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Restoration of Shortleaf Pine (*Pinus echinata*)-Hardwood Mixtures in Low Quality Mixed Upland Hardwood Stands Using Cluster Planting and Natural Regeneration

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Abstract: Cluster planting of shortleaf pine, along with various site preparation and release treatments, were tested to restore mixed shortleaf pine (*Pinus echinata* Mill.)–hardwood stands in areas where the shortleaf pine has diminished in recent years. Shortleaf pine–hardwood mixtures were once a common forest type throughout the Cumberland Mountains and Plateau physiographic regions of the southeastern United States. Knowledge of how to restore shortleaf pine–hardwood mixtures is limited throughout shortleaf pine's large native range. The objectives of this study were to compare planted shortleaf pine and natural hardwood regeneration survival, growth, and composition following various site preparation and early release treatments. Cluster planting and partial timber harvesting were used to reintroduce shortleaf pine and create two-aged stands in the Cumberland Mountains of Tennessee, USA. Results indicated that shortleaf pine survival, basal diameter, and height growth did not differ following four growing seasons among treatments. Natural regeneration stem densities and heights within shortleaf pine clusters did not differ significantly by treatment. Natural regeneration stem densities differed by species group and height class across the site, while the treatment × species interaction term was also significant. At this early stage of stand development, the brown-and-burn treatment appears poised for greater shortleaf pine growth rates than the other treatments. The herbicide treatment had the fewest regenerating hardwoods per hectare and the most desirable hardwood species composition.

Keywords: shortleaf pine; mixed-stands; cluster planting; site preparation and release; forest restoration; two-aged management

1. Introduction

Mixed shortleaf pine–hardwood forest types are defined as forests that contain approximately 25% to 75% pine species and 25% to 75% hardwood species as a percent of total stocking [1,2]. In the southeastern United States, these forest types occur more frequently on low productivity dry to xeric sites that have a history of frequent disturbance associated with mixed severity fire, logging, or wind events [3–5]. Successful regeneration of shortleaf pine requires disturbances that increase light levels and expose bare mineral soil [6]. Without regular disturbance, these sites will transition to mixed hardwoods over time [7,8]. In the Cumberland Mountains and Plateau as well as the southern Appalachian Mountain regions, a variety of hardwood and pine species occur with shortleaf pine to form mixed stands. Associated species include: black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus* *coccinea* Muenchh.), blackjack oak (*Quercus marilandica* Muenchh.), chestnut oak (*Quercus montana* Willd.), post oak (*Quercus stellata* Wangenh.), white oak (*Quercus alba* L.), pignut hickory (*Carya glabra* Mill.), mockernut hickory (*Carya tomentosa* Nutt.), blackgum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.), sourwood (*Oxydendrum arboretum* L.), and Virginia pine (*Pinus virginiana* Mill.).

Pine–hardwood forest types in mountainous areas of the southeastern U.S., such as the Cumberland and Appalachian Mountains, often develop following intense anthropogenic or lightning-caused wildfires. Site aspects where these forest types occur are often southern or western facing slopes that receive more sunlight than other aspects. Repeated high grading of hardwood species may have promoted pine species at irregular intervals [9]. Ridge tops and upper slope positions with southerly aspects throughout the southern Appalachian and Cumberland Mountains are more prone to recurrent fires than other aspects and slope positions from dryer conditions caused by greater solar radiation levels [10,11]. Stand replacement fires, either caused by lightning or anthropogenic ignition sources, are more likely on these sites, but still uncommon [12]. The dry and infertile edaphic conditions on some of these sites favor pine species and exclude many hardwood species [13,14]. Fire exclusion policies that began in the 1920s resulted in decades of shade-tolerant hardwood growth in mixed stands that precluded natural pine regeneration [15,16]. Without disturbance, these mixtures are transitional and unstable cover types because of the encroachment of shade-tolerant hardwood species and the inability of shortleaf pine to regenerate in closed canopy stands. Two-aged systems may be one avenue to retain these mixtures and regenerate pine.

The earliest U.S. Forest Service Forest Inventory and Analysis (FIA) report [17] for the Cumberland Plateau and Mountains region defined two pine–hardwood forest types. The southern yellow pine type was composed of up to 75% southern pines (primarily Virginia pine and shortleaf pine), while the upland hardwood–pine type had less than 25% southern yellow pine. This report revealed that approximately 1.6 million ha (31% of total forested area) in the Cumberland Plateau and Mountains region had mixed pine–hardwood forest types [17]. These stands had an average basal area of 12.6 m^2 ha^{-1} and an average volume of 21.1 m^3 ha^{-1} in stems over 10 cm in diameter [17]. Current definitions for pine–hardwood mixtures have an average pine basal area or stem density of 25–50% pine, according to [18]. As an example, these parameters suggest that shortleaf pine stand densities would equate to roughly 74 stems ha^{-1} that were 15 cm diameter and 7.6 m tall when using cubic foot volume tables provided by [19]. These historical stand structure values could provide targets for restoration activities in the region.

Forest types classified as shortleaf pine-dominated forests have been declining in area from 5.01 million ha in 1980 to 2.47 million ha in 2010 (52% loss) across the species' native range [20]. Most remaining shortleaf pine stems are in older, mature age classes with minimal young, regenerating age classes present [2,20]. Three of the primary factors for this decline include: change in the disturbance regime or absence of disturbance, increased planting of loblolly pine, and southern pine beetle (*Dendroctonus frontalis* Zimmermann.) epidemics [3,12,16,21].

Restoration of shortleaf pine–hardwood stands in the Cumberland and Appalachian Mountains will require artificial regeneration in areas that lack a seed source or have few mature trees. Classic methods of regenerating mixed pine–hardwood stands that include site preparation and planting seedlings at wide spacings (e.g., [22,23]) may be logistically difficult and more expensive to implement on steeper terrain. Planting seedlings under a residual overstory and initiating a two-age stand is not as well studied as even-age methods of initiating pine–hardwood mixtures. Although planted shortleaf pine seedlings can survive some partial shading (e.g., [24–26]), growth rates of seedlings planted under dense residual canopies decrease in proportion to the amount of residual overstory stocking compared to seedlings grown in more open conditions [26].

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 could gain a competitive advantage in the shade conditions created by a partial harvest [27]. 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 lower productivity sites [27,28]. 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 (*Pinus strobus* L.), and reduce the germinative and sprouting capacity of some competitor species [29]. Partial overstory harvests and two-age management may be a viable option to encourage shade intermediate species such as shortleaf pine and white oak species on sites where traditional row planting is not practical.

Cluster planting, or group planting, has been practiced as a form of artificial regeneration in Russia and Europe since the early twentieth century as an alternative to row planting [30]. Cluster planting consists of small areas (typically less than 85 m^2) that are planted with seedlings at close spacings (1–2 m) to either increase stocking with many clusters planted per unit area, or introduce desirable regeneration to canopy gaps in disturbed stands on more productive microsites with fewer clusters per unit area [31,32]. Wider spacings within clusters (>1 m) can allow natural regeneration to grow among the planted seedlings [31]. The number of seedlings planted per cluster can be adjusted to address stocking considerations, made to fit the space created by a canopy opening, or located on a favorable microsite. Cluster planting offers many possible benefits compared to classic row planting. Site preparation, planting, release, and thinning treatments can be concentrated within areas designated as clusters, reducing costs for these operations. 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 accelerates natural pruning [33]. Deer browse risk is decreased for seedlings planted in cluster patterns as compared to grid patterns [34]. Trees planted at high densities might receive less browse pressure per tree as saplings than individual trees in more open stands [34]. In addition, cluster planting may be more suited to conifers because of their stronger epinastic control compared to most hardwoods, which have a decurrent growth pattern [33]. Cluster planting is an attractive option for the reintroduction of shortleaf pine and establishment of natural hardwood regeneration in older, partially harvested hardwood stands that once had a shortleaf pine component.

The primary objective of this study was to evaluate the early establishment and development of two-age, mixed shortleaf pine–hardwood stands with cluster planting of shortleaf pine and establishment of natural hardwood regeneration within clusters on former shortleaf pine–hardwood sites in the Cumberland Mountains of east Tennessee. The survival and growth of planted shortleaf pine, as well as natural regeneration, were investigated for five site preparation and release treatments intended to alter the species composition and stem densities of natural regeneration.

2. Materials and Methods

2.1. Study Site and Treatments

The study site is located on Little Brushy Mountain in Morgan County, Tennessee, USA, at approximately 36.05376° N 84.43563° W, and owned by The University of Tennessee Institute of Agriculture. Elevations of the 30.76 ha Little Brushy Mountain study site range from 365 to 550 m, and aspects are primarily southwest to northwest facing. This area is characterized as the Thrust Block Interior, Wartburg Basin, and Jellico Mountains region of the Cumberland Mountains [35]. Bedrock in this area consists of strata that contain shales, siltstones, and coal [36]. Three soil types dominate the site: Gilpin-Boulin-Petros Complex, 25 to 80 percent slopes, very stony; Shelocta silt loam, 12 to 20 percent slopes; and Lily-Gilpin Complex, 20 to 35 percent slopes. These soil series and complexes were located at different slope positions throughout the site. Site indices at base age 50 years for these soils differ by species. Yellow-poplar (*Liriodendron tulipifera* L.) has the highest site index of any species at 27 m, black oak at 18 m, white oak at 23 m, and shortleaf pine at 18 m [37]. Rainfall in the area averages from 122–155 cm annually, while the mean temperature ranges from 5–19 °C [38].

Pre-harvest vegetation 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. Stand basal area averaged 22.3 m^2 ha^{-1}, and the area averaged 96 sawtimber stems (minimum diameter at breast height (dbh) 30 cm) ha^{-1}, and

111 pulpwood stems (minimum dbh 15 cm, maximum dbh 28 cm) ha^{-1}. 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 and white oak were still common, while black oak, hickories, and northern red oak (*Quercus rubra* L.) became more prevalent. Throughout most of the study site, midstory and regenerating species consisted primarily of red maple, eastern white pine, sourwood, and mountain laurel (*Kalmia latifolia* L.). Many identifiable stumps, logs, and snags, as well as small pockets of advanced shortleaf pine reproduction, were present across the site.

Study establishment began with retention tree marking prior to a commercial timber harvest. Retention trees were selected based on species, diameter, and canopy position. The target retention tree basal area per ha was 3.5–5 m^2 ha^{-1} to remain consistent for two-age deferment harvest guidelines for the region [39]. Though retention and take trees were individually marked, logging crews left higher residual basal areas than desired following the completion of logging operations. Retention tree basal area averaged 11.9 m^2 ha^{-1} while trees per hectare averaged 397 for stems 5 cm dbh and larger across the study site after release treatment implementation. More information on retention tree survival selection and survival trends can be found in [40]. After a commercial timber harvest, 150 8.5 × 8.5 m clusters were established on the site, averaging six clusters per ha. Five experimental units (ten clusters per experimental unit) were established in each of three blocks (A, B, and C) that were delineated by elevation (low, medium, and high) (Figure 1). Each experimental unit within a block was assigned one of five site preparation and/or release treatments (Figure 1). Treatments included: a no treatment control, herbicide only, herbicide and burn (here after referred to as brown-and-burn), burn only, and scarification by logging equipment. Within clusters, all stems greater than 90 cm tall were cut. Approximately 71% of those stems were less than 2.5 cm dbh. In addition, all logging slash was removed from the interior of clusters to facilitate planting crews and reduce burn treatment severity for clusters that received burn treatments. These cluster clearing operations were completed in all treatments (clearing was not necessary in some scarification treatment clusters due to removal of all slash and small stems by logging equipment) as a form of mechanical site preparation prior to planting.

The "subjective without preconceived bias" method [41] was used to subjectively assign treatments to an experimental unit. 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 an experimental unit in each block, where logging machinery had exposed the greatest area of bare mineral soil. Violation of the assumption of independence among experimental units for analysis of variance was an issue with assigning these three treatments in this manner. To ensure that experimental units across the site did not differ prior to treatment assignment due to understory and midstory stem density disparities, a pre-treatment stem density analysis was completed for stems cut during cluster establishment that were greater than 90 cm tall. Complete tallies were compiled of all stems greater than 90 cm tall in each 8.5 × 8.5 m cluster as they were established.

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 are 2nd generation material from U.S. Forest Service seed orchards in the Ouachita National Forest and have an Arkansas seed provenance. Currently, shortleaf pine seed orchards do not exist in Tennessee, and there are no shortleaf pine seed orchards within 320 km of the study area. Bareroot, 1-0 stock seedlings were planted on April 7 and 8, 2015 by hand planting crews. Most seedlings from this nursery average 25–30 cm in height and 4.7 mm basal diameter at planting [42]. Exactly 9548 seedlings were planted at 1.2 × 1.2 m spacing with an average of 63.7 seedlings per cluster, just under the 64 seedlings per cluster target.

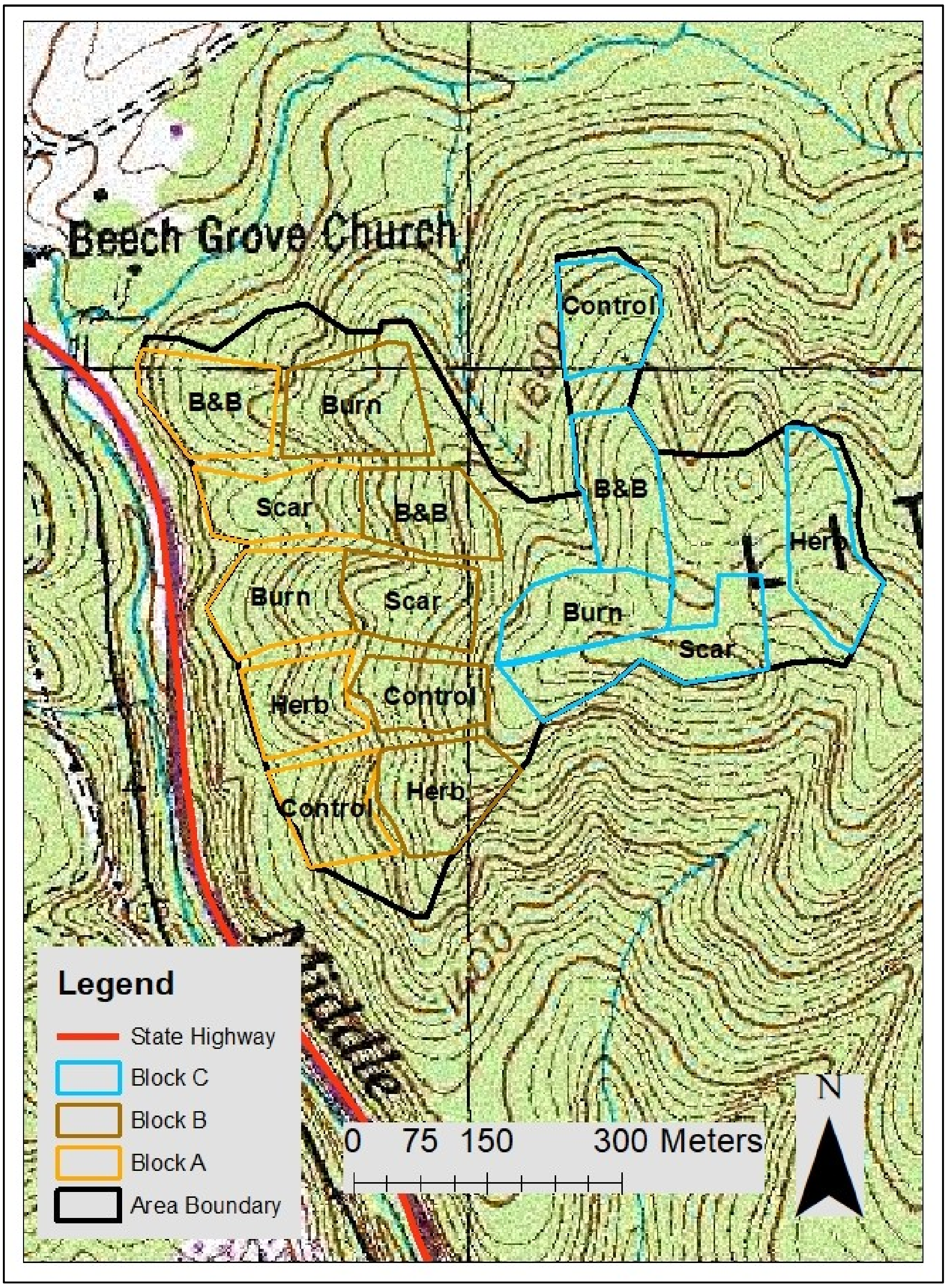

Figure 1. Study area boundary, block locations, and treatment assignments to experimental units are displayed over a Digital Raster Graphic topographic map of Morgan County, Tennessee, USA (courtesy of U.S. Geological Survey).

All stumps of stems that were cut in herbicide and brown-and-burn treatment clusters prior to planting were treated with a 9.3% solution of Arsenal® AC (salt of imazapyr) herbicide and water immediately following stem felling. This rate of imazapyr was used for greater control of hickory spp. These treatments also received a spot foliar herbicide release application using backpack sprayers when shortleaf pine seedlings developed a resting bud and had ceased height growth during mid-August 2015. The release targeted herbaceous and woody vegetation growing within the clusters and herbicide rates were based on recommendations from Yeiser [43] and BASF Corporation [44]. A tank mix of Arsenal® AC was applied at a rate of 877.2 mL ha^{-1} with 70 g ha^{-1} of Escort® (metsulfuron methyl). Herbicide solution was applied as needed to all non-shortleaf pine plants within a cluster.

The brown-and-burn and burn only treatment units were burned during March 2016. Weather conditions are provided in Table 1. When skid trails entered a unit, flames were initiated along the edges of the skid trail and were allowed to spread into the interior of the experimental unit(s). In interior portions of experimental units where burn coverage was poor, strip-head burn ignition patterns were used to improve coverage. Prescribed burn coverage was 100% in all experimental units.

Table 1. Weather conditions recorded during the burn and brown-and-burn treatments for the five site preparation and release treatments in Morgan County, Tennessee, USA.

Date	Time	Temperature (°C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction	Number of Experimental Units Burned
3/17/2016	17:00–19:00	18–21	14–18	3.1–3.6	W	2
3/18/2016	12:00–19:00	17–21	18–23	0–3.6	Variable	2
3/30/2016	13:00–18:00	21–24	22–29	2.6–5.1	SSE-SSW	2

Scarification treatment clusters that did not receive complete scarification coverage by logging equipment were scarified by hand using hand tools such as a fire rake and Pulaski. Most of the duff layer and O horizon were removed on the portions of clusters that were hand scarified. Logging equipment exposed the B horizon(s) in almost all instances. More information on quantifying the scarification treatment and its effects on planted shortleaf pine seedlings and natural regeneration are presented in [45].

2.2. Measurements

Survival of shortleaf pine seedlings along with the height and basal diameter of surviving seedlings were assessed in five randomly selected clusters out of ten per experimental unit, after four full growing seasons post-planting and three full growing seasons after all treatments were completed. Stem heights were measured to the tip of the terminal bud, and basal diameter was measured at ground level. Natural hardwood regeneration was assessed inside of three randomly selected clusters out of ten in each experimental unit. Natural regeneration was assessed within a circular 13.5 m^2 plot at the center of the cluster. All naturally regenerated stems greater than 15 cm tall and less than 2.5 cm dbh were tallied by species and placed into one of ten 15-centimeter height classes (15–30 cm, 30.1–60 cm, 60.1–90 cm, 90.1–121 cm, 121.1–152 cm, 152.1–182 cm, 182.1–213 cm, 213.1–243 cm, 243.1–274 cm, and 274.1+ cm). Woody species were grouped into one of nine species groups or woody vegetation classes for statistical analyses. Blackgum (*Nyssa sylvatica* Marshall), red maple, and yellow-poplar were assigned individual species groups. Eastern hemlock (*Tsuga Canadensis* L.), eastern white pine, Virginia pine, and shortleaf pine were grouped into conifers. Hickory spp. included mockernut hickory and pignut hickory. Miscellaneous hardwoods included sweetgum (*Liquidambar styraciflua* L.), black cherry (*Prunus serotina* Ehrh.), sweet birch (*Betula lenta* L.), sassafras (*Sassafras albidum* Nutt.), American beech (*Fagus grandifolia* Ehrh.), paulownia (*Paulownia tomentosa* Thunb.), cucumber tree (*Magnolia acuminate* L.), American holly (*Ilex opaca* Aiton.), mimosa (*Albizia julibrissin* Durazz.), white ash (*Fraxinus Americana* L.), striped maple (*Acer pensylvanicum* L.), flowering dogwood (*Cornus florida* L.), black locust (*Robinia pseudoacacia* L.), and downy serviceberry (*Amelanchier arborea* Michx.). Red oak spp. included scarlet oak, northern red oak (*Quercus rubra* L.), and black oak. Shrub spp. included mapleleaf viburnum (*Viburnum acerifolium* L.), deerberry (*Vaccinium stamineum* L.), smooth sumac (*Rhus glabra* L.), azalea (*Rhododendron* spp.), devil's walkingstick (*Aralia spinosa* L.), and buffalo nut (*Pyrularia pubera* Michx.). White oak spp. included chestnut oak and white oak. Measurements were completed during the late summer and fall of 2018, when precipitation deficits cause height growth to diminish.

The effect of overstory hardwoods on shading and infiltrating sunlight to the shortleaf pine seedlings and natural regeneration was quantified during July and August 2016, when leaves were fully developed. Instantaneous light value measurement methodology was used to quantify microsite light availability in the forest understory within each cluster using a handheld ceptometer capable of measuring photosynthetically active radiation (PAR) levels [46]. PAR levels were measured at each corner and the center point of each cluster for a total of five measurements per cluster. Photosynthetic photon flux density levels (μmol s^{-1} m^{-2}) were recorded using an Accupar Linear PAR/LAI Model PAR-80 ceptometer (Decagon Devices, Pullman, WA) at a fixed height (1.2 m) and carefully leveled at each point. All readings were taken during 1045 to 1430 h on days with overcast conditions [46]. An average value was computed from the five measurements taken in each cluster.

2.3. Statistical Analyses

Analysis of variance (ANOVA) as a randomized complete block design with sampling (five clusters per experimental unit, and sub-sampling for tree level measurements) using mixed models in SAS version 9.4 [47,48] was used to test for differences among treatments for understory light levels, shortleaf pine height and basal diameter, and pre-treatment regenerating woody stem densities. Differences in natural regeneration stem density among species and height groupings were tested using a randomized complete block design mixed model with treatment in the whole plot, and a factorial of species and height groupings in the sub-plot. Due to normality issues, the natural regeneration stem density analyses were transformed using a log transformation, and untransformed means and standard errors are reported. Blocking was used because of the elevation and soil texture differences from the bottom to the top of the mountain. Treatment was considered a fixed effect, while block was considered a random effect. Residuals were tested for normality using the Shapiro–Wilk test. Least-squares means were separated using Fisher's protected least significant difference and an alpha level of $p = 0.05$. The shortleaf pine basal diameter and height variables as well as the natural regeneration and height variables were transformed with a square root transformation due to slight skewness. Untransformed means and standard errors are reported. Shortleaf pine survival rate differences across treatments were evaluated using a generalized linear mixed model and the binomial distribution. Treatment was considered a fixed effect while block was considered a random effect.

3. Results

3.1. Shortleaf Pine Survival and Growth

Treatment was not a significant factor in explaining planted shortleaf pine seedling survival ($p = 0.94$) (Table 2). Survival only differed by 7.8% across the five treatments. Survival was numerically greatest in the herbicide treatment (42.6% ± 7.4%), while the control (34.8% ± 6.8%) and brown-and-burn (38.3% ± 7.1%) treatments had the lowest survival rates. The burn (38.7% ± 7.2%) and scarification (40.8% ± 7.3%) treatments were intermediate to the other three treatments.

Table 2. Planted shortleaf pine seedling mean, standard error, and letter grouping results are presented for survival, basal diameter (mm), and height (cm) variables following four growing seasons for the five site preparation and release treatments in Morgan County, Tennessee, USA. Treatment means followed by the same letter in a column indicate no significant differences ($p = 0.05$).

	Survival (%) $p = 0.939$	**Basal Diameter (mm) $p = 0.141$**	**Height (cm) $p = 0.126$**
Treatment	**Mean (SE)**	**Mean (SE)**	**Mean (SE)**
Brown-and-Burn	38.3 ± 7.1 a	34.8 ± 3.3 a	203.4 ± 20.1 a
Burn	38.7 ± 7.2 a	19.1 ± 3.3 a	129.5 ± 20.1 a
Control	34.8 ± 6.8 a	15.0 ± 3.3 a	108.7 ± 19.3 a
Herbicide	42.6 ±7.4 a	20.6 ± 3.3 a	129.8 ± 20.1 a
Scarification	40.8 ± 7.3 a	24.4 ± 3.3 a	187.7 ± 19.3 a

Treatment differences were not significant with shortleaf pine basal diameter ($p = 0.14$) (Table 2). Average basal diameters ranged from 34.8 ± 3.3 mm in the brown-and-burn treatment to 15.0 ± 3.3 mm in the control treatment. The scarification treatment seedlings had the second largest average basal diameter at 24.4 ± 3.3 mm.

Treatment was not a significant factor ($p = 0.13$) for explaining differences in shortleaf pine seedling height (Table 2). Seedling heights ranged from a high of 203.4 ± 20.1 cm in the brown-and-burn treatment to a low of 108.7 ± 19.3 cm in the control treatment. Numerically, the scarification treatment seedlings were the second tallest on average at 187.7 ± 19.3 cm.

3.2. Natural Regeneration Density, Growth, and Composition

Natural regeneration stem densities were not significantly different for stems taller than 90 cm prior to treatments being assigned to experimental units ($p = 0.49$). Stem densities ranged from an average of 1635 ± 377.6 ha^{-1} in the scarification treatment to 4878.5 ± 566.4 ha^{-1} in the control treatment.

Treatment (stem density and height) ($p = 0.58$, $p = 0.43$), the treatment x height class interaction ($p = 0.89$), and the species x height class interaction ($p = 0.18$) were not significant factors in explaining the number of naturally regenerating stems per hectare within clusters (Table 3). Differences in stem densities by species ($p = 0.001$), height class ($p = 0.02$), and the treatment x species interaction ($p = 0.05$) were statistically significant (Table 3). Numerically, the burn treatment had the most regenerating stems per hectare on average (58,069 ± 20,896 ha^{-1}), while the herbicide treatment (30,064 ± 5945 ha^{-1}) had the fewest stems per hectare. Average natural regeneration heights were tallest on average in the scarification treatment (113.0 ± 23.1), while heights were shortest on average in the burn treatment (51.8 ± 26.4).

Table 3. ANOVA table of natural regeneration stem density inside clusters plantings for the five site preparation and release treatments tested in the shortleaf pine–hardwood establishment study, following four growing seasons in Morgan County, Tennessee, USA.

Source	*df*	*p*-Value
Treatment	4	0.58
Species	8	0.001
Treatment × Species	32	0.05
Height Class	9	0.02
Treatment × Height Class	36	0.89
Species × Height Class	55	0.18
Treatment × Species × Height Class	116	0.99

Statistical differences in the number of stems by species group were apparent for cluster interiors ($p < 0.001$) (Table 4). Shrub spp. followed by yellow-poplar and miscellaneous hardwoods were the most frequently occurring species groups. Highly desirable hardwood species, such as red oaks, averaged 1108 ± 524 stems ha^{-1}, while white oaks averaged 1809 ± 569 stems ha^{-1} and were statistically similar in stem densities per hectare across the site (Table 4). Natural regeneration average height differed across the site four growing seasons following study establishment ($p = 0.02$). Most stems were concentrated in the two smallest height classes (15–30 and 30.1–60 cm) as well as the largest size class (274.1 cm–2.54 cm dbh) (Table 5). The treatment x species interaction was also statistically significant ($p = 0.05$). The burn treatment was dominated by shrub species (primarily deerberry) and was less diverse in terms of the number of regenerating species (Figure 2).

The high stem densities (5903–16,312 stems ha^{-1}) of shrub spp. in the burn, herbicide, and control treatments contributed to this interaction term being statistically significant. No other species or species group had over 3600 stems ha^{-1} per treatment on average (Figure 2). The herbicide treatment numerically had the greatest white oak spp. stem densities. This treatment had significantly more stems per hectare than the burn treatment but was statistically similar to the other three treatments. The herbicide treatment also had the fewest regenerating stems per hectare of all treatments. Numerically, yellow-poplar was most prevalent in the brown-and-burn and scarification treatments, yet these differences were not statistically significant. Red maple tended to have similar stem densities across all treatments (Figure 2).

Table 4. Natural regeneration mean, standard error, and letter groupings for species and species class are presented for inside cluster plantings for the five site preparation and release treatments tested in the shortleaf pine–hardwood establishment study, following four growing seasons in Morgan County, Tennessee, USA. Treatment means followed by the same letter in a column indicate no significant differences ($p = 0.05$).

	Stems ha^{-1} ($p < 0.001$)
Species	**Mean (SE)**
Blackgum	748.2 ± 1259.5 bcd
Conifer spp.	307.4 ± 1648.9 d
Hickory spp	177.4 ± 1303.9 d
Miscellaneous Hardwoods	1916.0 ± 424.8 bc
Red Maple	1713.4 ± 459.9 bc
Red Oak spp.	1108.9 ± 524.3 cd
Shrub spp.	6668.5 ± 635.8 a
White Oak spp.	1809.7 ± 569.1 c
Yellow-Poplar	2011.4 ± 363.7 b

Table 5. Natural regeneration mean, standard error, and letter groupings for height class across all treatments are presented for inside cluster plantings for the five site preparation and release treatments tested in the shortleaf pine–hardwood establishment study, following four growing seasons in Morgan County, Tennessee, USA. Treatment means followed by the same letter in a column indicate no significant differences ($p = 0.05$).

	Stems ha^{-1} ($p = 0.02$)
Height Class (cm)	**Mean (SE)**
15–30	3166.6 ± 434.3 a
30.1–60	2234.4 ± 442.7 ab
60.1–90	1706.6 ± 498.8 bc
90.1–121	1309.3 ± 560.2 cd
121.1–152	1444.2 ± 653.9 cd
152.1–182	1224.9 ± 769.4 d
182.1–213	1433.7 ± 726.3 cd
213.1–243	1190 ± 837.6 cd
243.1–274	1738.3 ± 917.2 bcd
274.1–2.5 cm dbh	2447.1 ± 1039.9 abc

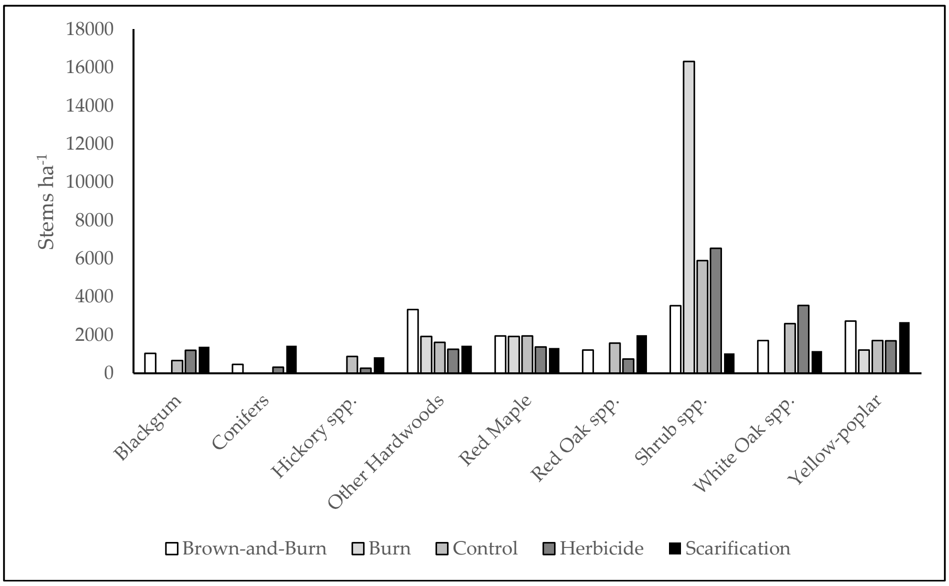

Figure 2. Regenerating woody species' average number of stems per hectare for the treatment × species interaction ($p = 0.05$) four growing seasons after study establishment for the shortleaf pine–hardwood restoration study located in Morgan County, TN, USA.

3.3. Understory Light Levels

Average PAR levels for each cluster indicated no significant differences in overstory light levels among treatments (p = 0.1), suggesting that overstory shade differences were not a possible confounding factor when testing for treatment differences with vegetation survival and growth. Percent of full sunlight averages ranged from 39.4% ± 2.2% in the control treatment to 72.9% ± 2.9% in the brown-and-burn treatment. The burn, control, and scarification treatments all averaged between 53.1–59.7% of full sunlight.

4. Discussion

4.1. Shortleaf Pine Survival and Growth

Shortleaf pine treatment differences for survival rates were not evident in this study, and survival was generally low across all treatments. Low survival rates may justify planting high densities of seedlings within clusters. Several factors may have contributed to these low survival rates including: later than normal seedling lifting date from the nursery; thin, rocky soils on most of the site; a second year drought with concomitant redheaded pine sawfly (*Neodiprion lecontei* Fitch.) defoliation; and burn treatments killing some seedlings [49]. The seedling lift date from the Tennessee Division of Forestry East Tennessee Nursery was 9 March 2015 [43]. Slightly lower survival rates with March lifting than January or February lifting have been reported, as have April planting dates as compared to January or February planting [50,51].

The Gilpin-Boulin-Petros complex soil type that covers most of the study area is considered very rocky. Stones that are 25–58 cm in diameter are present throughout the profile and comprise 35–60% of the soil by volume [37]. The presence of these stones and the thinness of the soil to bedrock could have contributed to low seedling survival rates due to poor tree soil rooting, low moisture holding capacity, or improper planting practices contributed by the rocky soil medium [52].

A severe drought occurred throughout the mid-South of the U.S. during the late summer and fall months of 2016, at the end of the study's second growing season [49]. Drought causes reduced survival in tree seedlings, and can increase the abundance of forest insect pests, which are more likely to damage or kill trees in their weakened state [53]. Redheaded pine sawfly was identified on seedlings during fall 2016 with the concurrent drought. Outbreaks of this insect occur most commonly in young pine stands less than 4.5 m tall and in pines growing near hardwoods with heavy vegetation competition and on poor productivity sites [54]. These characteristics were all present at this site.

Low survival rates in the two burn treatments are probably a result of some seedlings not surviving and resprouting following topkill. A 20–50% reduction in survival has been reported in topkilled two to three-year-old shortleaf pine seedlings [55,56]. A seedling's ability to resprout is a function of burn intensity and residence time, the physiological state of the seedling, the seedling's size, and the location of the basal crook (where dormant buds are located) in the duff or upper soil layer [57,58]. The removal of most larger logging slash (100, 1000, and 10,000 h fuels) from within clusters during establishment probably reduced the flame residence time and severity of the burns compared to areas around the burns [59]. Removal of large logging slash may partially explain why seedling survival was not significantly less in the burn treatments compared to treatments that did not include burning.

Shortleaf pine average basal diameter annual increment ranged from 2.6 mm year^{-1} in the control treatment to 7.5 mm year^{-1} in the brown-and-burn treatment. Average basal diameter was 4.7 mm at planting. This range of annual basal diameter increment is similar to at least two other shortleaf pine underplanting studies conducted in Arkansas and Missouri. The Arkansas [25] and Missouri studies [60] had comparable stocking levels to this study and revealed similar average basal diameter increments of 5.4 and 3.6 mm year^{-1} over three years and five years, respectively. The uniform basal diameter means across treatments at the time of measurement may partially be explained by shortleaf pine seedling developmental strategies. Aboveground shortleaf pine growth has been reported to increase dramatically within a couple of years post-planting after the initial development of a large root system [61,62]. Root system development was also most likely delayed under partial overstory conditions compared to full sunlight [63], resulting in less growth differentiation among treatments after only four growing seasons.

Shortleaf pine average annual seedling height increment ranged from 20.9 cm year^{-1} in the control treatment to 44.9 cm year^{-1} in the brown-and-burn treatment. Average height increment in the Arkansas [25] and Missouri [60] shortleaf pine underplanting studies with similar stocking levels averaged 32.3 and 21 cm year^{-1} after three and five years, respectively. Though differences were insignificant, shortleaf pine height growth trends were similar to basal diameter growth trends with the brown-and-burn and scarification treatments having numerically taller saplings than the control treatment. Height growth was likely affected in similar ways as basal diameter growth, but height growth should differentiate among treatments at a quicker rate than basal diameter or diameter growth as the stand develops [33]. Future measurements should be conducted to determine if this trend becomes more evident over time.

The combination of a limited time period since seedling planting; uniform, partially shaded conditions; and similar levels of hardwood competition prior to and after implementation of treatments probably contributed to the lack of treatment differences in basal diameter and height growth over the first four years after planting. In addition, late planting (early April in this case) has been shown to decrease height growth of cold stored or non-cold stored shortleaf pine seedlings by as much 10 cm as compared to planting in December or January [51]. This decrease in growth is likely due to a combination of seedlings breaking dormancy by April in most locations of the mid-South and transplant shock.

Shading of shortleaf pine seedlings by residual overstory trees has been shown to reduce seedling growth rates in other studies. A study in Missouri stated that level of overstory basal area or stocking (<2, 4–9, 10–14, and >14 m^2 ha^{-1}) explained 43% of basal diameter and 45% of height variation for three-year-old underplanted shortleaf pine [60]. The Missouri study also demonstrated wide ranges in average basal diameters from areas of high to low stocking (4.4–40.4 mm) five years after planting [60]. In an Arkansas study with underplanted shortleaf pine seedlings, the authors reported that average basal diameter and height increased more quickly over time under lower levels of residual basal area (basal area ranged from 0 to 9.2 m^2 ha^{-1}) [25]. In summary, shortleaf pine seedlings that receive partial overhead shade do not appear to grow as quickly as those growing in full sunlight, reflecting the shade intolerance reported for shortleaf pine. The relatively uniform residual overstory basal area and PAR levels could have contributed to uniform basal diameter and height growth across treatments.

4.2. Natural Regeneration Density, Growth, and Composition

Natural regeneration stem densities did not differ across areas of the study site prior to treatment assignment, indicating no issues with the lack of treatment randomization for the burn and scarification treatments. In addition, no statistical differences were detected among treatments for natural regeneration stem densities or average heights three growing seasons after treatment implementation. All treatments experienced an influx of new woody regeneration following timber harvest, site preparation, and release treatments. Increased light levels and seedbeds with reduced organic matter at the surface would have promoted new seedling germination from seed and sprout growth. As examples, a single prescribed burn under a residual overstory has been reported to increase woody stem densities in oak-pine mixtures in Tennessee, Georgia, and Kentucky [4,64]. In addition, scarification can increase stem densities of light-seeded species such as yellow-poplar [65].

Natural regeneration height classes did not differ in stem densities across the study site. This result is probably more a function of similar light levels and regeneration sources across treatments rather than treatments altering competitive effects, microsites, and microclimates within clusters at this early stage of stand development. New stems originated from a variety of regeneration sources, such as stump sprouts, seed, and seedling sprouts, which all grow at different rates depending on size, species, and environmental conditions [53]. The partially shaded conditions within all treatments of the study probably reduced germination and growth rates for some species similarly to the planted shortleaf pine seedlings while improving conditions for germination and growth in others. For instance, hardwood sprouts in a southern Appalachian Mountains study displayed greater growth rates one year after harvest following 30% and 40% overstory reduction compared to 10–20% overstory reduction [66]. 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 [67]. Natural regeneration growth rates will increase as regenerating stems reach larger size classes and as mortality rates of less competitive regenerating woody stems increase [51,68]. This pattern may not occur if residual overstory trees expand and fill the gaps where the clusters are located more quickly than regeneration can occupy gaps [69].

Though natural regeneration height was not taller than shortleaf pine seedlings on average by treatment, the height class analysis (Table 5) revealed a large number of stems in the smaller height classes that likely skewed this finding. Approximately 30% of naturally regenerating stems were less than 60 cm tall but greater than 15 cm tall. Conversely, approximately 29.9% of hardwood stems were taller than average shortleaf pine heights (108.7–203.4 cm) across treatments. A shortleaf pine–hardwood study in South Carolina demonstrated similar results four years after planting shortleaf pine at 3 × 3 m spacing on a clearcut site [70]. Results from [70] found a similar issue where a subset of larger hardwoods were overtopping planted shortleaf pines, but overall treatment means did not reflect this issue. One important difference between this study and the South Carolina study was the relative proportion of surviving seedlings compared to the number of overtopping hardwoods per unit area. In the South Carolina study, the number of overtopping hardwood trees per hectare was roughly similar to the number of surviving pines [70], whereas in this study the average number of overtopping hardwoods per hectare outnumbered planted shortleaf pine seedlings based on current survival rates. Research conducted in Missouri also reported that shortleaf pine seedlings were overtopped by hardwood competitors two and five years after study establishment in a shortleaf pine underplanting study [61]. They determined that shortleaf pine seedlings were growing at the same rate as hardwood competitors, but shortleaf pine seedlings were overtopped 0.5–1.5 m by hardwood competitors. Two reasons were postulated. Shortleaf pine seedlings were shorter at planting than understory hardwood competitors, and the one to two year lag in aboveground shortleaf pine growth after planting allowed hardwood competitors with established root systems to gain a height advantage over those growing seasons [60]. In this study, all hardwood competitors ≥90 cm within clusters were cut prior to planting shortleaf pine seedlings. Some hardwood competitors within clusters could have had 60 cm or more of a height advantage compared to the planted shortleaf pine seedlings. These hardwood seedlings and seedling sprouts would not have had transplant shock or root system establishment delays with regards to height growth during the first and second growing season.

Differences in stem densities by species group occurred across the study site four years after establishment. Shrub spp. and yellow-poplar tended to be the most frequently occurring species groups. Deerberry, mapleleaf viburnum, buffalo nut, and smooth sumac all reproduce prolifically by vegetative sprouting and rhizomes when the stem is damaged or killed and when growing space is increased [71–74]. The additional available light and disturbed forest floor conditions associated with release treatments and logging activities most likely resulted in extensive vegetative reproduction of these species and contributed to the high average stem count of the shrub spp. group. The most commonly observed shrub species was deerberry. *Vaccinium* species such as deerberry have been noted as being serious competitors in young southern pine stands in at least one other study [75], but because deerberry does not reach heights of more than 2 m, it is not considered a sunlight competitor but more of a soil water and nutrients competitor [71]. Yellow-poplar can reproduce prolifically from wind-disseminated seeds, and is a serious competitor for slower growing species such as oaks or shortleaf pine in moderate to high light levels. Partial canopy openings followed by prescribed burning or co-occurring with soil scarification can promote rapid colonization of yellow-poplar from seed [76,77].

White oak spp. had relatively high regenerating stem totals (4th of 9 groups) (Table 4). White and chestnut oak were two of the primary overstory species on site prior to study initiation, which provided a regeneration source. Intermediate light conditions and scarification of the seed bed following partial harvest could have contributed to new oak regeneration, while removal of competitor trees in the understory along with overstory stocking reductions most likely released any advanced white and chestnut oak regeneration present prior to study establishment. Both of these species are capable of persisting in understory light conditions for many years before a release event occurs [78,79]. They then can begin rapid height growth when released with residual stocking levels as high as 60% [79]. In general, oaks tended to be most prevalent in the three treatments that lacked fire. This trend is likely a result of less oak seedling mortality in the non-burn treatments. Oaks may also recover more quickly from release rate applications of imazapyr compared to other hardwoods, such as yellow-poplar, sweetgum (*Liquidambar styraciflua* L.), and flowering dogwood (*Cornus florida* L.) [80].

Red maple was the only additional single species common in more than one treatment. Red maple is capable of rapid resprouting in moderately low light levels and following disturbance events such as fire, windthrow, and timber harvests [81,82]. The scarification treatment had the fewest regenerating red maple stems of the five treatments. Scarification could have removed some red maple rootstocks capable of sprouting.

The significance of the species x treatment interaction indicated that regenerating species composition differed by treatment. A primary cause for the significance of this interaction term was the high stem densities of shrub spp. in all treatments except for the scarification treatments. All of the shrub spp. encountered in this study have rhizomes which are capable of prolific sprouting when the stem is topkilled. Shrubs in the burn treatment most likely had a vigorous sprouting response without a follow-up herbicide release treatment. This most likely resulted in the high shrub spp. stem densities in the burn treatment. The scarification treatment most likely removed or damaged a large proportion of shrub spp. root systems and rhizomes. Scarification by logging equipment down to the B horizon was common in this treatment [45,83].

5. Management Implications and Conclusions

Restoration of shortleaf pine in current mixed hardwood stands, with the intent to create two-age mixed shortleaf pine–hardwood stands, is still possible with current shortleaf pine survival rates (minimum of 53–67 mature stems ha^{-1}), yet the results indicated that overtopping understory hardwood competition may be an issue across all treatments on this site. Shortleaf pine can endure competition during the establishment and stem exclusion phase of stand development from some hardwood species (e.g., oaks and hickories for a limited number of years), but on the best sites where species such as red maple and yellow-poplar occur, shortleaf pine may not be successful at reaching overstory positions [62]. Both of these species were prevalent on this site, possibly necessitating an additional release treatment in order to maintain the current shortleaf pine component. In addition, shortleaf pine growth rates tend to be affected more than survival when understory hardwood competition occurs [60,84]. Shortleaf pine is capable of accelerated growth following release from overtopping understory and midstory hardwood competition [62,70,84]. Herbicide and prescribed fire both may be good shortleaf pine release options. Herbicides, such as metsulfuron methyl and imazapyr, can be applied over shortleaf pine during the late summer and early fall without damaging the pines, and these herbicides offer a wide spectrum of woody vegetation and bramble control when applied as a tank mix [43,84]. Prescribed fire is more challenging to apply as a release treatment, but previous research in the region has indicated that spring burns conducted when seedlings reach three-years-old or 1.5 m tall may greatly reduce stem topkill rates [45], while other studies have suggested that trees should have a groundline diameter of at least 10 cm to completely avoid instances of stem topkill [60]. Unless managers in the region can possibly conduct chemical site preparation treatments when establishing individual clusters, release treatments will have to be relied upon to improve shortleaf pine's chances of reaching overstory positions when attempting to restore shortleaf pine–hardwood mixtures using two-age management and cluster planting.

Early results suggest that two-aged management may be suitable to establish new age classes of shortleaf pine through planting and desirable hardwood species when relying on natural regeneration. Release treatments performed after the first growing season to prevent overtopping by hardwood competitors (especially undesirable species) did not result in any shortleaf pine survival or growth differences three growing seasons after treatments were applied. After three growing seasons, shortleaf pine growth in the brown-and-burn treatment appears to be differentiating from the other treatments. The herbicide treatment had the fewest hardwood stems per hectare, which may allow for more free-to-grow conditions for planted shortleaf pine as the stand develops. This treatment also had the most desirable hardwood species composition. Future assessments of this site are needed to determine if these trends continue.

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