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Impacts of logging and prescribed burning in longleaf pine forests managed under uneven-aged silviculture

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Abstract: The longleaf pine (*Pinus palustris* Mill.) ecosystem has historically been very important in the southeastern United States due to its extensive area and high biodiversity. Successful regeneration of longleaf pine forests requires an adequate number of well-distributed seedlings. Thus, mortality of longleaf pine seedlings during logging operations and prescribed burning appears to be important. Longleaf forests have been commonly managed using even-aged silvicultural methods, but, recently, interest in the use of uneven-aged (UEA) methods has increased in these forests. Research on the impact of UEA logging in longleaf forests is limited. In addition, the influence of overstory density on the impact of prescribed burning under UEA management has not been sufficiently studied in longleaf pine forests. In this study, impacts of UEA logging and prescribed burning (both growing and dormant seasons) on longleaf pine seedlings were observed. In addition, the impact of logging and burning on hardwood seedlings, which are detrimental for longleaf pine seedlings' survival, was also monitored. Damage of logging on longleaf pine seedlings was less than that on hardwood sprouts. A growing-season burning conducted in September 2011 killed most of the hardwood seedlings; however, most of the advance longleaf pine seedlings survived with an average survival rate of 91%. Impact of a dormant-season burning (conducted in January and February 2014) on the survival of 2-year-old longleaf seedlings increased with increasing stand density. This study shows that prescribed burning may be responsible for longleaf pine seedlings' mortality in some cases. It also suggests that damage of UEA logging on longleaf pine seedlings may be negligible.

Key words: Logging, longleaf pine, prescribed burning, survival, uneven-aged

1. Introduction

Longleaf pine (*Pinus palustris* Mill.) is one of the most important tree species in the United States, since longleaf forests exhibit some of the richest species diversity outside the tropics (Jose et al., 2006) containing more than 40 vascular plant species in 1 m^2 (Walker and Peet, 1983), produce high-quality timber (Boyer, 1979), and provide high-quality wildlife habitat for many animal species (Brockway et al., 2005). Longleaf pine forests occupied 38×10^6 ha in the southeastern United States prior to European settlement (Frost, 1993). Frequent fires caused by lightning strikes and fires by Native Americans to manipulate their environment (Carroll et al., 2002) made longleaf pine the dominant tree species in the South. Use of widespread fire by Native Americans favored longleaf pine forests in the region (Croker, 1987). However, with the arrival of European settlers, exploitation of longleaf pine forests began in the early 1700s (Jose et al., 2006). As a result, less than 1.6×10^6 ha dominated by longleaf pine area remained as of 1985 (Boyer, 1990a). At present, longleaf pine is considered an ecosystem at high risk in the United States (Jose et al., 2006). Thus, there has been a growing interest in the restoration and management of remaining longleaf pine forests (Brockway and Outcalt, 2000; Guldin, 2006).

Natural regeneration of longleaf pine is known to be problematic (Croker and Boyer, 1975) due to low survival rate, slow seedling growth (Boyer, 1993a), intolerance to shade and competition with more aggressive species (Ramsey et al., 2003), poor and irregular seed crop at 5- to 7-year intervals (Wahlenberg, 1946), limited seed dispersal because of large and heavy seeds (Wahlenberg, 1946), and brown-spot needle blight (Brockway et al., 2006). Successful regeneration of longleaf pine stands requires the establishment of an adequate number of well-distributed seedlings and survival of those seedlings through to the time when they are released from competition (Croker and Boyer, 1975; Boyer, 1979; Boyer, 1993a).

Although silvicultural treatments such as thinning, partial cutting, and overstory removal are required to release advance longleaf pine reproduction (Croker and Boyer, 1975; Boyer, 1999; McGuire et al., 2001), some

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seedlings may be damaged during logging operations depending on the intensity of harvesting. Single-tree selection and other types of partial cuts are considered to be of higher risk for damage to residual seedlings (Lamson et al., 1985). Impacts of harvesting on seedlings in uneven-aged (UEA) management may be higher because more extensive road networks may be needed to support UEA management (Wolf et al., 2007). Harvesting damage using even-aged (EA) methods in longleaf pine forests has been mentioned (Croker and Boyer, 1975; Maple, 1977), but research on the impacts of UEA logging is limited.

Fire has been an important component of the longleaf pine ecosystem (Barnett, 1999). Germination of longleaf seed requires exposed mineral soil (Boyer and White, 1990), which can be accomplished by fire (Jose et al., 2006). Longleaf seeds become very resistant to fire within a year of germination. Since longleaf seedlings do not have a stem and cambium while in the grass stage, which is a unique and distinctive development phase, they are not directly exposed to surface fire (Brockway et al., 2005). Longleaf seedlings do not grow much in height during the first 5 years of their life, but they develop their root system instead and save their energy in the top root, which facilitates recovery after fire (Chapman, 1932). When seedlings reach a root-collar diameter of 1.3 cm, they have thicker bark to protect them from fire (Boyer, 1974a). In addition, the large needles protect the terminal bud from burning (Brockway et al., 2006). Since longleaf pine is a competition-intolerant species, it cannot compete with other aggressive pine species and hardwoods in the absence of fire, and, eventually, longleaf will be eliminated from the stand. Although prescribed fire is an essential silvicultural tool in longleaf pine forests (Barnett, 1999), fire may be at least partly responsible for mortality of seedlings in some cases (Boyer, 1963). Fire-caused mortality is higher when seedlings are newly germinated and while the terminal bud is in the flaming zone during the burning (Brockway et al., 2006).

In this study, 9 longleaf pine plots were harvested using varying levels of residual basal area (RBA) under UEA management using a single-tree selection method. Although not common, the use of selection methods in longleaf pine forests has been increasing (Brockway et al., 2005). Due to limited research on the impacts of UEA logging in longleaf pine forests, damage of single-tree selection harvesting on advanced longleaf seedlings and hardwood sprouts was observed. Responses of seedlings after the disturbances were monitored. In addition to harvesting damage, the effects of a growing-season prescribed burning on the advance longleaf seedlings and hardwood sprouts were observed. Furthermore, due to limited research regarding the influence of stand density on the impact of burning, the effects of a dormant-season burning on 2-year-old longleaf seedlings under varying levels of RBA were monitored. We hypothesize that the damage by logging is proportional to the amount of timber skidded. We also hypothesize that the impact of prescribed burning on hardwood sprouts is higher in comparison to longleaf pine seedlings and that the impact of burning on longleaf seedlings is associated with overstory density.

2. Materials and methods

2.1. Study site

The study was conducted in the Escambia Experimental Forest, which is located 11 km south of Brewton, Alabama, in the southeastern USA. This 1214-ha forest was established in 1947 to study the ecology and management of longleaf pine forests. About 80% of the forest is dominated by longleaf pine, and the remainder consists of slash pine (*Pinus elliotti* Engelm.) and mixed hardwoods. Average site index for longleaf pine is about 21–23 m (base age: 50). Soils are coarse to fine, loamy, siliceous thermic Paleudults (Adams et al., 2003). The predominant soil type in the forest is Troup fine sand (Boyer, 1987). The climate is mild and humid, bordering on subtropical. Annual precipitation is about 1520 mm and average range of temperature is –7 to 37 °C (Adams et al., 2003). Elevation ranges from about 30 to 87 m above sea level. Topography is flat to rolling, and most slopes are in the range of 3% to 10% (Adams et al., 2003).

2.2. Experimental design

The study was laid out as a completely randomized design. In the winter of 2010, 9 square plots of 2 ha each were established and randomly assigned to 1 of 3 levels of RBA: 9.2, 13.8, and 18.4 m^2 ha^{-1}. Each treatment was replicated 3 times. Assigned treatments were applied to the entire plot (the experimental unit). Treatment response was estimated by subsampling. Each study plot included 6 square overstory measurement subplots of 100 m^2 and 18 circular understory subplots of 10 m^2. Overstory and understory subplots were systematically located within each plot.

Simple linear regression (α-level = 0.05) was used to test the relationships between logging and damage, between RBA and number of germinants, and between RBA and seedling survival. R-Statistical software (R-Project 2008) was used for the analyses.

A wildfire occurred on plot 3 before the first growing season (21 May 2012). All new germinants were consumed; hence, data from this plot were not included in the analysis of subsequent measurement periods.

2.3. Harvesting

Harvest operations were completed during the first week of May 2011. Stands were marked to the defined treatment RBA using single tree-selection based on the proportional-B method (Pro-B). Pro-B is an UEA system loosely based on structural control that allows one-pass marking of a stand. We used a standard 'target structure' defined by a q-value of 1.3 (for 5-cm diameter class) and a largest-diameter tree (LDT, 46 cm). This structure has its basal area (BA) distributed among 3 product classes (0–15 cm, 15–30 cm, >30 cm) at a ratio of approximately 1:2:3 (Loewenstein, 2005). Loewenstein (2009) outlines the following steps to create a marking guide using the Pro-B method (Table 1):

- Conduct current inventory and sum BA by size class;
- Decide on a RBA (target is based on proportions);
- Subtract target BA from current inventory;
- Calculate proportion to cut (1 – target BA / current inventory);
- Record 'simplified' marking guide.

Tree markers line up along a border of the stand, about 20 m apart from each other. Each tree marker walks through the stand only once. A staggered start allows each marker to work off the shoulder of the one ahead and thereby thoroughly cover the entire stand. Each person applies the marking guides for each diameter-class while walking through the stand. The marking is based on the idea of "Take the worst and leave the best" (Baker et al., 1996).

2.4. Prescribed fire

Study plots were burned in the first week of September 2011, following harvest and prior to seed dispersal, in order to reduce competition and expose the mineral soil. Burning during this time of the year is not common due to the potential damage to overstory trees. However, our prescription for the prescribed fire was tightly controlled to minimize these risks while addressing our primary intent to eliminate hardwood sprouts and other woody plants and to prepare the seedbed before seed dispersal of longleaf pine, which occurs in late October. No damage to the overstory trees was evident following the prescribed fire. After the first burning, an excessive number of germinants was observed across all plots during germination period (January 2012). Two years later, a second burning was conducted in the dormant season of 2014 (January and February). The aim of this burning was to reduce competition of longleaf pine seedlings with hardwoods, to monitor the survival of longleaf seedlings, and to observe the influence of stand density on the impact of burning on 2-year-old seedlings. In order to obtain higher survival of longleaf pine seedlings, we conducted dormant-season burning instead of growing-season burning since its impact is usually relatively less than that of growing-season burning.

2.5. Measurements

Each plot was inventoried preharvest, and current longleaf seedlings were tagged to determine the number and size of advance reproductions already on the site. In addition, hardwood sprouts were also recorded in each plot. Damages and survival of advance longleaf seedlings and hardwood sprouts were observed following harvest (May 2011) and following the first prescribed burning (September 2011). All the seedlings and sprouts with broken stems and those completely destroyed were classified as damaged. In addition, new germinants were counted after the germination period (January 2012), and 3 germinants in each regeneration subplot were randomly selected and tagged before the dormant-season burning (January and February 2014). Their mortality was monitored during the dormant-season burning when they reached 2 years of age.

3. Results

Following harvest using the Pro-B method, the target RBAs were closely reached across all plots ($P < 0.05$). The deviations from the target RBAs were within –4.1% to 6.2%, with 2 exceptions (Table 2). The greater deviations in plot 7 and 9 (–12.9% and +17.1%, respectively) were due to the presence of large diameter trees in these plots. Missing one large marked tree or cutting a large unmarked tree during harvesting resulted in substantial deviation from the target in these plots. The lightest harvest occurred on plot 8 (18% of the initial BA) while the highest removal was on plot 3 (48% of initial BA) during harvest operations (Table 2).

3.1. Harvest damage

Prior to the harvest operations, there was no significant relationship between overstory density and number of hardwood sprouts ($P = 0.09$). However, under lower initial BA plots (plots 6, 7, and 9), average heights of sprouts were greater. On plots 1, 2, 3, and 4, higher amounts of BA were removed (more than 10 $m^2 ha^{-1}$). Impact of harvest on the hardwood sprouts within these plots was higher than on the remaining ones. More than 40% of sprouts were

Table 1. An example of a marking guide.

Diameter (DBH)	Inventory	Target	Harvest	Proportion	Guide
<15 cm	11 $m^2 h^{-1}$	10	1	0.09	None
15–30 cm	45 $m^2 h^{-1}$	20	25	0.56	3 of 5
>30 cm	50 $m^2 h^{-1}$	30	20	0.4	2 of 5

Table 2. Summary of the harvesting in each plot.

Plot #	Initial BA ($m^2\ ha^{-1}$)	Target RBA ($m^2 ha^{-1}$)	Amount cut ($m^2 ha^{-1}$)	Final BA ($m^2 ha^{-1}$)	Deviation from the target BA (%)
1	30	18.4	12.4	17.6	−4.1
2	24.9	13.8	10.2	14.7	+6.2
3	29.6	13.8	15.1	14.5	+4.9
4	29.8	18.4	11.6	18.2	−0.9
5	19.2	13.8	5.4	13.8	0.0
6	11.5	9.2	3.5	8.0	−12.9
7	13.7	9.2	3.8	9.3	+1.0
8	21.8	18.4	3.8	18.0	−2.2
9	15.9	9.2	5.1	10.8	+17.1

broken or completely destroyed during harvesting in these plots. Damage on plot 4 was highest. Plot 4 is adjacent to plot 5, and trees cut on plot 5 were skidded through plot 4 and consequently increased the damage. Even though the least removal occurred on plot 6, the damage was high, as the trees from adjacent plot 7 were carried out through plot 6, increasing the harvesting damage on plot 6. Thus, there was a statistically significant relationship between the amount of timber skidded and the level of damage on hardwood sprouts (Figure 1) ($P = 0.006$). It was observed that most of the damage was associated with skid trails, with seedlings on skid trails usually being completely destroyed.

There were no advance longleaf pine seedlings on plots 1 and 3 prior to harvesting. Damage of harvesting on advance longleaf pine seedlings was moderate in comparison to damage on hardwood sprouts. There was no significant relationship between the amount of timber skidded and the level of damage on advance longleaf seedlings (Figure 1) ($P = 0.55$). Damage of harvesting on longleaf pine seedlings ranged from 9% to 17% across all plots. Most of the grass-stage longleaf seedlings (87%) were alive following the logging because they did not have stem during this stage.

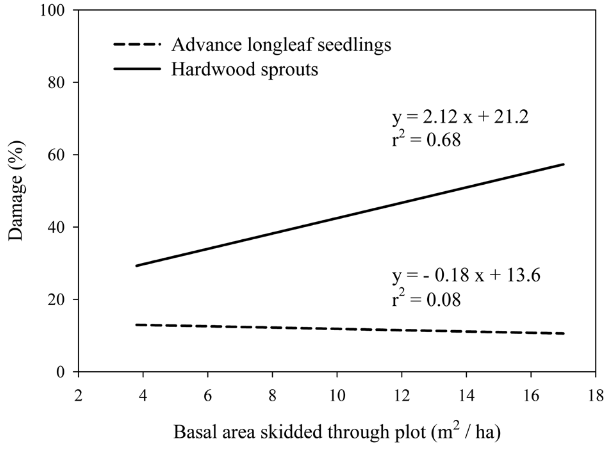

Figure 1. Relationships between basal area skidded through the plot and percent damage.

3.2. Burning damage

Preburning measurements were done about 4 months after harvesting operations (late August 2011). No new longleaf seedling was recorded in any plot. On the other hand, the number of hardwood sprouts considerably increased following harvesting operations in all plots. Hardwood sprouts are detrimental to longleaf seedlings because they are more competitive; thus, they negatively impact survival and growth of longleaf seedlings. The highest increases of sprouting occurred in the plots (plot 1, 2, 3, and 4) in which removals from initial BAs were greater.

Litter layer was significantly reduced on all plots after prescribed fires. In general, mineral soil was exposed across all plots. No scorch was observed following burning. More than 93% of the hardwood seedlings were killed by growing-season prescribed burning across all plots (Table 3). Hardwood seedlings larger than 5 cm in ground-line diameter usually survived. On the other hand, advance longleaf seedlings were not severely affected by the fire (Table 3). The damage to longleaf seedlings ranged from 5% to 15%. The heights of longleaf seedlings that were killed by the fire ranged from 30.1 to 48.7 cm. Most of the grass-stage seedlings survived and resprouted after prescribed burning in all plots.

Following the first burning (September 2011), excessive numbers of germinants were observed across all plots during the germination period (January 2012). We observed that the number of germinants was inversely related to stand density ($P = 0.016$). This relationship was present in the second year of germination as well

Table 3. Mortality of seedlings following the first burning (September 2011).

Plots	Mortality following the growing-season burning (%)	
	Hardwood seedlings	Advance longleaf seedlings
1	100	-
2	100	10
3	100	-
4	100	13
5	100	6
6	93	7
7	96	10
8	100	15
9	97	5

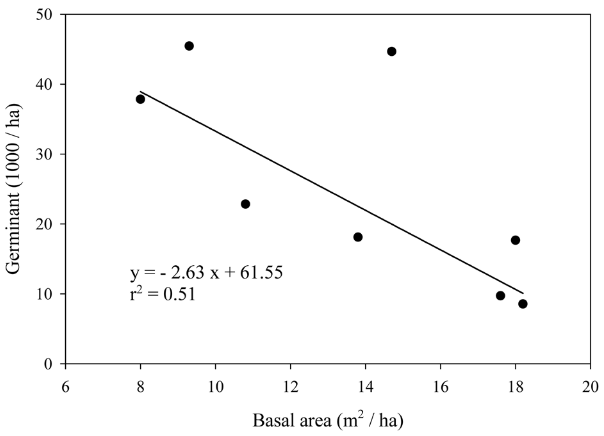

Figure 2. Relationship between basal area and number of longleaf pine germinants.

(July 2013) (P = 0.047) (Figure 2). Higher numbers of germinants were observed from lower RBA plots (Figure 2). Excessive numbers of germinants were obtained in all plots, but, for the purpose of successful regeneration, it is important to know how many of those germinants would survive the prescribed burning and whether there would be an adequate number of established seedlings following burning. One of the assumptions was that stand density significantly influences the impact of burning on the germinants. Thus, survival of those germinants was monitored during the dormant-season burning at seedling age of 2 (January and February 2014).

Most of the hardwood seedlings were killed by the dormant-season burning. However, there was a statistically significant relationship between RBA and survival of 2-year-old longleaf germinants following the dormant-season burning of 2014 (P = 0.0015). Survival rate ranged from 26% to 87% across all plots and increased with decreasing stand density (Figure 3). Root-collar diameter of germinants during the third growing season following the burning was measured, and a significant inverse relationship between RBA and root-collar diameter growth was found (P = 0.0064).

4. Discussion

4.1. Harvest damage on seedlings

Stump sprouting probability was not affected by overstory density prior to harvesting, as has been shown in other studies (Olson and Boyce, 1971; Gardiner and Helmig, 1997; Dey and Jensen, 2002). However, density influenced the size of sprouts. Dey and Jensen (2002) concluded that overstory density (clear-cut vs. single-tree selection methods) had no effect on the amount of sprouting, yet density significantly reduced the height of oak sprouts.

The level of damage on hardwood sprouts was proportional to the amount of timber skidded from the stand because the higher amount of removal required more skid trails and caused more disturbances. However, logging did not significantly impact advance longleaf pine seedlings. Boyer (1990a) stated that logging of the overstory trees can destroy 50% of the seedlings depending on the amount of removal and seedling size. Similarly, Maple (1977) observed the impacts of logging on longleaf seedlings and found that 55% of seedlings were lost to logging activities. They used the shelter-wood method, which probably required more intensive tree removal and resulted in higher mortality than our mortality rates (from 9% to 17%) during logging. In addition, since longleaf pine exists where any overstory disturbances occur (Croker and Boyer, 1975), most of the advance longleaf pine seedlings were usually present under canopy openings of the plots or under low overstory densities before the harvesting operations. As mentioned earlier, with the Pro-B method, tree markers walk through the stands and mark the undesired trees based on the marking guides. We think that few or no trees were marked near or at those canopy openings, or where overstory density was already low. This probably caused less logging traffic near/around advance reproductions where they were present.

Boyer (1964) stated that grass-stage seedlings are more resistant to logging damage than those experiencing height growth. In addition, it was stated that mortality due to logging is least when seedlings are at age 1 or 2 (Boyer, 1974b). In this study, 13% of the grass-stage longleaf seedlings were lost to logging. In a similar study, Boyer (1964) monitored the logging damage to grass-stage longleaf seedlings following clear-cut logging and stated that 11% of grass-stage seedlings were killed by logging when the landings were outside the harvesting area.

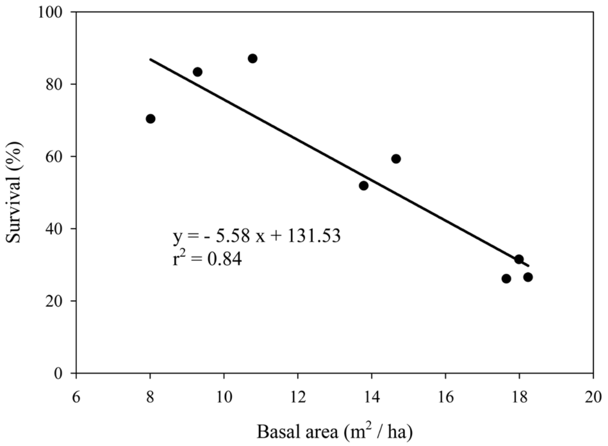

Figure 3. Relationship between basal area and survival of longleaf pine seedlings following a dormant-season burning at age 2.

Although the clear-cut method requires more intensive and heavier vehicle traffic in the harvesting area, Boyer's (1964) study suggests that grass-stage seedlings usually survive even under heavy harvesting conditions. Even though it has been suggested that UEA silviculture may result in higher damage to residual seedlings, it appears that the impact of single-tree selection using Pro-B method in longleaf pine stands is acceptable.

4.2. Burning damage on seedlings

Because preburning measurements were conducted before longleaf pine seed dispersal period, no new longleaf germinants were recorded in any plot prior to the first burning. However, increased light availability apparently encouraged hardwood sprouts to invade the areas. This may be ascribed to the fact that an increase in light intensity encouraged epicormic sprouting in these plots following the removal of trees. Olson and Boyce (1971) suggested that the suppressed buds of seedlings under the soil are protected from logging damage, and they emerge after the top of seedling dies back. In addition, Jack et al. (2006) reported that a significant increase in hardwood sprouts after harvesting seems to be logical.

The growing-season burning killed most hardwood sprouts (93%) across all plots. Similarly, when monitoring the effects of growing-season burning on hardwood seedlings, Boyer (1990b) found that mortality of hardwood seedlings of larger than 2.5 cm in diameter at breast height (DBH) was between 89% and 99%. In addition, Hayward (1939) also stated that prescribed fire can kill all hardwoods smaller than 5 cm in DBH. Moreover, Elliott et al. (2004) observed the effects of understory burning and concluded that all the oak seedlings were killed by burning. On the other hand, higher survival rate of advance longleaf seedlings (85%) during the first burning substantiated the fact that longleaf seedlings become fire-resistant when they reach a ground-line diameter of 0.75 cm (Bruce, 1954). Similarly, Jack et al. (2010) observed the impacts of both growing- and dormant-season burnings on the survival of all seedling size classes and concluded that more than 80% of longleaf seedlings survived. In this study, the first burning killed seedlings that ranged from 30.1 to 48.7 cm in height. Bruce (1951) also determined that the greatest impact of fire was on the seedlings that ranged from 30 to 60 cm in height. Brockway et al. (2006) suggested that longleaf seedlings may be affected by fire while the terminal bud is in the flaming zone. Although flame length was not measured during the burnings in this study, the height range of the seedlings killed by the burning suggests that the terminal bud of those seedlings was probably within the flaming zone during the burning. Most of the grass-stage seedlings survived the first burning. Relevantly, Croker and Boyer (1975) observed the mortality of grass-stage seedlings and concluded that more than 90% of grass-stage seedlings survived. Given the relevant studies in the literature, our findings on the impact of growing-season burning seem to be logical.

The number of germinants was inversely related to overstory density, ranging from 8000 to 45,500 germinants per hectare in the second year following harvesting and prior to the second burning. Similarly, Boyer (1963) reported an average of 31,000 germinants per hectare under varying levels of RBA. Since overstory density of longleaf pine trees affects cone production and consequently the number of germinations (Boyer, 1993b), a higher number of germinants was monitored under lower stand densities. RBA influenced the impact of a dormant-season burning on longleaf pine germinants at age 2. In denser plots a higher amount of pine needles was accumulated, as expected (Boyer, 1963). Although needle accumulation was not measured prior to the second burning, a statistically significant relationship between stand density and needle accumulation prior to first burning ($P = 0.033$) may substantiate the existence of this relationship prior to the second burning as well. As a result, a greater volume of surface fuels resulted in higher fire intensity and higher mortality rates among understory seedlings in denser plots. Similarly, several studies concluded that mortality of longleaf seedlings increases with higher litter accumulation (Boyer, 1963; Croker and Boyer, 1975; Platt et al., 1988; Grace and Platt, 1995; Jack et al., 2010). Grace and Palik (1995) monitored the effects of tree density and fire on the survival of longleaf juveniles; they found that needle density significantly affected the mortality of juvenile survival and that survival ranged from 14% to 32% depending on the overstory densities. Since our germinants were 1 year older than Grace and Palik's (1995) juveniles, we monitored higher survival of germinants (ranging from 26% to 87%), especially under lower overstory densities.

In addition, seedling size positively affected the survival rate of longleaf seedlings (Croker and Boyer, 1975) but was negatively affected by stand density (Grace and Platt, 1995; Brockway et al., 2006). When longleaf seedlings reach a root-collar diameter of 0.7 cm, they usually have thicker bark to protect them from fire (Bruce, 1954). In this study, a significant inverse relationship between RBA and root-collar diameter growth suggested that germinants under lower stand densities had reached larger sizes and root development and had become more resistant to fire.

Although the single-tree selection method is known to be of higher risk of damage to the residual seedlings during logging, this study suggests that the impact of single-tree selection logging may be moderate on longleaf pine seedlings. Tree marking using the Pro-B method probably caused fewer trees to be marked near/around advance longleaf seedlings, and consequently less logging traffic occurred where advance longleaf seedlings were present. This study shows the importance of planning skid trails during logging operations, especially while using single-tree selection. In addition, this study recommends the use of the Pro-B marking method in selection silviculture of longleaf pine forests. Longleaf pine is known to be a fire-dependent species; however, this study suggests that burning may partially affect the survival of longleaf seedlings in some cases. Overstory density, density of needle accumulation, and size and height of the seedlings influence the survival of longleaf seedlings during burning activities. This study demonstrates that overstory density influences not only the germination and growth of longleaf seedlings, but also longleaf pine survival during burning. This study also shows the effectiveness of prescribed burning to control/suppress hardwood sprouts in longleaf pine forests. For further conclusions, more data on the impact of flame height on the longleaf pine seedling's survival may be required. Moreover, our data show that an excessive number of longleaf pine germinants can be obtained even under high stand density. However, as stated earlier, stand density negatively impacts the survival of germinants during prescribed burning in the years that follow. In order to increase the survival of longleaf seedlings under overstory canopy, stand density may be decreased and/or burning following germination may be delayed for a few more years to make the new seedlings more resistant to burning.

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