences in seedling phenology (e.g., actively growing versus dormant) throughout the year can result in added or reduced mortality following a burn (Miller 2000). Clipping mimics a nonburning disturbance that kills the stem but does not damage dormant buds near the root collar. Establishment and maintenance of mixed pine/oak forests, savannas, and woodlands through shortleaf pine sprouts and a build-up of advance reproduction (either natural, planted, or both) with time might prove more effective than relying on germination from seed alone in fire-dependent systems due to shortleaf pine’s annual variability in seed production (Baker 1992).

Burn residence time and intensity also can affect survival and subsequent sprout growth. Plant cells begin to die at 50–55 °C, but residence time and temperature can greatly affect this threshold (Wright and Bailey 1982). High temperatures for a short period of time can result in plant mortality (Martin 1963), but low temperatures for long periods of time can also result in plant mortality (Ursic 1961). Seasonal high or low concentrations of plant compounds can also affect a plant’s heat tolerance (Miller 2000). Bark thickness differences
at varying tree ages and sizes can contribute to varying survival rates given similar residence times and intensities (Keeley and Zedler 1998). Burn residence time could influence survival rates and the sprouting capability of shortleaf pine and should be considered when assessing sprouting following a burn.

Although several references indicate that shortleaf pine will sprout following burning or other disturbances that cause seedling damage (e.g., Mattoon 1915, Little and Somes 1956, Guldin 1986), there are no definitive studies in the literature that express the percentage of seedlings that might be expected to sprout and survive following disturbances. The present research explores burning and clipping to study shortleaf pine sprouting potential on the Cumberland Plateau in Tennessee and might have application to the broader question of shortleaf pine restoration using prescribed burning in other parts of its range.

The objectives of this study were to determine the effects of shortleaf pine seedling clipping and season of burning on seedling survival, number of sprouts, and total height by individual seedling ages. In addition, this study evaluated the effects of burn residence times and temperatures on cumulative seedling height growth and number of sprouts with homogenous fuel conditions.

**Methods.** The study site was located on land owned by the University of Tennessee’s Forest Resources Research and Education Center on the foot slope (elevation 410 m) of Little Brushy Mountain (36°02’57.35”N, 84°28’46.56”W), a subregion of the Cumberland Plateau in Morgan County, Tennessee (Smalley 1982). The landscape is characterized by weakly dissected plateau surface and undulating hills with some larger ridges. This area is the southern terminus of the Cumberland Mountains, which is a physiographic section of the Appalachian Plateau and Mountains. The soils are Lonewood silt loams, which are fine-loamy, siliceous, semiactive, mesic, Typic Hapludults. Slopes range from 5% to 12%. Precipitation averages 140 cm to 153 cm annually (Thornwaite 1948, National Cooperative Soil Survey 2007, USDA NRCS 2012). Average annual temperature in this region ranges from 14 °C to 16 °C (NOAA 2014).

The site was a previously mown 540 m² area that was burned during February 2011 to facilitate planting. Shortleaf pine seedlings were purchased from the Tennessee Division of Forestry Nursery in Delano, TN. Forty-two experimental units were planted with 50 bare-root, 1-0 stock seedlings each on February 25, 2011, totaling 2,250 seedlings. Seedling ages given throughout the paper are age since planting and do not include the time in the nursery. Experimental units were 1.2 m × 2.7 m with 1.8-m buffers on each side. Seedlings were planted at 30.5 cm × 30.5 cm spacing. Experimental units consisted of 5 rows of 10 seedlings each. Seedlings averaged 28 cm tall at planting.

Three blocks containing 14 randomized experimental units each were established (Table 1). Treatments included experimental clipping and burning applied during different times of year and to seedlings of different ages. Individual treatments were applied to one experimental unit in each of three blocks on the same day. Blocking was incorporated into the experimental design to account for shade and moisture differences from east to west across the site due to slope and morning and afternoon shading from older, adjacent stands. There were three clip experimental units and three control experimental units per block. Each had year assigned randomly. The clip treatment was implemented to compare top-killing a seedling without use of fire compared to seedlings top-killed by fire. Seedlings in one experimental unit per block were clipped during March 2011, 2012, or 2013. An early growing season burn was applied to seedlings in one experimental unit per block during March or April 2011, 2012, or 2013. Midgrowing season burns were administered to one experimental unit per block during June or July 2011, 2012, or 2013. Early dormant season burns were applied to one experimental unit per block during November 2011 or 2012. For simplicity, references for the

<table>
<thead>
<tr>
<th>Experimental design component</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of experimental units</td>
<td>42</td>
</tr>
<tr>
<td>Number of blocks</td>
<td>3</td>
</tr>
<tr>
<td>Number of years</td>
<td>3</td>
</tr>
<tr>
<td>Number of treatments per year</td>
<td>5</td>
</tr>
<tr>
<td>Replications per block</td>
<td>1</td>
</tr>
</tbody>
</table>

* The November 2013 burn treatment (three experimental units) was not included in the analyses because the time between treatment implementation and data collection in January 2014 did not allow enough time for a response to the treatments to be observed.
Barn treatments were standardized as April, July, and November even though burns might have been conducted earlier or later than the designated month because of fire-weather conditions (Table 2). Each experimental unit received only one treatment. Treatment years corresponded with seedling age (e.g., 2011 treatments with seedlings that were 1 yr old at the time of treatment). Each dependent variable was analyzed by individual year to reduce the variability that would occur with seedlings of different ages when measured at one point in time. Three control experimental units in each block received no treatment. One of the control experimental units in each block corresponded with each annual treatment.

Clipped seedlings were severed approximately 2.5 cm to 5 cm above ground level to avoid damaging dormant buds located at or near the root collar. Sprouts that had initiated prior to treatments were clipped so that all seedlings resumed growth under similar conditions. Seedlings were clipped at the end of March each year of the study so that height growth rates could be monitored for a full growing season following the treatment.

Fuels were controlled in experimental units in order to reduce burn variability among treatments and years with regard to fuel type, loading, and moisture. Per experimental unit, approximately 13.4 mT ha\(^{-1}\) or 4.5 kg per plot of eastern white pine needles from adjacent plantations were applied as evenly as possible among seedlings. This fuel type was used because of its uniformity, its proximity to the study site, and how it could be evenly applied to experimental units. This average fuel load amount is similar in weight (15.2 mT ha\(^{-1}\)) to the average fuel load weight reported by Metz, Wells, and Kormanik (1970) in a 17-yr-old shortleaf pine plantation in Virginia. Grass, weeds, and woody plants were controlled with clipping and herbicide (glyphosate) application to diminish the influence of these fuels on burn behavior prior to adding white pine needles as the fuel source in each burn plot. Herbicide application was done by sponge wicking over the clipped vegetation in order to reduce herbicide damage to the seedlings. Herbicide application was completed at least a month before burns to ensure vegetation control and easier removal of grasses, woody, and herbaceous plants prior to burning.

Ambient air temperature, relative humidity, and surface wind speed were monitored during burns. Each 1.2 m \(\times\) 2.7 m burn experimental unit was ignited in a ring ignition pattern using a drip torch to ensure that the entire unit was burned, which resulted in a convective burn that spread inward. We recognize and acknowledge that burning temperatures were probably different on the perimeter of the unit compared to the interior of the unit, but we only measured temperatures on the interior of these small units. Burns were conducted in the afternoon hours.

**Measurements and Data Analysis.** Fuel and ground temperature data were measured using a Kintrex digital infrared laser thermometer with an infrared sensor for detecting thermal infrared energy remotely. The thermometer recorded temperatures in a 14-cm-diameter circular target area located at the exact midpoint of the experimental unit between the fifth and sixth tree of the third row. Fuel and ground temperatures were recorded every 15 sec until complete flameout (no visible flame or smoke) and until ground temperatures were similar to the ambient air temperature. Measurements on individual seedlings were made on all 42 experimental units during December.

### Table 2. Mean soil surface temperature and residence time variables used in the covariate analysis are presented by treatment and individual experimental unit for the shortleaf pine seedling sprouting study in Morgan County, TN.

<table>
<thead>
<tr>
<th>Burn date</th>
<th>Mean burn temperature (°C)</th>
<th>Median burn temperature (°C)</th>
<th>Maximum burn temperature (°C)</th>
<th>Burn duration (sec)</th>
<th>Burn temperature SD (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 14, 2011</td>
<td>132.2</td>
<td>85.0</td>
<td>355.9</td>
<td>360</td>
<td>114.5</td>
</tr>
<tr>
<td>July 14, 2011</td>
<td>134.4</td>
<td>113.8</td>
<td>380.0</td>
<td>360</td>
<td>94.4</td>
</tr>
<tr>
<td>November 10, 2011</td>
<td>174.2</td>
<td>153.7</td>
<td>453.2</td>
<td>730</td>
<td>97.8</td>
</tr>
<tr>
<td>March 20, 2012</td>
<td>192.5</td>
<td>170.6</td>
<td>446.9</td>
<td>420</td>
<td>100.6</td>
</tr>
<tr>
<td>June 26, 2012</td>
<td>213.5</td>
<td>187.8</td>
<td>472.8</td>
<td>290</td>
<td>111.4</td>
</tr>
<tr>
<td>November 19, 2012</td>
<td>84.7</td>
<td>52.6</td>
<td>435.0</td>
<td>435</td>
<td>87.1</td>
</tr>
<tr>
<td>March 14, 2013</td>
<td>116.9</td>
<td>77.7</td>
<td>408.2</td>
<td>730</td>
<td>102.4</td>
</tr>
<tr>
<td>July 12, 2013</td>
<td>79.8</td>
<td>53.9</td>
<td>258.3</td>
<td>370</td>
<td>60.5</td>
</tr>
</tbody>
</table>
Table 3. Means, standard errors, and treatment differences (means differ at \( P = 0.05 \) level for an individual year) for survival rate, number of sprouts, and total height (cm) are presented for shortleaf pine (Pinus echinata Mill.) seedlings in the 2011, 2012, and 2013 treatment years in Morgan County, TN.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Survival (%)</th>
<th>Number of sprouts</th>
<th>Total height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011, ( P )</td>
<td>0.03</td>
<td>(&lt; 0.01)</td>
<td>(&lt; 0.01)</td>
</tr>
<tr>
<td>April burn</td>
<td>42.7 ± 4.1 bc</td>
<td>2.6 ± 0.5 b</td>
<td>103.0 ± 14.2 d</td>
</tr>
<tr>
<td>July burn</td>
<td>38.0 ± 4.0 b</td>
<td>5.0 ± 0.5 a</td>
<td>78.0 ± 15.5 c</td>
</tr>
<tr>
<td>November burn</td>
<td>48.0 ± 4.1 bc</td>
<td>2.8 ± 0.4 b</td>
<td>99.3 ± 14.0 cd</td>
</tr>
<tr>
<td>March clip</td>
<td>66.7 ± 3.9 ab</td>
<td>2.1 ± 0.4 b</td>
<td>129.8 ± 14.0 b</td>
</tr>
<tr>
<td>Control</td>
<td>75.8 ± 3.5 a</td>
<td>0.9 ± 0.4 c</td>
<td>212.3 ± 13.7 a</td>
</tr>
</tbody>
</table>

2012, \( P \) | 0.06 | \(< 0.01\) | \(< 0.01\) |
| April burn | 58.7 ± 4.0 a | 5.0 ± 1.1 c | 121.5 ± 10.5 b |
| July burn | 49.3 ± 4.1 a | 10.9 ± 1.1 b | 54.0 ± 10.6 c |
| November burn | 52.7 ± 4.1 a | 15.2 ± 1.3 a | 50.1 ± 11.3 c |
| March clip | 67.3 ± 3.8 a | 4.7 ± 0.8 c | 119.5 ± 10.5 b |
| Control | 82.0 ± 3.1 a | 0.3 ± 0.8 d | 203.6 ± 10.4 a |

2013, \( P \) | 0.25 | \(< 0.01\) | \(< 0.01\) |
| April burn | 69.3 ± 3.9 a | 21.4 ± 4.5 a | 55.0 ± 17.3 b |
| July burn | 46.7 ± 3.8 a | 9.1 ± 4.3 b | 24.1 ± 18.1 c |
| March clip | 52.0 ± 4.1 a | 28.6 ± 4.2 a | 55.8 ± 17.1 b |
| Control | 76.0 ± 3.5 a | 0.5 ± 4.2 c | 185.6 ± 16.9 a |

* Different letters within the same column indicate significant differences according to Fisher’s protected least significant difference at the \( P = 0.05 \) level.

2013 and January 2014. Surviving seedlings were either not completely top-killed by a burn or were top-killed and resprouted either from dormant buds on the root collar or stem. Height, sprout number, and survival (dependent variables) were assessed for all surviving seedlings planted in an experimental unit. Height measurements were taken to the nearest 0.5 cm on the single tallest sprout or surviving stem of each seedling. For seedlings that still had live foliage in their crown after a burn treatment, total height was only measured to the top of the leader of the tallest living branch or stem. For sprout counts, if a main stem was not killed, then only new sprouts that originated around that stem were counted.

An unanticipated response for the 2012 and 2013 treatments was that some seedlings became large enough so that they were not top-killed by the three burn treatments (Table 3). Top-killed seedlings had no living foliage on the residual stem following treatment, but may have subsequently produced sprouts from the root collar region at the time of assessment indicating that the seedling was alive. Stems were considered alive if they resprouted. Nontop-killed seedlings had visible living foliage on the stem at the time of assessment, and the main stem was still alive. Seedlings were classified as dead if no living foliage or new sprouts were present. Top-killed and nontop-killed seedlings within a treatment year were separated for the number of sprouts and total height data analyses, and nontop-killed results are not reported.

Analysis of variance (ANOVA) as a randomized block design for mixed models (Proc Mixed, SAS 9.4) (Littell et al. 1996, SAS Institute 2012) tested for statistical differences among treatments by individual years or seedling ages (independent variables) for number of sprouts and seedling height. Survival (alive or dead) was analyzed with Proc Glimmix using the binomial distribution. Measurements were not averaged for each experimental unit. Data were tested for normality using the Shapiro-Wilk test and fit the normal distribution. Least squares means were separated using Fisher’s protected least significant difference and an alpha level of \( P = 0.05 \). A square-root transformation was used for the sprout number and height variables due to a lack of equal variance among treatments. Untransformed means and standard errors are reported.

Five covariates were tested for the number of sprouts and height analyses using backward elimination in order to account for temperature and burn residence time effects. A covariate was considered significant when all terms were significant for a dependent variable. Means per experimental unit for soil surface temperature, median soil surface temperature, maximum soil surface temperature, mean soil surface temperature standard deviation, and burn residence time during observed flaming combustion were all tested for
Results. Seedling Survival. Treatment was a significant factor explaining seedling survival for the 2011 treatments ($P = 0.03$) (Table 3). Mean separation revealed that the control treatment had the greatest survival, followed by the clip treatment. The April burn and November burn were statistically the same, while the survival rate of the July burn treatment was the lowest of the three burn treatments. No statistical differences for survival were observed for the 2012 treatments ($P = 0.06$) (Table 3). The range of survival spanned from a low of 49.3% for the July burn treatment to 76.0% for the control.

Number of Sprouts. Treatment was a significant factor explaining number of sprouts for the 2011 treatments ($P < 0.01$) (Table 3). No tested covariates significantly affected number of sprouts. Mean separation revealed the July burn treatment seedlings had the most sprouts on average, whereas the control treatment seedlings produced the fewest sprouts. The number of sprouts for the April burn, November burn, and clip treatments were statistically similar.

The top-killed shortleaf pine seedlings in the 2012 treatments exhibited statistical differences ($P < 0.01$) for the average number of sprouts (Table 3). The mean separation indicated that the April burn and March clip treatments were statistically similar. The November burn produced the most sprouts on average, and the control produced the fewest on average as expected. The maximum soil surface temperature covariate had a significant effect ($P < 0.01$) on average sprout number. Maximum soil surface temperature averaged across the three experimental units was lowest in the November treatment 435.0 ± SD 12.6 °C as compared to the April 446.9 ± SD 56.9 °C and July treatments 472.8 ± SD 47.2 °C. Individually, the maximum soil surface temperature covariate explained 58.0% ($P < 0.01$) of the differences in the number of sprouts associated with the 2012 shortleaf pine seedling treatments, with the greater maximum soil temperatures resulting in fewer sprouts per seedling for two of the three burn treatments. The adjusted April average sprout production was 5.5 ± SE 0.8, July was 10.6 ± SE 0.8, and November was 15.6 ± SE 1.0.

The seedlings in the 2013 treatment displayed significant differences among treatments ($P < 0.01$) for average number of sprouts (Table 3). The mean separation revealed that the April burn and March clip were statistically similar, whereas the July burn and control treatments were different from the other treatments (Table 3). No tested covariates significantly affected treatment means when included in the ANOVA. Some nontop-killed seedlings did sprout from the burn injury at the root collar; however, these sprouts were secondary to the main stem and not considered in the data analyses.

Height Growth. Treatment was a significant factor explaining seedling height growth for the
2011 treatments ($P < 0.01$) (Table 2). The mean separation showed that the April burn treatment and the November burn treatment seedling height totals were 50% to 60% of the cumulative 3-yr-height of the control treatment (Table 3). The July burn treatment displayed a shorter average seedling height than the April or November burns. The 2012 treatment seedlings displayed significant differences in average total height ($P < 0.01$) (Table 3). The April burn and March clip treatments were statistically similar as were the July and November burns. No covariates had significant effects on total seedling height. The control seedlings were tallest on average 203.6 ± SE 10.4 cm.

The 2013 treatment seedlings displayed significant differences in average height ($P < 0.01$) (Table 3). Mean separation results indicated that total heights had a range of 161.5 cm from the tallest average treatment (control) to the shortest average treatment (July burn), and the seedling heights for the April burn and March clip were similar. No covariates significantly affected treatment heights when included in the ANOVAs.

**Seedling Top Kill.** The top-kill rates of burn seedlings declined as seedlings aged (Table 4). All burn treatment seedlings were top-killed in the 2011 burns. The first burn treatment where a nontop-killed seedling occurred was the July 2012 burn treatments, where one out of 74 surviving seedlings (1.4%) was not top-killed. The percentage of nontop-killed seedlings increased in the November 2012 burns to 35 of 79 seedlings or 44.3%. The nontop-killed seedling rate decreased slightly in the March 2013 burn treatments to 37.1% or 26 of 70 seedlings. The July 2013 burn treatment displayed the greatest nontop-killed rate at 70.6%, 72 of 102 seedlings.

Table 4. Number and percentage (%) of surviving shortleaf pine seedlings by burn treatment year, month, and top-kill or nontop-kill category assessed during December 2013 and January 2014 (three growing seasons after planting, $n = 150$ per treatment) for the shortleaf pine seedling sprouting study in Morgan County, TN.

<table>
<thead>
<tr>
<th>Treatment year</th>
<th>Treatment season</th>
<th>Number of surviving seedlings after treatment</th>
<th>Top-killed seedlings n (%)</th>
<th>Nontop-killed seedlings n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>April</td>
<td>63</td>
<td>63 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>57</td>
<td>57 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>73</td>
<td>73 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>2012</td>
<td>April</td>
<td>88</td>
<td>88 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>74</td>
<td>73 (98.6)</td>
<td>1 (1.4)</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>79</td>
<td>44 (55.7)</td>
<td>35 (44.3)</td>
</tr>
<tr>
<td>2013</td>
<td>April</td>
<td>70</td>
<td>44 (62.9)</td>
<td>26 (37.1)</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>102</td>
<td>30 (29.4)</td>
<td>72 (70.6)</td>
</tr>
</tbody>
</table>

**Discussion.** Seedlings that survived burn treatments had two possible outcomes in this study. Either the stem was not killed and growth of the original stem resumed after a burn treatment, or the original stem was top-killed and sprouting occurred from a point on the stem or root collar. Survival of 2011 seedlings (1-yr-old) after the three seasonal burn treatments after two complete growing seasons were statistically similar. The survival rate range for the 2011 burn treatment seedlings in this study (38–48%) was similar to the April burn survival rate (43.0%) reported in a study completed in Arkansas with artificially and naturally regenerated, 6-yr-old seedlings under residual basal areas ranging from 0 to 6.9 m$^2$ ha$^{-1}$ (Lilly et al. 2012).

Cain and Shelton (2000) observed no survival for 1-yr-old seedlings following an August burn, whereas January burn and control treatment seedlings had similar survival rates after two growing seasons (95% and 91%, respectively). These were greater than any of the 2011 treatment numbers in this study. In contrast, Ferguson (1957) reported lower survival rates with large shortleaf pine seedlings to small pole-sized trees burned during August as compared to December. Shelton and Cain (2002) hypothesize that hotter temperatures during growing season burns likely cause more damage to dormant buds and result in lower survival rates. That observation was not apparent in this study because survival percentages did not differ across seasons in the 2011 treatments. One aspect that might have contributed to that result was the consistency of fuels in this study across seasons. In addition, the timing between treatments and measurements were different. In this study, survival was measured 2 yr following treatment for the 2011 seedlings versus 1 yr in Cain and Shelton (2000). Although weather, fuels, and seedling ages...
were similar between this study and the two cited studies, disparities in firing techniques and intensities (e.g., ring versus head fire) could have affected survival rates (Cain and Shelton 2000, Shelton and Cain 2002). Seedling state of dormancy (paradormancy versus endodormancy) could explain differences in survival of 1-yr-old shortleaf pine seedlings. Seedlings burned during the three periods of the year in this study were probably not in endodormancy as were the seedlings burned during January in the Cain and Shelton (2000) study. Seedlings in this study were likely in paradormancy during the November burn, whereas seedlings burned during the other two periods were actively growing. Usually woody stem injury or death sustained during periods of active growth results in greater mortality rates and less propensity to sprout (Waldrop and Lloyd 1991, Brose and Van Lear 1998). Survival differences were not evident in this study between clipping and burning and within the three burning seasons for each of the three seedling ages.

As seedlings age and grow larger, they become more tolerant of burns, which results in a lower top-kill rate (Little and Somes 1956, Ferguson 1957). During the course of 2012, seedlings in the July burn treatment, and even more so by the November burn treatment, had become large enough to survive the controlled fuel-load conditions. Once seedlings had completed two growing seasons after planting, they generally had taller stems, larger root systems, and presumably greater stored carbohydrates reserves and were better able to survive the burns.

Sprout production was affected by variability in burn conditions in only one of the three seedling ages tested. Maximum soil surface temperature significantly affected number of sprouts in 2-yr-old (2012) seedlings (covariate analysis). The variability of the burning conditions during 2012 probably contributed to the significant covariate response as compared to 2011 or 2013. Adjusted means for the 2012 burn treatments revealed slightly greater sprout production in the April and November burns, whereas the July burn had slightly less average sprout production. This result was probably due to greater maximum soil temperatures during July. The most sprouts were produced in the November burn when the average maximum soil surface temperatures were lower across experimental units. The ability of the November burn seedlings to produce the most sprouts during this year is likely a combination of the maximum soil surface temperature and a function of the seedlings’ carbohydrate reserves and planting depth (Wade and Jackson 1986; Drewa, Platt, and Mosier 2002). Research with other species has indicated that greater carbohydrate storage during dormant season fires can result in greater propensity to sprout during the next growing season following a burn (Pate et al. 1990; Waldrop and Lloyd 1991; Matlack, Gibson, and Good 1993). The position of the dormant buds in the soil and duff layers, seedling size and age, and bark thickness affect the capacity of dormant buds to sprout following a burn (Stone and Stone 1954, Little and Somes 1956, Lilly et al. 2010, Will et al. 2013).

The assessment of the 3-yr-old seedlings so soon after treatment likely altered the survival response seedlings would have displayed if they had been assessed a full growing season after treatments were applied. The third growing season, (2013 treatment) was the first year that a burn treatment produced a greater survival rate than a clip treatment. This response was likely due to some nontop kill among the April burn treatment seedlings. A clipping study by Campbell (1985) examined sprouting response in 4-yr-old shortleaf pine seedlings clipped in February at ground level and reported a survival rate of 40–60%, which was similar to 3-yr-old clipped seedlings in this study. The control treatment averaged less than one sprout per seedling, demonstrating that seedling injury or top kill promotes sprouting in shortleaf pine.

Unexpected soil surface temperature and burn residence time trends occurred in the two 2013 burn treatments. The July 2013 burn were cooler on average than the April burn treatments (Table 2). The April burns averaged 6 min longer than the July burns. Even though July burns are usually hotter than burns conducted in the spring or fall, the weather conditions during and prior to July 2013 were atypically wet (June, 3.1 cm and July, 10.8 cm greater than normal) (NOAA 2016) leading to greater fuel moisture levels and cooler July burns in 2013. For top-killed seedlings, the April burn stimulated more than two times the number of sprouts per seedling than the July burn. The lower intensity and shorter residence time of the July 2013 burns probably resulted in fewer sprouts as compared to the April burn or March clip treatments. Most of the seedlings not top-killed following the July burn treatments (70.6%)
produced fewer sprouts and were measured only five months following the burns, leaving less time for the seedlings to produce sprouts posttreatment.

The 3-yr-old seedlings/saplings in this study produced more sprouts on average than other studies with older saplings. Lilly et al. (2012) documented fewer sprouts per stem in 6-yr-old seedlings and saplings burned during April in Arkansas compared to the April burn seedlings in this study. This might have been the result of the 3 yr difference in age. A study in New Jersey that compared the effect of clipping and burning with fertilization on number of shortleaf pine sprouts reported that clipped trees produced more sprouts than trees burned during April in older saplings and pole-sized trees (Grossmann and Kuser 1988), indicating that burning, though promoting sprouts, might also damage some dormant buds capable of sprouting. These results, along with the trend in the 2013 treatment, suggest that as seedlings age and become larger, they can produce sprouts more readily following clipping than burning.

Several factors could impact height growth following top kill by burning or clipping, such as annual precipitation totals, browsing, and burn damage reduction of seedling height. Growth rates were within the 30 cm to 90 cm range per year expected for young, vigorous seedlings (Williston 1972). Approximately 24% of experimental units contained surviving seedlings that were browsed after resprouting, which affected total height growth. Sprouts from seedlings clipped in March would also have longer growing periods than seedlings burned in April, July, or November of the same year. Also, seedlings that were burned and resprouted were shorter than clipped seedlings perhaps because the burned seedlings incurred some heat damage to dormant buds. Clipped seedlings without heat damage also tended to have a greater height growth response than seedlings that were top-killed and resprouted (along with April burns in 2012 and 2013). Little and Somes (1956) observed that sprouting postburn will only occur below areas exhibiting char at the root collar or below, which could delay or prohibit the initiation of sprouting.

Total heights were greater with the 2012 and 2013 April burns than burns conducted later in the season, probably due to the longer length of the growing season and because growth resources were mobilized for sprouting in April after the dormant season. Growing season burn seedlings in July had shorter heights, whereas those conducted in November (entering dormancy) had heights that were shorter than April burns but generally taller than July burns. Burning during the growing season with greater temperatures and lower root carbohydrate reserves is postulated to damage woody plants more than at other times of the year (Cain and Shelton 2000, Shelton and Cain 2002, Robertson and Hmelowski 2014). However, variable weather conditions (particularly above normal precipitation and high humidity as encountered during the July 2013 treatment) could result in less damage to dormant buds and greater growth.

The burns conducted on the small experimental units in this study were 1.2 m \( \times \) 2.7 m and do not approximate the burning conditions that would occur across larger areas where burning conditions would be more of a mosaic of fuels and landscape conditions resulting in greater variability in seedling survival and growth (Dey and Hartman 2005, Lilly et al. 2012). Although great efforts were made to have similar burning conditions with homogenous fuels in each experimental unit, the ring ignition pattern of burning from the outside inward resulted in greater burn residence times, temperatures, and severity in the center of experimental units as compared to the perimeters (Waldrop and Goodrick 2012). Correspondingly, the 3-yr-old seedlings on the perimeter of the treatment units with shorter burn residence times and lower soil surface temperatures were not top-killed as often.

Of the 172 surviving 3-yr-old shortleaf pine seedlings prior to treatments in the March and July 2013 burn units, 65% were not killed above ground by the burns. Many of these seedlings (84 individuals) exceeded the minimum 153 cm height requirements suggested by Walker and Wiart (1966). Burning might not be necessary to maintain shortleaf pine seedlings that are at least 3 yrs old on similar sites during normal to above average precipitation years because many of these larger seedlings/saplings that survive the burning are not top killed and sprouting is not required for survival (Bowers et al. 2016). However, frequent burning to maintain woodland or savannah structure can be continued without affecting shortleaf pine once seedlings are large enough to withstand prescribed burns.

The shortleaf pine seedling control treatments (nine experimental units) that were not burned or
clipped had greater survival, less average sprout production, and greater total heights compared to other treatments (clip or burn) within an individual treatment year. With adequate initial site preparation and vegetation control, this early growth of shortleaf pine in even-aged stands is satisfactory for these sites (Smalley and Bailey 1974). Burning to promote sprouting is not necessary. Burning might be necessary while seedlings are young if there is concern about controlling the presence of loblolly-shortleaf pine hybrids, or the overall vegetation community response to burning compliments ecosystem restoration or maintenance goals or promoting fire dependent vegetation (Waldrop and Goodrick 2012, Stewart et al. 2015). The March clipping treatment simulates seedling damage (top kill) associated with burning without the temperature increases. Seedling survival percentages for clipping did not differ from each of the burning treatments. Total heights and sprout production were similar between the April burns and the March clips, except for the height in the 2011 treatments. Early growing season clipping as opposed to early growing season burning did not appear to affect seedling survival (sprouting), number of sprouts, or total heights within a treatment year.

Survival of burned seedlings was 51.5% for planted shortleaf pine (average across treatment years), regardless of season of burning and age of the seedling. This information could be used by managers to plan planting operations and burn regimes in stands with natural or planted shortleaf pine seedlings for desired stocking levels. Sprout height growth and top-kill rate results could also be used to create guidelines for burn frequencies to reduce seedling losses where periodic burns are desired. Although prescribed fire can be used to favor shortleaf pine seedlings with their sprouting ability, burning is also detrimental by causing death of seedlings. This study only investigated the impacts of burning on survival, number of sprouts, and height of young, planted shortleaf pine seedlings after one burn under consistent fuels and burning conditions. Multiple burns and more variable burning conditions might have different impacts on shortleaf pine sprouting and growth.

The results from this study lead to further research questions about the regeneration and development of shortleaf pine, particularly in mixed pine-hardwood stands. Considering that hardwoods reproduce vegetatively through sprouting, do shortleaf pine sprouts gain a competitive advantage over hardwood sprouts following a burn or a series of burns (Barnes et al. 1998)? In addition, what silvicultural pathways are available with burning and shortleaf pine sprouting ability to successfully establish and manage shortleaf pine in mixed species stands, especially after a harvest or to restore cutover, degraded stands? Millions of hectares of degraded hardwood stands exist on former shortleaf pine sites (Oswalt 2012). Restoration and rehabilitation of these stands with a component of shortleaf pine could enhance their diversity and value.

Conclusions. Shortleaf pine seedling survival ranged from 38% to 69% (mean 51%) for the three seasons of burning across the three treatment years. No differences in seedling survival among seasons occurred at any seedling age. Season of burning does not appear to be a discerning influence for seedling survival, yet a portion of 1- to 3-yr-old seedlings do succumb to burning in each season tested. Many seedlings in the 2013 treatments and the 2012 November burn treatment were not top-kill by the burn methods used.

Early growing season disturbances (March clip and April burn) produced similar numbers of sprouts in each of the three ages evaluated. Sprout heights were greater with treatments conducted early in the growing season in the 2012 and 2013 treatments (second and third growing season) than those conducted later in the growing season. Number of sprouts differed by season of burning for each of the three ages tested.

Shortleaf pine has declined in areas lacking periodic disturbances because environmental conditions are not present for seed germination and seedling development. Shortleaf pine appears to be a disturbance-dependent species because of characteristics such as the ability of seedlings to sprout. However, based on controlled experiments in this study, just as many seedlings died as sprouted on average, regardless of season of burning or until seedlings were large enough (late year two or three) to withstand controlled burning conditions imposed. Prescribed burning implemented in areas with artificially regenerated shortleaf pine should be delayed until seedlings reach sizes that are large enough to survive the burns, or more seedlings should be planted than desired to account for anticipated mortality.
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