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Eight years of seasonal burning and herbicidal brush control influence sapling longleaf pine growth, understory vegetation, and the outcome of an ensuing wildfire

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ABSTRACT

To study how fire or herbicide use influences longleaf pine (*Pinus palustris* Mill.) overstory and understory vegetation, five treatments were initiated in a 5–6-year-old longleaf pine stand: check, biennial arborescent plant control by directed herbicide application, and biennial burning in March, May, or July. The herbicide or prescribed fire treatments were applied in 1999, 2001, 2003, and 2005. All prescribed fires were intense and averaged 700 kJ/s/m of fire front across all 12 burns. Using pretreatment variables as covariates, longleaf pine survival and volume per hectare were significantly less on the three prescribed fire treatments than on checks. Least-square means in 2006 for survival were 70, 65, 64, 58, and 56% and volume per hectare was 129, 125, 65, 84, and 80 m^3/ha on the check, herbicide, March-, May-, and July-burn treatments, respectively. A wildfire in March 2007 disproportionately killed pine trees on the study plots. In October 2007, pine volume per hectare was 85, 111, 68, 98, and 93 m^3/ha and survival was 32, 41, 53, 57, and 55% on the check, herbicide, March-, May-, and July-burn treatments, respectively, after dropping trees that died through January 2009 from the database. Understory plant cover was also affected by treatment and the ensuing wildfire. In September 2006, herbaceous plant cover averaged 4% on the two unburned treatments and 42% on the three prescribed fire treatments. Seven months after the wildfire, herbaceous plant cover averaged 42% on the two previously unburned treatments and 50% on the three prescribed fire treatments. Before the wildfire, understory tree cover was significantly greater on checks (15%) than on the other four treatments (1.3%), but understory tree cover was similar across all five treatments 7 months after the wildfire averaging 1.1%. The greater apparent intensity of the wildfire on the previously unburned treatments most likely resulted from a greater accumulation of fuels on the check and herbicide plots that also collectively had a higher caloric content than fuels on the biennially prescribed burned plots. These results showed the destructive force of wildfire to overstory trees in unburned longleaf pine stands while also demonstrating the rejuvenating effects of wildfire within herbaceous plant communities. They caution for careful reintroduction of prescribed fire even if fire was excluded for less than a decade.

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1. Introduction

Longleaf pine (*Pinus palustris* Mill.) forests once constituted a major ecosystem in the southern United States stretching from southeastern Virginia to central Florida and west into East Texas (Landers et al., 1995; Outcalt and Sheffield, 1996). These forests covered a wide range of site conditions from wet pine flatwoods to dry mountain slopes, but intensive exploitation reduced the extent of longleaf forests to only about 1.3 million hectares by 1993.

The loss of longleaf pine forests has caused the increased rarity of nearly 200 associated taxa of vascular plants and several vertebrate species (Brockway and Outcalt, 2000). Protecting the remaining longleaf pine forests and restoring longleaf pine plant communities within their historical ranges are paramount for conserving these species. In the restoration process, however, longleaf pine trees are often absent or too few in number to be an adequate seed source for natural regeneration techniques to work well, and a good option for reestablishing longleaf pine becomes removal of the woody vegetation, site preparation, planting, and the reintroduction or continued use of prescribed fire from seedling establishment through stand maturity (Wahlenberg, 1946; Landers et al., 1995; Haywood and Grelen, 2000).

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Newly established longleaf pine seedlings may develop little above ground for several years as the root system develops (Wahlenberg, 1946; Harlow and Harrar, 1969). The bunch of needles at the surface resembles a clump of grass, hence the term "grass stage" describes the juvenile period of growth. Because above ground growth of longleaf seedlings is initially slow, rapidly growing loblolly pine (*Pinus taeda* L.) regeneration and hardwood brush can crowd and overtop longleaf pine regeneration, which is a problem managers must address, and the favored tool for this purpose is prescribed fire (Landers et al., 1995) partly because burning is less expensive than hand or chemical brush control. For example, on the Kisatchie National Forest, where this study was conducted, prescribed burning, herbicide application, and hand-felling cost \$52, \$236, and \$410 U.S. dollars per hectare in 2008, respectively, before administrative costs were added. However, prescribed fires are not always executed on schedule because of adverse weather conditions and lack of resources. If fire is not used or is delayed too long, competing woody vegetation has to be controlled by cutting or application of herbicide on many sites (Brockway and Outcalt, 2000; Haywood, 2000).

Despite their value in controlling brush, neither fire nor herbicides are panaceas for managing longleaf pine stands. Fire can destroy seedlings and sapling trees, and later the use of fire can adversely affect stand growth and yield (Wahlenberg, 1946; Bruce, 1951; Boyer, 1987; Boyer and Miller, 1994). The season in which prescribed fires are repeatedly applied can affect stand stocking and productivity differently (Grelen, 1975, 1978, 1983; Haywood and Grelen, 2000; Haywood et al., 2001). Herbicides that are not handled or applied properly can injure desirable plants, contaminate soil and water resources, and can be injurious to humans, domestic and wild animals. *Use all pesticides selectively and carefully; follow recommended practices for the disposal of surplus pesticides and pesticide containers.*

Still, the risks from using fire or herbicides are acceptable to obtain desired forest cover in longleaf pine stands managed for multiple uses. One desired future condition can be described as a longleaf pine dominated overstory with a midstory largely free of hardwoods and a rich and productive herbaceous and low woody plant community in the understory. Conversely, without vegetation management, a mixed overstory will eventually develop of loblolly, longleaf, and hardwoods trees, with a midstory of trees and shrubs that shades out most of the understory herbaceous vegetation (Haywood and Grelen, 2000; Haywood et al., 2001).

To study the use of seasonal prescribed burning and herbicide to manage for the desired future condition previously described, this research was started in a sapling stand of planted longleaf pine and addresses several objectives based on past work (Grelen, 1975, 1978, 1983; Haywood and Grelen, 2000; Haywood et al., 2001): (1) determine how suspension of vegetation management affects overstory longleaf pine trees and understory plant development, (2) determine the different effects prescribed fire or herbicide have on overstory and understory plant development, (3) determine if biennial prescribed burning in May influences plant communities differently than burning in March or July, and (4) determine if biennial March and July burning have different effects.

2. Methods

2.1. Study area

The study is located on the Kisatchie National Forest in central Louisiana (92°37′W, 31°1′N) at 53 m above sea level on a gently sloping (1–3%) Beauregard silt loam (fine-silty, siliceous, superactive, thermic Plinthaquic Paleudults) and Malbis fine sandy loam (fine-loamy, siliceous, subactive, thermic Plinthic Paleudults) complex (Kerr et al., 1980). The water table is high and fluctuates throughout the year because a finely textured horizon restricts drainage. The natural pine and mixed hardwood forest cover was clearcut harvested in the mid 1980s, and the site was sheared and windrowed in 1991. A low cover of herbaceous and scattered woody vegetation developed after windrowing, and it was rotary mowed in July and August 1992.

2.2. Study establishment

Initially, 15 research plots were established in a randomized complete block split-plot design and re-mowed in December 1992 (Haywood, 2000). Blocking was based on proximity to windrows and drainage. Each of the 15 plots (5 blocks by 3 main plot treatments) measured 25.6 by 25.6 m (0.066 ha) and contained 14 rows of 14 longleaf pine seedlings arranged in 1.83 by 1.83 m spacing. The center 100 seedlings (10 rows of 10 trees each) were divided into two subplots, and year-of-planting was randomly assigned to the 50-seedling subplots. One subplot was planted in February 1993 and the other subplot was planted in January 1994 using the same Mississippi seed source in both years. The container seedlings were grown using the best current practices (Barnett and McGilvray, 1997) over a period of 42 weeks for the 1993 and 28 weeks for the 1994 plantings. The seedlings were planted with a punch of the correct size for the root plug, the soils were wet, and no planting problems occurred in either year.

In the initial work, three treatments were randomly assigned to three plots per block (Haywood, 2000): (1) no vegetation management control after planting, (2) two annual applications of hexazinone herbicide (3-cyclohexyl-6-[dimethylamino]-1-methyl-1,3,5-triazine-2,4[1H,3H]-dione), and (3) mulching. Despite treatment, hardwood and loblolly pine brush crowded and overtopped many of the planted longleaf pine seedlings on all plots. The brush was manually severed in 1997 and the regrowing plants were individually sprayed with triclopyr (3,5,6-trichloro-2-pyridinyloxyacetic acid) herbicide in a 1% herbicide product (Remedy™, Dow AgroSciences Canada Inc., Calgary, Alberta), 1% surfactant, and 98% water solution in April 1998. The most commonly treated plant was wax myrtle (*Morella cerifera* (L.) Small.).

After completing the initial vegetation management research and reporting the findings (Haywood, 2000), a new phase of research was initiated to address seasonal prescribed burning and herbicide application (Haywood, 2002). This shift was possible because in the original design, the block, seedling age (subplot), and treatment-by-age interaction effects were not significant at the $\alpha = 0.05$ level. In the design reconfiguration, the three original treatments – check, herbicide application, and mulching – became the blocks. Blocking was justified because of significant differences in longleaf pine total height among the original treatments (Haywood, 2000).

In the new design, five treatments were randomly assigned within the three blocks: Check, there was no more vegetation control after 1998; herbicide—arborescent vegetation over 60 cm tall was biennially treated in May with a directed application of triclopyr herbicide as a 1% Remedy™, 1% surfactant, and 98% water solution (blackberry (*Rubus* spp.) and woody vines were not intentionally treated); and for the third, fourth, and fifth treatments, plots were biennially prescribe burned in March, May, or July. The herbicide and three prescribed fire treatments were applied in 1999, 2001, 2003, and 2005.

2.3. Prescribed fire

Before setting fires, fuel samples were collected on five randomly located 0.22 m^2 subplots per measurement plot to be burned (the measurement plot being the central 100 planting locations per plot). The fuels were in three classes considered combustible based on Deeming's et al. (1977) fire-danger-rating system: (1) living foliage of trees, shrubs, vines, grasses, and forbs within 1 m of the ground, (2) living blackberry canes, woody stems, and vines no more than 6 mm in diameter within 1 m of the ground, and (3) 1 h time-lag dead fuels (surface litter and duff to a 0–6 mm depth and small roundwood and stubble no more than 6 mm in diameter). Fuel samples were again collected one week after the burns to determine fuel consumption on a dry-weight basis.

All burns were striphead fires set with drip torches and were monitored to determine their intensity as in Haywood (1995). First, a backfire was set along the downwind side of the plot. After the fired line was secure, strips about 8 m apart were set and allowed to burn together. Byram's fire intensity was calculated for each burn (Haywood, 1995) and results reported in Table 1.

2.4. Vegetation sampling and chemical analysis

Before initiating treatments, longleaf pine total height was measured on each measurement plot with a calibrated rod to the nearest 3 cm in February 1999 to use as a covariate in future analyses (Haywood, 2002). Diameter at breast height (dbh) was not taken because not all trees were tall enough for this measurement. After treatments were initiated, total height and dbh of trees over 1.4 m tall were annually measured in the fall of 1999 through 2006. Once the tallest trees exceeded 8 m in total height, all tree heights were measured with a laser instrument. Tree dbh was measured with a diameter tape. Outside-bark stemwood volume was determined with Baldwin and Saucier's (1983) formulas.

In September 2001, the understory vegetation was surveyed on five systematically located 0.22 m^2 subplots per measurement plot. A subplot was located in the middle of the measurement plot and in the center of each quarter section of the measurement plot. In each subplot, percent cover by species was estimated.

In January 2003, 10 soil samples were randomly collected from the upper 15 cm of mineral soil on each measurement plot. After air-drying, samples were ground in a soil mill and sieved through a 2 mm screen before determining the percent N with a CNS gas analyzer and Mehlich-3 extractable P in ppm of soil with a colorimetric spectrophotometer.

In January 2003, longleaf pine needle samples were collected from current-year flushes in the upper third of the tree crown from five dominant trees per measurement plot. More than 100 fascicles per measurement plot were collected. The needles were ground in a Wiley mill, sieved through a 2 mm screen, and oven-dried at 70 °C for 48 h in a forced-air oven before determining percent N, or digested in acid before determining percent Ca, K, Mg, and P. The same analytical equipment used for the soil samples was used in the N and P foliar analyses, and an atomic absorption spectrophotometer was used for the Ca, K, and Mg analyses.

In September 2006, percent cover of understory vegetation was estimated for five taxa of plants – grasses, forbs (which included grasslike-plants and ferns), trees, shrubs (which included blackberry), and woody vines – with the following technique. The central 100 planting locations on each measurement plot formed 81 adjacent squares. Within each square, the percentage of each taxon was estimated, and the 81 values for each taxon were averaged to get a 100% estimate of cover for each measurement plot by taxa. Additionally, it was noted if woody vines were climbing on the bole of the planted longleaf pine trees above a height of 50 cm.

2.5. Wildfire

On March 21, 2007, an arsonist set a wildfire that burned across the study site. Often wildfires of this type are spotty, intensely burning over parts of a site but far less intensely elsewhere or missing areas all together. However, this wildfire burned intensely over the entire study site. Based on a post-fire survey of the plots, nearly all of the living foliage of trees, shrubs, vines, grasses, and

Table 1
Fuel loads and fire intensities for prescribed fires conducted on a longleaf pine site from 1999 through 2005 and the analyses of variance by year and across all years.

Years and treatments	Burning date	Oven-dried fuel load (kg/ha)	Rate of spread (m/s)	Range in fire intensity (kJ/s/m)	Average fire intensity (kJ/s/m)[a]	Average fire intensity analysis of variance		
						Sources	df[b]	$p > F$-value
1999								
March burn	March 2	3702	0.06	319–429	385a[c]	Block	2	0.7495
May burn	May 14	6003	0.03	290–378	341a	Burn date	2	0.1209
July burn	July 8	4377	0.08	400–688	590a	EMS	4	14062.1167
2001								
March burn	March 13	5287	0.06	522–561	544b	Block	2	0.8170
May burn	April 30	6171	0.06	548–827	734ab	Burn date	2	0.0388
July burn	July 31	6323	0.08	871–1026	943a	EMS	4	14576.3904
2003								
March burn	March 11	6240	0.08	905–1035	962a	Block	2	0.2803
May burn	May 6	6543	0.05	504–662	579b	Burn date	2	0.0021
July burn	July 22	4863	0.05	334–534	417b	EMS	4	5687.0015
2005								
March burn	March 11	7030	0.08	818–1304	1067a	Block	2	0.7991
May burn	May 13	8692	0.06	809–992	899a	Burn date	2	0.6448
July burn	July 26	7097	0.07	768–1145	943a	EMS[b]	4	46216.6840
						Repeated measures analysis of variance		
						Year (Yr)	3	<0.0001
						Yr × block	6	0.9858
						Yr × burn[b]	6	0.0042
						Error (Yr)		21863.4620

[a] A low intensity winter backfire would be between 0 and 173 kJ/s/m.
[b] df, degrees of freedom, EMS, error means square, and Yr × burn–Year-by-burn-date interaction.
[c] Within-year average fire intensities followed by the same letter were not significantly different based on Duncan's Multiple Range Tests at $p \geq 0.05$.

forbs and living blackberry canes and woody stems no more than 6 mm in diameter were incinerated and longleaf pine crown scorch averaged over 50% on all plots. Nearly all of the 1- and 10-h time-lag dead fuels, as described by Deeming et al. (1977), were consumed. Among plots, understory conditions could no longer be distinguished except for a dead remnant of brush on the check plots and dead vines on the pine trees.

The uniformity of the fire meant that post wildfire comparisons among treatments were possible. In October 2007, total height and dbh of the surviving longleaf pines were remeasured and understory vegetation was resurveyed. Several of the surviving trees appeared to be fading and additional mortality was likely. Therefore in January 2009, longleaf pine survival was again surveyed, but the trees were not remeasured as the area was not deemed safe enough for extended measurements. None of the pine trees surviving in January 2009 appeared to be stressed from the wildfire.

2.6. Data analysis

Analyses of covariance for a randomized complete block design model with three blocks as replicates at the $\alpha = 0.05$ level (Steel and Torrie, 1980) were used to compare longleaf pine total height, basal area and volume per tree and number of trees, basal area and volume per hectare. In the analyses of covariance, dependent variables were pretreatment mean total height and number of longleaf pine trees per hectare in February 1999. Four linear contrasts were used to determine treatment differences that address several objectives associated with prescribed burning based on past research (Grelen, 1975, 1978, 1983; Haywood and Grelen, 2000; Haywood et al., 2001): (1) Suspension of woody plant control will affect overstory longleaf pine trees and understory plant development–check versus management (treatment 1 versus treatments 2, 3, 4, and 5); (2) Vegetation control with either prescribed fire or herbicides will have different effects on the overstory and understory—herbicide versus prescribe fire (treatment 2 versus treatments 3, 4, and 5); (3) Burning in May will have different effects than burning in March or July (treatment 4 versus treatments 3 and 5); and (4) March and July burning will have different effects (treatment 3 versus treatment 5).

Prescribed fire intensities (kJ/s/m) among treatments 3, 4, and 5 were compared yearly with a randomized complete block design model with the three blocks as replicates at the $\alpha = 0.05$ level (Steel and Torrie, 1980). If dates of burning were significantly different, Duncan's Multiple Range Tests were used for determining means separation. In addition, a repeated measures analysis of variance model was used to compare fire intensities across all four series of burns.

Percentage of N and parts per million of P in the upper 15 cm of mineral soil, percentages of N, P, K, Ca, and Mg in the live longleaf pine foliage, percentages of understory plant cover, and percentage of longleaf pines with vines growing on the bole were compared with a randomized complete block design model with three blocks as replicates at the $\alpha = 0.05$ level (Steel and Torrie, 1980). The four linear contrasts used in the longleaf pine analyses were also used to determine treatment differences in these analyses. Percentages were arcsine transformed before analysis (Steel and Torrie, 1980).

After the wildfire in March 2007, longleaf pine total height, basal area and volume per tree and number of trees, basal area and volume per hectare that were remeasured in October 2007 were compared by analyses of covariance for a randomized complete block design model at the $\alpha = 0.05$ level (Steel and Torrie, 1980) after dropping trees that died through January 2009 from the database. The dependent variables were the same as those used in the 2006 analyses. In addition, percentage change in pine survival, percentage of longleaf pines with vines growing on the bole, and percentages of understory plant cover by taxa were compared with a randomized complete block design model (Steel and Torrie, 1980). In all analyses, treatment means were compared using the aforementioned linear contrasts and percentages were arcsine transformed before analysis.

3. Results and discussion

3.1. Prescribed fire

The first series of prescribed burns was conducted in grass-dominated rough that was over 6 years old and similar in species composition as reported by Pearson et al. (1987). Grasses were dominant because woody competitors were controlled on all plots before the study began (Haywood, 2002). Fire intensities in 1999 ranged from 290 to 688 kJ/s/m of fire front (Table 1), and were greater than Deeming's et al. (1977) recommended maximum intensity of 173 kJ/s/m.

In 2001 and 2003, fire intensities increased relative to the first set of prescribed fires as expressed in the significant year effect in the repeated measures analysis. Additionally, high fuel load and rate of spread in July 2001 resulted in significantly more intense fires than in March 2001 (Table 1). Similarly, high fuel load and rate of spread in March 2003 resulted in significantly more intense fires than in May or July 2003. Therefore, fuel load and spread rates are more important in determining fire intensity than the month chosen for burning in a particular year.

Average fire intensity in 2005 (970 kJ/s/m) was greater than intensities in 1999 (439 kJ/s/m), 2001 (740 kJ/s/m), and 2003 (653 kJ/s/m). However, fire intensities were not significantly different among burn treatments in 2005 (Table 1). The significant difference in fire intensities among years and the lack of a pattern of fire intensities among burning dates within years resulted in a significant year-by-burn-date interaction in the repeated measures analysis.

Although there was no significant relationship for season of burning across years in this study, May prescribed fires (638 kJ/s/m) averaged a lower fire intensity across the four series of burns than March (740 kJ/s/m) or July (723 kJ/s/m) prescribed fires, and fire intensities in May are never the highest for the year and May fires were the least intense in 2 out of 4 years partly because rates of spread were never highest in May (Table 1). In addition, Grelen (1983) argued that new grass growth in May contributed to lower fire intensities than burning mostly dead grasses in March.

Fire intensities averaged 700 kJ/s/m of fire front across the 12 burns, and this average intensity was 37–90% greater than fire intensities achieved in grass-dominated roughs in two other Louisiana studies (Haywood, 2005, 2007) and 35% greater than fire intensities reported for a similar kind of study in Alabama (Boyer, 1987). The high fire intensities in this study were partly due to large available fuel loads that averaged 4694, 5927, 5882, and 7606 kg/ha on a dry-weight basis in 1999, 2001, 2003, and 2005, respectively (Table 1). These fuel loads were comparable to or 37% greater than fuel loads reported in two other studies with similar cover conditions (Haywood, 2005, 2007).

Fuel bed condition was also a likely factor. In Louisiana, the dominant grass on upland sites similar to this one is usually little bluestem (*Schizachyrium scoparium* (Michx.) Nash) with less slender little bluestem (*S. tenerum* Nees); for example, Pearson et al. (1987) reported that in a grass-dominated rough in Louisiana 42% of the grass cover was little bluestem and 10% of the grass cover was slender little bluestem. On this study site, 48% of the grass cover was little bluestem and 14% of the grass cover was slender little bluestem in 2001. This mixture of little and slender little bluestem resulted in loosely packed fuel beds of dry dead foliage and stems with green vegetation growing through them that were 60 cm deep in places. These fuel beds burned quickly as the striphead fires moved over the plots generating high fire intensities, and crown scorch averaged from 50 to 90% on all burns as well.

3.2. Longleaf pine

Total height was similar among treatments at the beginning of the study (Haywood, 2002). However, height differences developed over the next 8 years (Fig. 1). After the 2006 growing season, longleaf pine total height was significantly greater on the herbicide treatment (9.0 m) than on the three prescribed fire treatments (average of 8.3 m) and was shortest on the March-burn treatment (7.7 m) (Table 2). Total height was comparable on the check and herbicide treatments. Basal area per tree followed a similar growth pattern as total height but with a greater magnitude of differences among treatments (Fig. 1). After the 2006 growing season, the two unburned treatments (average of 1.18 dm^2) had significantly more basal area per tree than the three prescribe fire treatments (average of 0.86 dm^2) and basal area was least on the March-burn treatment (0.72 dm^2) (Table 2). The effect of fire on the growth of the March-burn trees was obvious in Fig. 1 where there is a dip in the March-burn basal area curve at the 2001, 2003, and 2005 data points. Volumes per tree results were similar to the basal area per tree results (Table 2). The unburned treatments had significantly more stemwood per tree (average of 63 dm^3) than the three prescribed fire treatments (average of 43 dm^3), and trees were smallest on the March-burn treatment (34 dm^3). In a study similar to this one in Alabama, Boyer (1987) found that longleaf pine trees on checks had greater annual volume growth than trees on plots that were biennially prescribed burned in winter, spring, and summer over a 10-year period.

Grelen (1978, 1983) argued that the date of the fire in relation to the development of longleaf pine buds influenced growth differences when prescribed burning in either March or May. In early March, the new shoot or "candle" is elongating and is bare except for a coat of white hairs and is vulnerable to heat injury. By early May, needles are developing on the candle, forming an insulating barrier that may prevent heat damage to the new shoot,

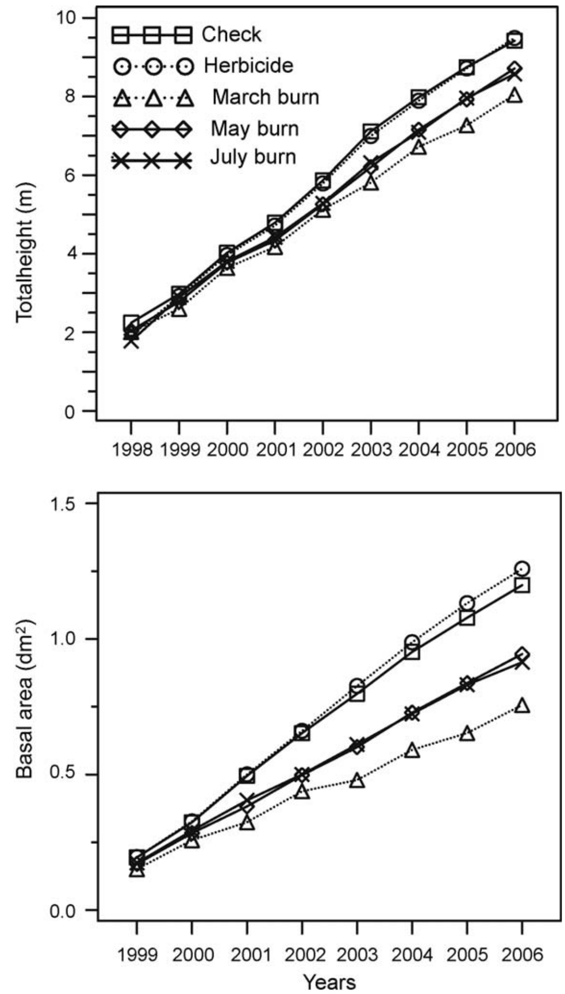

Fig. 1. Longleaf pine least-square mean total height and basal area per tree on five treatments: check, arborescent plant control by directed herbicide application, and prescribed burning in March, May, or July; herbicide and prescribed fire treatments were applied in 1999, 2001, 2003, and 2005.

Table 2
Least-square means for longleaf pine total height, basal area, and outside-bark volume per tree and number of trees, basal area, and volume per hectare in 2006 following understory vegetation control with either herbicides or prescribed fire in 1999, 2001, 2003, and 2005 and the analyses of covariance with total height and stocking in February 1999 as covariates.

Treatments and sources		Total height (m)	Basal area (dm^2)	Volume (dm^3)	Number of trees (trees/ha)	Basal area (m^2/ha)	Volume (m^3/ha)
Check		9.1	1.16	62.3	2078	24.1	129
Herbicide[a]		9.0	1.20	64.1	1948	23.4	125
March burn		7.7	0.72	33.9	1924	13.8	65
May burn		8.7	0.94	48.2	1746	16.4	84
July burn		8.6	0.92	47.8	1682	15.5	80
Analysis of covariance	df[a]	Probability > *F*-value					
Block	2	0.4901	0.2807	0.2852	0.7635	0.8766	0.8293
Treatment	4	0.0195	0.0001	<0.0001	0.0550	0.0026	0.0025
Contrasts							
Check vs[a] managed trts[a]	(1)	0.0628	0.0015	0.0011	0.0399	0.0013	0.0012
Herbicide vs prescribed fire	(1)	0.0273	<0.0001	<0.0001	0.1822	0.0007	0.0006
May vs March + July burn	(1)	0.1124	0.0260	0.0231	0.5918	0.1793	0.1503
March vs July burn	(1)	0.0392	0.0071	0.0029	0.1217	0.2070	0.1008
Covariates							
Feb[a] 1999—total height	1	0.0014	0.0029	0.0007		0.0200	0.0070
Feb 1999—trees/ha	1				0.0374	0.3905	0.4799
Error mean square	6/7 [a]	0.14342	0.00349	12.75335	18,968.6906	2.86331	99.44701

[a] Herbicide—arborescent plant control with directed applications of herbicide, df—degrees of freedom, vs—versus, and trts—treatments, Feb—February, and 6/7—df for error mean square was 6 when two covariates were used and 7 when one covariate was used in the analysis.

and the shoot is larger and having a higher heat capacity can absorb more energy without injury (Byram, 1958). The actual differences in average fire intensities in this study also supported the argument that May was a better time to burn than March (Table 1). In another study, Grelen (1975) found that seven prescribed burns in either March or July reduced sapling longleaf pine height growth compared to May burning through the first 12 growing seasons from seed. However by age 37 years, Haywood et al. (2001) found that mean dbh and volume per tree were similar on the May and July burns but were significantly less on the March burns after a series of 20 prescribed fires on Grelen's (1975) original study site. Grelen's (1975) and Haywood's et al. (2001) findings supported the individual tree development results in this study; that is, March burning was more injurious to longleaf pine trees than May or July burning.

After the 1999 prescribed burns, longleaf pine survival decreased from an average of 82% in February 1999 to an average of 67% in November 2000 on the three prescribed fire treatments, and the dead trees averaged less than 60 cm in height (Haywood, 2002). Longleaf pine seedlings are most vulnerable to fire related mortality until the seedlings are at least 1–2 m tall (Bruce, 1951). Tree mortality was low on the check and herbicide plots, survival averaged 86% in February 1999 and 81% in November 2000, and the dead trees averaged less than 30 cm in height (Haywood, 2002). Survival continued to decline on all treatments through 2006. However, mortality was proportionally less following the last three series of prescribed burns, and in fall 2006, survival averaged 60% or 1784 trees/ha on the three prescribed fire treatments (Table 2). Survival was still significantly greater on the checks (70%) than on the four managed treatments (average of 61%), but all study plots were considered fully stocked after the 2006 growing season. Basal area and volume per hectare were significantly greater on the two unburned treatments (average of 24 m^2/ha and 127 m^3/ha) than on the three prescribed fire treatments (average of 15 m^2/ha and 76 m^3/ha) with no statistically significant differences among prescribed fire treatments in basal area and volume per hectare in 2006.

Grelen (1975) found that mortality of longleaf pine seedlings was higher following July burning than after March or May burning. In this study, longleaf pine survival was not different among prescribed fire treatments, but prescribed fire was first applied when the trees were 5 or 6 years old. In the continuation of Grelen's (1975) work, longleaf pine stands burned in May were significantly more productive than longleaf pine stands burned in July after 20 prescribed fires (Haywood et al., 2001), but this was because of the initial differences in longleaf pine survival reported by Grelen (1975).

3.3. Nutrition

After two series of prescribed fires, *N* percentage and concentration of *P* in the upper 15 cm of mineral soil were not significantly affected by treatment and averaged 0.05% N and 0.9 ppm P (Table 3). Soil N percentages were comparable to those reported by Boyer and Miller (1994) for a longleaf pine site in southeastern Alabama. The concentration of P in this study was 42% greater than Boyer and Miller (1994) reported. However, P concentration in this study was 42% less than found by Haywood (2007) on another longleaf pine site in central Louisiana.

Foliar percentages of N, P, Ca, and Mg were not significantly affected after two series of treatments and averaged 0.97, 0.06, 0.16, and 0.09%, respectively (Table 3). Percentages of N, Ca, and Mg were at or above sufficiency levels suggested by Blevins et al. (1996) of 0.95% N, 0.10% Ca, and 0.06% Mg. Phosphorus was deficient compared to Blevins' et al. (1996) sufficiency level of 0.08%, but P is normally found to be deficient on central Louisiana sites (Kuehler et al., 2004; Haywood, 2005, 2007). Percentage of foliar K was significantly less on the July-burned plots than March-burned plots (Table 3) but was still above sufficiency levels on all treatments compared to Blevins' et al. (1996) sufficiency level of 0.3%. Kuehler et al. (2004) found that biennial prescribed burning for 40 years resulted in less foliar concentration of Mg if burning was conducted in July than if burns were conducted in March or May, but Kuehler et al. (2004) did not report a significant difference in foliar K levels among prescribed fire treatments.

3.4. Understory vegetation

Cover of understory vegetation was significantly affected by treatments (Table 4). An average of 67% of the longleaf pine trees on the two unburned treatments had vines growing on the bole above a height of 50 cm compared to 5% of the trees on the three prescribed fire treatments, and there were no significant differences among the three burning treatments in September 2006. Grass cover averaged 3% on the two unburned treatments and 37% on the three prescribed fire treatments and forb cover averaged 1%

Table 3
Percentage of N and ppm of P in the upper 15 cm of mineral soil and percentage of N, P, K, Ca, and Mg in live longleaf pine foliage after two treatment cycles had been completed in 1999 and 2001; the soil and foliage were sampled in January 2003.

Treatments and sources		Soil		Foliage				
		N (%)	P (ppm)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Check		0.047	0.82	1.00	0.063	0.428	0.167	0.091
Herbicide[a]		0.052	0.86	1.04	0.060	0.453	0.148	0.087
March burn		0.046	0.95	0.97	0.065	0.487	0.165	0.100
May burn		0.048	0.80	0.94	0.063	0.444	0.162	0.093
July burn		0.047	0.93	0.91	0.060	0.403	0.153	0.097
Analysis of variance[a]	df[a]	Probability > *F*-value						
Block	2	0.4125	0.3105	0.3811	0.7613	0.4565	0.9695	0.1766
Treatment	4	0.9271	0.8991	0.5864	0.4808	0.2141	0.9256	0.5050
Contrasts								
Check vs[a] managed trts[a]	(1)	0.7517	0.6654	0.6236	0.6173	0.4936	0.6248	0.6374
Herbicide vs prescribed fire	(1)	0.4233	0.8038	0.1595	0.3052	0.7754	0.5771	0.1431
May vs March + July burn	(1)	0.9439	0.4143	0.9694	0.9958	0.9943	0.9225	0.4763
March vs July burn	(1)	0.9429	0.9306	0.5862	0.1636	0.0315	0.6418	0.6812
Error mean square	8	0.01580	0.05162	0.09184	0.00227	0.02895	0.04825	0.00763

[a] Herbicide—arborescent plant control with directed applications of herbicide, percentages were arcsine transformed before analysis, df—degrees of freedom, vs—versus, and trts—treatments.

Table 4
Percentage of longleaf pine trees with vines climbing on the bole above 50 cm from the ground and percentages of understory ground cover in September 2006.

Treatments by years		Percentage of pine trees with vines climbing on the bole	Percent cover of understory plants by taxa					
			Grasses	Forbs	Trees	Shrubs	Vines	Total
Check		61	1.6	0.8	14.5	38.9	12.6	68.4
Herbicide[a]		73	4.5	1.2	0.5	4.3	10.6	21.1
March burn		4	35.4	3.2	2.6	14.9	1.9	57.9
May burn		5	32.0	2.9	1.9	7.7	1.3	45.8
July burn		6	44.4	8.6	0.2	7.4	1.5	62.1
Analysis of variance [a]	df[a]	Probability > *F*-value						
Block	2	0.7049	0.0053	0.2768	0.9751	0.5886	0.9818	0.1176
Treatment	4	0.0004	<0.0001	0.0015	0.0052	0.0019	0.0561	0.0011
Contrasts								
Check vs[a] managed trts[a]	(1)	0.0020	<0.0001	0.0051	0.0005	0.0002	0.0268	0.0054
Herbicide vs prescribed fire	(1)	<0.0001	<0.0001	0.0032	0.3882	0.1246	0.0276	0.0003
May vs March + July burn	(1)	0.7426	0.0292	0.0409	0.6858	0.3691	0.9396	0.0621
March vs July burn	(1)	0.9528	0.0284	0.0062	0.1353	0.1646	0.8201	0.5793
Error mean square	8	0.02786	0.00187	0.00151	0.00623	0.00870	0.01141	0.00896

[a] Herbicide—arborescent plant control with directed applications of herbicide without intentionally treating herbaceous plants and vines, percentages were arcsine transformed before analysis, df—degrees of freedom, vs—versus, and trts—treatments.

on the two unburned treatments and 5% on the three prescribed fire treatments. Month of burning significantly affected herbaceous plant cover, July-burn plots had significantly greater grass and forb cover than March-burn plots and May-burn plots. Forb cover likely decreased for several months following the prescribed burns (Brockway and Outcalt, 2000; Hiers and Mitchell, 2007) only to increase over a year later to the levels shown in Table 4 fourteen to eighteen months after the last prescribed burn or herbicide application. In other work (Grelen, 1975; Haywood et al., 2001), biennial prescribed burning for 37 years did not significantly affect herbaceous plant productivity whether plots were burned in March, May, or July. Therefore, greater cover on the July-burn plots was unexpected because changes in understory herbage productivity are inversely related to basal area (Grelen and Lohrey, 1978; Wolters, 1982) but basal area per hectare among the three prescribed fire treatments were not significantly different (Table 2). However, Waldrop et al. (1992) found that periodic summer burning increased the number of forbs per hectare compared to winter burning. Also, the greater forb cover on the July-burn plots in this study was comparable to cover percentages reported by Brockway and Outcalt (2000) two and three growing seasons after a prescribed burn.

Tree and shrub cover were significantly greater on checks than on the four management treatments with no significant differences in tree and shrub cover among the herbicide and three prescribed fire treatments (Table 4). However, there was more than 100% greater tree and shrub cover on the March-burn plots than on the May- and July-burn plots perhaps because growing season burning is more stressful on hardwoods than dormant season burning. For example, Haywood et al. (2001) found that biennial burning in March for 37 years resulted in greater tree and shrub stocking compared to biennial burning in May or July. Boyer (1993) also found that biennial winter burning over a 20-year period resulted in greater midstory density and understory hardwood stocking than biennial spring or summer burning. Waldrop et al. (1992) found that periodic or annual burning in winter resulted in greater numbers of shrubs per hectare than burning in summer. Thus, the trend in greater tree and shrub cover on the March-burn plots in this study might have become more evident had burning continued.

Woody vine cover was significantly greater on the two unburned treatments (average of 12%) than on the three prescribed fire treatments (average of 2%) (Table 4). There were no significant differences among the three prescribed fire treatments and fire normally suppresses native woody vine development in central Louisiana. Woody vines were not intentionally treated on the herbicide plots, and so, vine cover was similar on the check and herbicide plots.

Total understory plant cover was significantly greater on the checks than the average for the four managed treatments principally because the tree, shrub, and vine cover on the checks (66%) was greater than this kind of cover on the four managed treatments (average of 14%) (Table 4). The herbicide plots had significantly less total plant cover than the three prescribed fire treatments principally because herbaceous vegetation was smothered by falling needles and other litter on the herbicide plots, which reduced herbaceous cover to 6%, while prescribed burning continually released the herbaceous vegetation on the prescribed fire treatments resulting in an average herbaceous plant cover of 42% on the burned plots. As a result, the herbicide treatment had the least total understory cover among the five treatments because herbicides were applied to control arborescent vegetation and the herbaceous vegetation was smothered by falling litter.

3.5. Wildfire

3.5.1. Longleaf pine

The wildfire in March 2007 radically changed stand condition. Longleaf pine survival decreased by 37, 24, 11, 2, and 1 percentage points on the check, herbicide, March-, May-, and July-burn treatments, respectively, from October 2006 to January 2009 (Tables 2 and 5). The decline in survival was significantly greater on the checks than on the four managed treatments ($p = 0.0023$) and significantly greater on the herbicide treatment than the average for the three prescribed fire treatments ($p = 0.0035$). As a result of the changes in stand stocking, there were no longer significant differences in number of pine trees, basal area and volume per hectare among the five treatments in October 2007 (Table 5). The wildfire was followed by a decrease in stand basal area of 41 and 17%, respectively, on the check and herbicide treatments from October 2006 to October 2007 (Tables 2 and 5). Similarly, stand volume decreased by 34 and 11%, respectively, on the check and herbicide treatments. On the three prescribed fire treatments, average stand basal area and volume increased by 5 and 13%, respectively.

Table 5
Least-square means for longleaf pine total height, basal area, and outside-bark volume per tree and number of trees, basal area, and volume per hectare 7 months after a wildfire in March 2007, the analyses of covariance with total height and stocking in February 1999 as covariates, and stocking was adjusted for survival in January 2009.

Treatments and Sources		Total height (m)	Basal area (dm^2)	Volume (dm^2)	Number of trees (trees/ha)	Basal area (m^2/ha)	Volume (m^3/ha)
Check		11.4	1.46	87.6	971	14.2	85
Herbicide[a]		11.1	1.58	90.5	1230	19.5	111
March burn		8.8	0.83	42.6	1587	13.2	68
May burn		9.5	1.05	57.7	1700	17.8	98
July burn		9.3	1.01	56.0	1659	16.8	93
Analysis of covariance	df[a]	Probability > *F*-value					
Block	2	0.7974	0.5613	0.3573	0.8820	0.8361	0.8371
Treatment	4	0.0006	<0.0001	<0.0001	0.3547	0.6816	0.6762
Contrasts							
Check vs[a] managed trts[a]	(1)	0.0009	0.0001	<0.0001	0.1047	0.5449	0.7448
Herbicide vs prescribed fire	(1)	0.0003	<0.0001	<0.0001	0.2574	0.4145	0.3450
May vs March + July burn	(1)	0.2333	0.0233	0.0092	0.8118	0.5349	0.4974
March vs July burn	(1)	0.2029	0.0112	0.0024	0.8692	0.3718	0.3103
Covariates							
Feb[a] 1999—total height	1	0.0031	0.0021	0.0003		0.2327	0.1663
Feb 1999–trees/ha	1				0.7746	0.5552	0.5278
Error mean square	6/7 [a]	0.18376	0.00367	10.81491	178,524.1540	41.37757	1440.82676

[a] Herbicide—arborescent plant control with directed applications of herbicide, df—degrees of freedom, vs—versus, and trts—treatments, Feb—February, and 6/7—df for error mean square was 6 when two covariates were used and 7 when one covariate was used in the analysis.

The wildfire killed longleaf pine trees that were collectively smaller in stature than the surviving trees, as happened following the first series of prescribed burns in 1999 (Haywood, 2002). On the three prescribed fire treatments, average total height, basal area, and volume per tree increased by 10, 12, and 20%, respectively, from October 2006 to October 2007 (Tables 2 and 5). Because pine mortality was greater on the check and herbicide plots, total height, basal area, and volume per tree increased by 25, 26, and 41%, respectively, on the checks, and by 23, 32, and 41%, respectively, on the herbicide treatment.

There could be several reasons for the differences in mortality among treatments after the wildfire, but the caloric content and amount of combustible fuels might best explain the outcome. Average available fuel loads on prescribed burned plots in this study ranged from 3702 to 8692 kg/ha from 1999 to 2005, respectively, on a dry-weight basis (Table 1), which was estimated to have a caloric content of 4067 kcal/kg based on Hough's (1969) caloric values for live and dead herbaceous plants and scrub litter and Wiegert and Monk's (1972) caloric value for longleaf pine needles. This translated into a caloric content of from 15 to 35×10^6 kcal/ha on the prescribed burned plots. Wiegert and Monk (1972) determined that annual litter fall in a 13-year-old longleaf pine stand had a caloric content of about 25×10^6 kcal/ha, which is also the mean caloric values calculated for this study. However, Wiegert and Monk (1972) also reported that the forest floor detritus in a 13-year-old longleaf pine stand had a caloric content 48×10^6 kcal/ha with an estimated dry weight of 11,800 kg/ha. This suggests that the forest floor on the unburned check and herbicide treatments might have had a greater caloric content and mass than the fuels available for burning on the three prescribed fire treatments, and the greater amount of heat that would have been released on the heretofore unburned plots might be the chief reason the check and herbicide plots suffered greater mortality than the biennially burned plots following the wildfire in March 2007. Hiers et al. (2007) and Outcalt and Wade (2004) also argued that fuel build-up is a likely outcome of lengthening the period between prescribed burns and that a subsequent fire might cause extensive longleaf pine mortality especially when there is virtually complete consumption of the forest floor (Outcalt and Wade, 2004) as happened in this study.

Other reasons for greater mortality on the heretofore unburned plots might be prolonged combustion of fuels that accumulated around the base of trees leading to excessive heat injury and cambial death in the lower bole (Byram, 1958) and mortality of shallow roots that would have developed beneath and within the 8-year-old O-horizon on the check and herbicide plots (Brose and Wade, 2002; O'Brien et al., 2007). In addition, fire may weaken longleaf pine trees, making them susceptible to attacks by insects and pathogens (Hanula et al., 2002; Sullivan et al., 2003), although increased beetle activity does not guarantee that trees will be killed by beetles (Campbell et al., 2008).

How the fuel bed was constructed might have influenced pine mortality. Before the wildfire, grass and forb cover was greater on herbicide plots than checks, but conversely, tree and shrub cover was greater on checks than herbicide plots (Table 4). The grasses and forbs would break up an otherwise uniform "carpet" of pine litter and there would have been less ladder fuels on the herbicide plots. These differences in fuel bed construction could have affected the root environment in the O-horizon as well as lessening the amount of excessive heat reaching the upper crown of the pine trees on the herbicide plots compared to checks.

3.5.2. Understory vegetation

Percentage of pine trees with vines climbing on the boles decreased by 31 and 65 percentage points on the check and herbicide treatments, respectively, from September 2006 to October 2007 (Tables 4 and 6). On the three prescribed fire treatments, however, there was little change in percentage of pine trees with climbing vines. Checks had a significantly greater percentage of trees with climbing vines than the other four treatments 7 months after the wildfire (Table 6). Additionally, checks had a greater number of trees (291 trees/ha) with climbing vines than the herbicide treatment (98 trees/ha) or the average for the three prescribed fire treatments (93 trees/ha).

Vine cover decreased on the previously unburned treatments after the wildfire by 7 percentage points on the checks and 9 percentage points on herbicide plots from September 2006 to October 2007, but vine cover was similar on the prescribed fire treatments between measurement dates (Tables 4 and 6). The greater decrease in climbing vines and vine cover on the herbicide

Table 6
Percentage of longleaf pine trees with vines climbing on the bole above 50 cm from the ground and percentage of understory ground cover in October 2007 after a wildfire in March 2007.

Treatments and sources		Percentage of pine trees with vines climbing on the bole	Percent cover of understory plants by taxa					
			Grasses	Forbs	Trees	Shrubs	Vines	Total
Check		30	25.1	12.3	2.4	34.0	5.7	79.4
Herbicide[a]		8	32.0	13.7	0.2	12.9	1.3	60.1
March burn		5	38.1	14.3	1.8	13.9	1.1	69.1
May burn		5	34.2	10.0	0.7	8.5	1.0	54.4
July burn		7	36.7	18.0	0.4	6.9	1.4	63.4
Analysis of variance [a]	df[a]	Probability $>$ *F*-value						
Block	2	0.8987	0.1704	0.5511	0.9361	0.5194	0.8679	0.3569
Treatment	4	0.3127	0.4476	0.6799	0.3113	0.0260	0.2431	0.4533
Contrasts								
Check vs[a] managed trts[a]	(1)	0.0487	0.1033	0.6025	0.1464	0.0030	0.0333	0.1110
Herbicide vs prescribed fire	(1)	0.7544	0.4896	0.9998	0.2671	0.4590	0.9094	0.8818
May vs March + July burn	(1)	0.9222	0.6701	0.2397	0.7788	0.7638	0.9842	0.4233
March vs July burn	(1)	0.7115	0.8784	0.5210	0.2437	0.2385	0.6833	0.7318
Error mean square	8	0.05730	0.01093	0.00883	0.00468	0.01209	0.00623	0.04305

[a] Herbicide—arborescent plant control with directed applications of herbicide without intentionally treating herbaceous plants and vines, percentages were arcsine transformed before analysis, df—degrees of freedom, vs—versus, and trts—treatments.

plots than on checks might have also been due to differences in fuel condition as previously discussed.

Grass cover increased on the check and herbicide plots by 24 and 28 percentage points, respectively, but on the three prescribed fire treatments, grass cover decreased by 1 percentage point from September 2006 to October 2007 (Tables 4 and 6). As a result, there were no significant differences in grass cover on the five treatments, and grass cover averaged 33% across all five treatments 7 months after the wildfire (Table 6).

Forb cover, principally legumes, increased on all treatments following the wildfire and averaged 14% across all five treatments with no statistical differences among treatment means (Table 6). Brockway and Outcalt (2000) applied a prescribed fire in June and reported a decrease in forb cover 3 months later. In this study, forbs had 7 months to recover after the wildfire, and forb cover matched those reported by Brockway and Outcalt (2000) two and three growing seasons after a prescribed burn when supplemental treatments with herbicide were used for added brush control.

Tree cover in the understory was not significantly different among the five treatments 7 months after the wildfire (Table 6). The decrease in tree cover was greatest on the checks, declining from 15% in September 2006 to 2% in October 2007, but tree cover decreased on the other four treatments as well from 1.3% in September 2006 to 0.8% in October 2007 (Tables 4 and 6).

Shrubs recovered after the wildfire. In September 2006, shrub cover was 39% on checks and averaged 9% on the four managed treatments, and in October 2007, shrub cover was 34% on checks and averaged 11% on the four managed treatments (Tables 4 and 6). Checks had significantly more shrub cover than the average for the other four treatments 7 months after the wildfire, but there were no significant differences in shrub cover among the four managed treatments (Table 6). There were no statistical differences among treatments in total understory cover following the wildfire, and total cover ranged from 54 to 79% in October 2007.

4. Conclusions

Fire intensities in this study were probably above normal for the West Gulf Coastal Plain, but high fire intensities are common when burning grass-dominated fuels (Haywood, 2005, 2007). Delaying the first series of prescribed fires allowed many of the longleaf seedlings to reach a stature where they could better tolerate heat injury (Bruce, 1951; Greene and Shilling, 1987; Haywood, 1995), and mortality was mostly among the smallest seedlings that were of little consequence toward future stand development (Haywood, 2002). Originally, it was thought that allowing fuels to accumulate for over 6 years was a factor in the intensity of the first series of prescribed fires applied in 1999 (Haywood, 2002), but available fuel loads were less in 1999 than in the last three series of prescribed fires (Table 1). Consistently high fire intensities resulted in significant growth losses among the longleaf pine trees and especially when fires were set in March. However, although growth differences among treatments continued to increase with each series of fires (Fig. 1), stand integrity was not compromised and a desired condition of open longleaf pine forest with few midstory hardwoods and a productive and rich herbaceous and low wood plant cover in the understory was maintained by prescribed burning.

Among prescribed fire treatments, May or July burning resulted in less tree and shrub cover than burning in March, and growing season burning was more effective than winter burning at reducing arborescent midstories in other work (Waldrop et al., 1992). However, the biennial application of fire in either winter or summer for several decades will reduce or restrain arborescent plant stature, although arborescent vegetation will not be eradicated and can recover from long-periods of burning once fire is no longer applied (Waldrop et al., 1992; Haywood and Grelen, 2000; Haywood et al., 2001).

Initially, use of herbicides to control understory arborescent vegetation had an adverse, sublethal effect on the sapling longleaf pines (Haywood, 2002), but the trees overcame this (Fig. 1 and Table 2), and the herbicide treatment was successful for maintaining a productive longleaf pine overstory with an open midstory. However, the herbicide plots lost their herbaceous plant cover that was smothered out by falling litter, and although the use of herbicide maintained a desired open forest condition, an equally desirable, productive herbaceous community was largely lost in 8 years.

The wildfire resulted in high longleaf pine mortality on the previously unburned treatments, most likely because fuels that accumulated on the check and herbicide plots collectively had a higher caloric content than fuels on the prescribed burned plots (Hough, 1969; Wiegert and Monk, 1972), and the live foliage, small diameter stems, and 1- and 10-h time-lag dead fuels were almost entirely consumed as can occur in intense fires (Outcalt and Wade, 2004). Additionally, although fuels were accumulating on both the check and herbicide plots, fuel bed conditions were different enough to result in less longleaf pine mortality and vine cover on herbicide plots than checks after the wildfire.

The wildfire released the herbaceous vegetation restoring the grass and forb cover on the previously unburned plots. The high percentage of forb cover on all plots was comparable to cover percentages achieved in other work when both fire and herbicides were used for herbaceous plant release (Brockway and Outcalt, 2000).

The first two series of management treatments had little influence on soil and foliar nutrition and there was little chance that future effects would have developed based on other work (Boyer and Miller, 1994; Kuehler et al., 2004; Haywood, 2005, 2007). Foliar macronutrients were at sufficiency levels for longleaf pine, except for P (Blevins et al., 1996), and as such, soil and foliar nutrition on this longleaf pine site was typical for central Louisiana.

Therefore, if prescribed fire introduction is delayed until after plantation longleaf pine trees are sapling size, it can be applied without undo loss of pine trees to maintain the herbaceous plant community. However, the encroaching brush will likely need treatment before the introduction of fire in a rough that is over 6 years old. Thereafter, biennial burning will likely have a negative effect on longleaf pine productivity because of sublethal injury or stress to the pine trees but will continue to benefit the herbaceous plant community, and an open stand structure with a rich and productive herbaceous plant community is the expected outcome. Prescribed burning after the first flush has had time to develop will be less injurious to the pine trees and will provide better woody plant control than burning earlier in the year. Herbicides can be beneficially used as a supplemental treatment in longleaf pine stands where understory brush and midstory trees and shrubs need to be effectively controlled as part of the restoration process before the introduction of fire. However, herbicide use alone results in the decline of the herbaceous plant community and in fuel bed conditions that increase the risk to wildfire. Caution should be used during the introduction of prescribed fire even if fire has been excluded for less than a decade.

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