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Influence of herbicides and felling, fertilization, and prescribed fire on longleaf pine growth and understory vegetation through ten growing seasons and the outcome of an ensuing wildfire

James D. Haywood

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Abstract Restoring longleaf pine (*Pinus palustris* Mill.) over much of its original range requires artificial regeneration. In central Louisiana, USA, two fertilization levels—No (NF) or Yes (F-36 kg/ha N and 40 kg/ha P) in combination with three vegetation treatments—Check, four prescribed fires (PF), or multi-year vegetation control by herbicidal and mechanical means (IVM) were applied to container-grown longleaf pine plantings in a grass savanna. After 10 years, P concentration in longleaf pine foliage was less on NF plots than F plots, but fertilization did not significantly affect tree stature. Survival was greater on NF plots than F plots, and so, NF plots were more productive (NF—63 m^3/ha and F—45 m^3/ha). Pine trees on IVM plots (37 dm^3/tree) were significantly larger than on Check and PF plots, which averaged 17 dm^3/tree. Survival was better on IVM plots (88%) than PF plots (78%), which was better than Checks (58%). Consequently, IVM plots were most productive (99 m^3/ha), followed by PF plots (44 m^3/ha), and lastly Checks (28 m^3/ha). PF plots had greater grass cover (38%) than Check and IVM plots, which averaged 5%, whereas PF and IVM plots had less understory arborescent cover (an average of 25%) than Checks (91%). A wildfire in March 2007 reduced pine survival by 22, 14, and 1 percentage points on IVM, Check, and PF plots, respectively. Seven months later, longleaf pine production had decreased to 92 m^3/ha on IVM plots while increasing to 55 m^3/ha on PF plots and 30 m^3/ha on Checks. Overall, the wildfire rejuvenated the herbaceous plant community. Grass cover on Check and IVM plots averaged 20% while grass cover on PF plots was 36%. Forb cover increased on all treatments from 2% before the wildfire to 13% seven months after the wildfire. Understory arborescent cover decreased on Checks to 62% but increased slightly on PF and IVM plots and averaged 30%.

Keywords Arson · Diammonium phosphate · Hexazinone · *Pinus palustris* Mill. · Sethoxydim · Triclopyr · Vegetation management

J. D. Haywood
USDA Forest Service, Southern Research Station, 2500 Shreveport Highway, Pineville, LA 71360, USA

J. D. Haywood (✉)
RWU-4158, Alexandria Forestry Center, 2500 Shreveport Highway, Pineville, LA 71360, USA
e-mail: dhaywood@fs.fed.us

Introduction

Longleaf pine (*Pinus palustris* Mill.) forests in the southern United States are among the most ecologically diverse temperate forests in the world with more than 900 indigenous species that include 30 federally listed threatened or endangered species, 10 designated candidate species, hundreds of species of migratory birds, and species of conservation concern (US Fish and Wildlife Service 2009). Since European settlement, however, the once extensive longleaf pine forests have declined to about 3% of their historic range. Recovery of longleaf pine is considered essential for the protection of hundreds of plants (Hardin and White 1989) and animals (US Fish and Wildlife Service 2009).

In the restoration process, natural regeneration is a practical management option for existing longleaf pine forests provided there is an adequate seed source and receptive seedbed (Brockway et al. 2006). 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. 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).

Although recommended, prescribed fire is not a panacea for managing longleaf pine stands. Fire can destroy seedlings and saplings, and later, the use of fire can adversely affect stand yield and soil properties (Wahlenberg 1946; Bruce 1947, 1951; Ferguson et al. 1960; Boyer 1987; Boyer and Miller 1994; Haywood 2009a). However, some type of vegetation management program is usually necessary because brush can outgrow young longleaf pine seedlings and saplings and loss of herbaceous understory plants follows development of midstory and understory brush in pole size stands (Haywood and Grelen 2000; Haywood et al. 2001; Haywood 2009a).

If land managers are reluctant to use fire, an alternative system would be post-plant vegetation control by chemical or mechanical means (Pessin 1944; Nelson et al. 1985; Schmidtling 1987; Loveless et al. 1989; Haywood 2000, 2005; Ramsey et al. 2003; Brockway et al. 2009). In fact, total competition control is not necessary (Nelson et al. 1985); reducing plant cover to about 50% is sufficient to assure early seedling growth (Haywood 2000, 2005).

Nutrient amendment has been shown to increase loblolly (*P. taeda* L.) and slash pine (*P. elliottii* Engelm.) yields (Tiarks 1983; Haywood and Tiarks 1990). When plants were controlled with herbicides, early fertilization with diammonium phosphate increased longleaf pine seedling survival and emergence from the grass-stage on a sandy loam soil (Loveless et al. 1989). Phosphorus amendment was more beneficial than N or K amendment through 15 growing seasons on loamy sand to sand soils (Lewis 1977). On a fine sandy loam, Schmidtling (1987) reported gains in growth in a 25-year-old stand of longleaf pine from N, P, and K fertilization at time of planting when coupled with cultivation. Without plant control, Derr (1957) had poor results after applying N, P, and K fertilizer to planted seedlings on a sandy loam soil because of severe grass competition. In addition, fertilization with N, P, and K reduced longleaf pine seedling survival and did not influence height growth through two growing seasons on a sandy loam soil (Ramsey et al. 2003).

In this research, several available management options were examined with a randomized complete block factorial design model. Objectives were to determine how fertilization (No or Yes) in combination with vegetation treatments (Check, prescribed fire, and intensive vegetation management) influenced (1) longleaf pine growth, survival, and production, (2) foliar nutrition, and (3) understory plant cover through 10 growing seasons, and how an ensuing wildfire in the 11th growing season changed outcomes. Haywood (2007) addressed longleaf pine survival, emergence from the grass stage, incidence of brown-spot needle blight (caused by *Mycosphaerella dearnessii* M. E. Barr.), and height growth; soil and foliar nutrition; and understory plant production and stature through six growing seasons. Results pertain directly to establishment of longleaf pine within its native range in the southern United States. However, use of fire, herbicides, and hand weeding to control vegetation and nutrient amendments are of interest to forest managers worldwide.

Methods

Study site

The study site is within the humid, temperate, coastal plain and flatwoods province of the West Gulf Region of the southeastern United States (McNab and Avers 1994). The site is on the Kisatchie National Forest (KNF) in central Louisiana (92°37′ W, 31°1′ N) at 53 m above sea level and is 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). Both soils are deficient in P for growing pine trees (Tiarks 1983; Haywood and Tiarks 1990), but the site is suitable for restoring loamy dry-mesic upland longleaf pine forests (Turner et al. 1999). A natural pine and mixed hardwood forest cover was clearcut harvested in the mid 1980s, and the site was sheared and windrowed in 1991 (Table 1). The low cover of herbaceous and scattered arborescent vegetation that developed after windrowing was treated with prescribed fire in March 1993 and 1996. The vegetation was rotary mowed in October 1996, and the site was a grass savanna before study establishment.

Study establishment

Research plots were established in December 1996 (Table 1). Six fertilization-vegetation treatment (FERT-VT) combinations were assigned in a randomized complete block 2 (FERT) by 3 (VT) factorial design (Steel and Torrie 1980). The 24 research plots (4 blocks by 6 FERT-VT combinations) each measured 22 by 22 m (0.048 ha) and contained 12 rows of 12 seedlings arranged in a 1.83- by 1.83-m spacing. The center 64 longleaf pine seedlings (8 rows of 8 seedlings each) were the measurement plot. Blocking was based on drainage, and the blocks were established parallel to windrows formed in 1991.

Container longleaf pine seedlings were grown in Ray Lech “Cone-tainer” cells (Stuewe & Sons, Inc., Tangent, Oregon, USA) at the US Forest Service research center in Pineville, LA, USA using management practices recommended by Barnett and McGilvray (1997). Seedlings were started in April 1996 with a Mississippi seed source, and after 48 weeks were planted in March 1997 using a container dibble of the correct size for the root plug (Table 1).

The two fertilization levels per block were as follows: (NF) No fertilizer applied and (F) broadcast application of 200 kg/ha diammonium phosphate (36 kg/ha N and 40 kg/ha P) in May 1997 (Table 1). The fertilizer rate was based on a preliminary nutrition trial with planted longleaf pine seedlings (Burton 1984). The three vegetation treatments per block were as follows: Check—no management activities after planting, (PF) Prescribed fire—plots were burned four times in the second through ninth growing seasons, and (IVM) Intensive vegetation management—herbicides were applied after planting for herbaceous

Table 1 Chronological listing of management activities from the mid 1980s through 2007; fertilization levels were NF—not fertilized and F—fertilized, and vegetation treatments were Check—no treatment after 1996, PF—prescribed fire, and IVM—intensive vegetation management

Dates	Activity and treatments
Mid 1980s	Study site was clearcut harvested
March 1991	Study site was windrowed
March 1993	Prescribed fire applied to study site
March 1996	Prescribed fire applied to study site
October 1996	Rotary mowed study site
December 1996	Research plots were established
December 1996	Rotary tilled IVM plots
March 1997	Container-grown longleaf pine seedlings were planted
May 1997	Broadcast 200 kg/ha DAP on F plots
May 1997	Applied sethoxydim and hexazinone to IVM plots
April 1998	Applied sethoxydim and hexazinone to IVM plots
April 1998	Directed application of triclopyr to arborescent vegetation on IVM plots
May 1998	Prescribed fire applied to PF plots
May 1999	Directed application of triclopyr to arborescent vegetation on IVM plots
May 2000	Prescribed fire applied to PF plots
February 2001	Hand-cut arborescent vegetation on IVM plots
May 2003	Prescribed fire applied to PF plots
May 2005	Prescribed fire applied to PF plots
March 2007	Wildfire set by an arsonist burned across the study site

DAP Diammonium phosphate fertilizer

and arborescent plant control, and arborescent re-growth was hand felled. The six FERT-VT combinations were NF-Check, NF-PF, NF-IVM, F-Check, F-PF, and F-IVM.

The native grass sod on IVM plots was rotary tilled in December 1996 before planting in March 1997 (Table 1). Sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) herbicide was used for post-plant bluestem grass (*Andropogon* spp. and *Schizachyrium* spp.) control in combination with hexazinone (3-cyclohexyl-6-[dimethylamino]-1-methyl-1,3,5-triazine-2,4[1H,3H]-dione) herbicide for general herbaceous plant control. In May 1997 and April 1998, sethoxydim and hexazinone in aqueous solution were applied in 0.9-m bands over the rows of unshielded longleaf pine seedlings. Within the 0.9-m bands, the rate of sethoxydim was 0.37 kg active ingredient (ai)/ha, and for hexazinone the rate was 1.12 kg ai/ha. Triclopyr (3, 5, 6-trichloro-2-pyridinyloxyacetic acid) herbicide at 4.8 g acid equivalent/liter was tank mixed with surfactant and water and applied as a directed foliar spray to competing arborescent vegetation in April 1998 and May 1999. Recovering brush was hand-cut in February 2001.

The first prescribed fire was in May 1998 or 14 months after planting (Table 1). Consumption of available fuels varied. The F-PF plots burned cleaner and more intensely than NF-PF plots because of a greater amount of fine fuels. The NF-PF plots were lightly vegetated in areas, and so fuel consumption was more variable. Nevertheless, all fires were acceptable.

The second through fourth prescribed fires were in May 2000, 2003, and 2005 (Table 1). For each year, available fine fuels were living foliage and 1-h time-lag dead fuels as described by Deeming et al. (1977), which were sampled before firing on four randomly selected 0.2-m^2 subplots per PF plot. Samples were dried in a forced-air oven before determining moisture content and oven-dried mass. Plots were inspected after the fire to determine how much of these fuels were consumed. Rates of spread were measured during the fires. Based on these measurements, Byram's fire intensity was calculated (Haywood 1995). In 2003 and 2005, crown scorch was estimated 2 weeks after each fire to the nearest percent.

All fires in 2000 through 2005 consumed large amounts of available fine fuels and were more intense than the maximum of 173 kJ/s/m recommended by Deeming et al. (1977) (Table 2). Crown scorch was similar on both NF-PF and F-PF plots and averaged 88% in 2003 and 83% in 2005. High fire intensities and scorch percentages have resulted from striphead fires in grass-dominated understories at other study sites (Haywood 2005; 2009a). For each year, differences between NF-PF and F-PF treatments in fuel consumed or fire intensity were not statistically significant.

Climatic conditions

Mean January and July temperatures were 10 and 28°C, respectively, from 1977 through 2007 in central Louisiana (National Climatic Data Center 2009). Annual precipitation averaged 1,477 mm/year; October was the driest month (96 mm/year) and December was the wettest month (150 mm/year) during the 11-year period.

Based on Palmer Drought Severity Index (PDSI) values obtained from the National Climatic Data Center (2009), drought conditions occurred 44% of the time in central Louisiana from 1997 through 2007 (Fig. 1). The study was planted in March 1997, which was a drought-free year. A severe 4-month drought occurred in 1998 that was followed by an extreme 20-month drought spanning 1999 and 2000 based on the PDSI values (Hayes 2010). Mild 5- and 6-month droughts developed in 2002 and 2003, respectively, and a moderate 17-month drought spanned 2005 and 2006. A mild 3-month drought occurred in 2007.

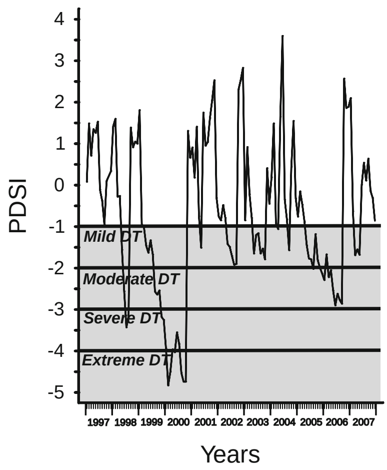
Table 2 Available fine fuel loads and fire intensities for prescribed fires conducted in May on a longleaf pine site from 1998 through 2005

Year and fertilization treatment	Oven-dried fuel load (kg/ha)	Fire intensity (kJ/s/m)[a]
1998		
No	–[b]	Low
Yes	–	Low
2000		
No	4,133	300
Yes	4,693	431
2003		
No	6,616	480
Yes	9,080	846
2005		
No	8,553	755
Yes	8,424	703

[a] A low intensity winter backfire would be between 0 and 173 kJ/s/m (Deeming et al. 1977)

[b] No samples were collected

Fig. 1 Palmer Drought Severity Index Values (PDSI) for central Louisiana from 1997 through 2007; lines mark the mild, moderate, severe, and extreme drought thresholds (DT)



Sampling procedures

Longleaf pine survival counts and height measurements were taken annually. Total heights were measured with a calibrated rod to the nearest cm through three growing seasons, and to the nearest 3 cm thereafter. Once the tallest trees exceeded 8 m in total height, all tree heights were measured with a laser instrument (Criterion 400 Survey Laser, Laser Technology, Inc, Centennial, CO). Tree dbh was measured with a diameter tape beginning in the eighth growing season. Total height and dbh were used to calculate outside-bark stemwood volume with Baldwin and Saucier's (1983) formulas.

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 [*Rubus* spp.]), and woody vines—with the following technique. The central 64 planting locations on each measurement plot formed 49 adjacent 1.83- by 1.83-m squares. Within each square, the percentage of each taxon was estimated to the nearest percent, and the 49 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 planted longleaf pine trees above a height of 50 cm.

In January 2007, longleaf pine needle samples were collected from the previous year flushes in the upper third of the tree crown from five dominant or codominant trees per plot that were selected in an "x" pattern, with a pine tree chosen near the center of each quarter and near the middle of each measurement plot. More than 100 fascicles per plot were collected. The needles were oven-dried at 70°C for 48 h in a forced-air oven, ground in a Wiley mill, and sieved through a 2 mm screen. Foliar samples were then submitted to A&L Plains Agricultural Laboratories, Inc, Lubbock, Texas for analysis.

Wildfire

On 21 March 2007, an arsonist set a wildfire that burned across the study site (Table 1). 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 understory trees, shrubs, vines, grasses, and forbs and the 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. This wildfire burned across a nearby study as well (Haywood 2009a).

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, longleaf pine survival was again surveyed in January 2009, but the trees were not remeasured. None of the pine trees surviving in January 2009 appeared to be stressed from the wildfire.

Data analysis

For the tenth growing season measurement in September 2006, longleaf pine total height, basal area, and volume per tree and number of trees, basal area, and volume per hectare were compared between the 2 fertilization levels and among the 3 vegetation treatments with a randomized complete block factorial design model with four blocks as replicates at the $\alpha = 0.05$ level (Steel and Torrie 1980; SAS Institute Inc. 1985). In addition, percent understory cover, percent longleaf pine with vines climbing on the bole, and percent N, P, K, Ca, and Mg in longleaf pine foliage were analyzed with this model.

Post-wildfire longleaf pine variables based on the October 2007 measurements were compared with the previous model (Steel and Torrie 1980; SAS Institute Inc. 1985) after dropping trees that died through January 2009 from the record. In addition, percent change in pine survival between September 2006 and January 2009; percentage of longleaf pines with vines growing on the bole, and percent understory plant cover by taxa in October 2007 were compared with the previous model.

If there were significant differences among vegetation treatments, mean comparisons were made with Duncan's Multiple Range Tests at $\alpha = 0.05$. Percentages were arcsine transformed before analysis to equalize variances (Steel and Torrie 1980). Analyses were done with non-transformed and transformed percentages and transformation did not change interpretation of results.

Results

Longleaf pine

Total height differences among the six FERT-VT combinations increased during the early growing seasons, but those differences were generally constant from the eighth through tenth growing seasons (Fig. 2). Droughts appeared to have little effect on height growth (Figs. 1, 2). Volume per tree was first calculated in the eighth growing season, and through the tenth year, differences among the FERT-VT combinations were generally constant as well.

After 10 growing seasons, fertilization did not significantly affect total height, basal area, or volume per longleaf pine tree, and pine trees averaged 6.0 m tall, 0.59 dm^2 in basal area, and 24 dm^3 of stemwood per tree across all six FERT-VT combinations (Table 3). Pines were tallest with the most stemwood volume on NF-IVM plots (8.0 m and 39 dm^3) and shortest with the least stemwood volume on NF-Check plots (4.5 m and 15 dm^3) (Fig. 2).

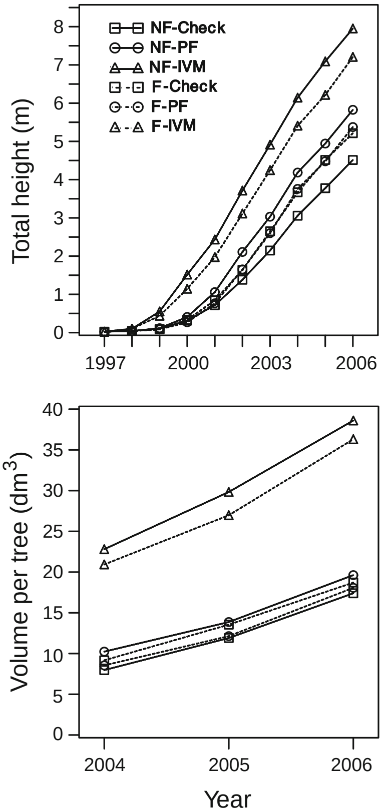


Fig. 2 Total height of longleaf pine trees through 10 growing seasons and volume per tree from the eighth through tenth growing seasons; fertilization levels were NF—not fertilized and F—fertilized, and vegetation treatments were Check, prescribed fire (PF), and intensive vegetation management (IVM)

Fertilization early in the first growing season resulted in significantly lower longleaf pine stand density at age 10 years (Table 3). The adverse effect on pine survival was especially severe on F-Checks primarily because nutrient amendment increased arborescent stand density and stature overtopping the longleaf pine regeneration (Haywood 2007), and eventually seedlings died from a lack of sunlight, nutrient, and water resources and smothering by falling litter. The high loss of seedlings on F-Checks compared to the other five FERT-VT combinations was expressed as a significant FERT-VT interaction (Table 3). This interaction occurred partly because earlier in the study smaller pines were dying more quickly on F-Checks than NF-Checks (Haywood 2007), and by age 10 years, the remaining trees on average were taller and had more stemwood volume on F-Checks than NF-Checks (Fig. 2). The overall greater stand density on NF plots than on F plots resulted in longleaf pine trees producing significantly more basal area and volume per hectare on NF plots than on F plots (Table 3).

Vegetation treatment also affected longleaf pine growth and production through 10 growing seasons. The IVM plots had significantly greater pine total height, basal area, and volume per tree and greater stand density, basal area, and volume per hectare compared to Check and PF plots (Table 3). Pine trees on PF plots were significantly taller than pine trees on Checks. The PF plots also had significantly greater stand density, basal area, and volume per hectare compared to Checks. There were no significant FERT-VT interactions affecting longleaf pine stature or stand production besides the interaction affecting stand density.

Table 3 Longleaf pine total height, basal area, and outside-bark volume per tree and number of trees, basal area, and volume per hectare after 10 growing seasons and the analyses of variance

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)
Fertilization (FERT)							
No (NF)		6.1	0.58	24.2	2,585a[a]	15.1a	62.6a
Yes (F)		5.9	0.59	23.7	1,884b	11.0b	44.7b
Vegetation treatments (VT)							
Check		4.9c	0.41b	15.9b	1,734c	7.1c	27.6c
Prescribed fire		5.6b	0.50b	18.7b	2,324b	11.6b	43.5b
Intensive vegetation management		7.6a	0.84a	37.4a	2,645a	22.4a	99.0a
FERT–VT interaction							
NF-Check					2,382bc		
NF-Prescribed fire					2,569ab		
NF-Intensive vegetation management					2,803a		
F-Check					1,086d		
F-Prescribed fire					2,079c		
F-Intensive vegetation management					2,487ab		
Analysis of variance	*df*[a]	Probability > *F*-value					
Block effect	3	0.5959	0.6295	0.6212	0.4307	0.3250	0.3271
FERT	1	0.5388	0.9700	0.8072	<0.0001	0.0025	0.0049
VT	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
FERT × VT interaction	2	0.0895	0.7343	0.5821	0.0026	0.7487	0.8747
Error mean square	15	0.40854	0.01003	22.21410	60169.1000	5.64669	129.91455

[a] Within columns, fertilization or vegetation treatments and interactions followed by a different letter are significantly different based on Duncan's Multiple Range Tests ($\alpha = 0.05$) and *df*—degrees of freedom

Nutrition

Fertilization significantly increased foliar P concentration through 10 growing seasons whereas vegetation treatment did not significantly affect foliar P concentration (Table 4). Concentrations of foliar N and K were not significantly affected by fertilization level or vegetation treatment. The IVM plots had a significantly higher concentration of foliar Ca than Check or PF plots and PF plots had a significantly lower concentration of foliar Mg than Check or IVM plots. There were no significant FERT-VT interactions affecting longleaf pine foliar nutrition.

Understory vegetation

Percentage of longleaf pine trees with vines climbing on the bole above 50 cm of the ground and percent cover of vines in the understory were not affected by fertilization at age 10 years (Table 5). However, IVM plots had significantly more pine trees with vines climbing on the bole and a greater percentage of vine cover in the understory than either

Table 4 Percentage of N, P, K, Ca, and Mg in live longleaf pine foliage sampled after 10 growing seasons

Treatments and sources	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Fertilization (FERT)					
No	0.98	0.043b[a]	0.38	0.20	0.096
Yes	0.97	0.053a	0.40	0.21	0.092
Vegetation treatments (VT)					
Check	1.02	0.044	0.35	0.19b	0.098a
Prescribed fire	0.95	0.050	0.44	0.19b	0.084b
Intensive vegetation management	0.95	0.051	0.39	0.23a	0.100a

Analysis of variance	*df*[a]	Probability > *F*-value[a]				
Block effect	3	0.7972	0.4760	0.0608	0.4315	0.2335
FERT	1	0.7739	0.0011	0.5647	0.8119	0.2717
VT	2	0.1608	0.0594	0.0987	0.0159	0.0041
FERT × VT interaction	2	0.7558	0.0858	0.6178	0.5007	0.5557
Error mean square	15	0.04719	0.00605	0.10766	0.03282	0.00666

[a] Within columns, fertilization or vegetation treatments followed by a different letter are significantly different based on Duncan's Multiple Range Tests ($\alpha = 0.05$) and *df*—degrees of freedom. Percentages were arcsine transformed before analysis. However, transformation of the data did not affect interpretation of results

Check or PF plots, and Checks had significantly more pine trees with vines climbing on the bole and percentage of vines in the understory than PF plots.

Fertilization was associated with less grass and forb cover but greater tree and shrub cover in the understory (Table 5). The F plots averaged 14% herbaceous and 60% arborescent plant cover compared to 23% herbaceous and 34% arborescent plant cover on NF plots, and total understory cover on F plots was significantly greater than total cover on NF plots.

PF plots had greater grass and forb cover than Check and IVM plots and Checks had greater grass cover than IVM plots (Table 5). Checks had significantly greater tree and shrub cover than PF or IVM plots. After 10 years, total understory cover on Check plots (110%) was significantly greater than on PF and IVM plots (an average of 62%). Significant interactions occurred. Grass cover on NF-IVM and F-IVM plots was similar and averaged 3%, and tree cover on the NF-IVM and F-IVM plots was similar and averaged 10%. The interactions were in contradiction to the main effect differences between NF and F plots.

Wildfire

Seven months after the March 2007 wildfire, percentage of longleaf pine trees with vines growing on the bole had decreased by 17 and 39 percentage points on Check and IVM plots, and vine cover in the understory decreased by 4 and 17 percentage points on Check and IVM plots, respectively (Tables 5, 6). On PF plots, climbing vines increased by 6 percentage points while understory vine cover remained the same. After the wildfire, IVM plots still had more pine trees with vines growing on the bole than PF and Check trees (Table 6); however, it was observed that the original larger vines that were climbing into the canopy were dead and the current vines were mostly new growth.

Table 5 Percentage of longleaf pine trees with vines climbing on the bole above 50 cm from the ground and percentages of understory ground cover after 10 growing seasons

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
Fertilization (FERT)							
No (NF)	39	20a[a]	3a	16b	18b	12	69b
Yes (F)	37	12b	2b	29a	31a	12	87a
Vegetation treatments (VT)							
Check	31b	7b	1b	48a	43a	10b	110a
Prescribed fire	9c	38a	4a	10b	14b	4c	70b
Intensive vegetation management	74a	3c	1b	11b	16b	23a	54b
FERT-VT interaction							
NF-Check		13c		33b			
NF-Prescribed fire		44a		5d			
NF-Intensive vegetation management		4d		11cd			
F-Check		2d		63a			
F-Prescribed fire		32b		15c			
F-Intensive vegetation management		2d		10cd			

Analysis of variance	*df*[a]	Probability > *F*-value[a]						
Block effect	3	0.0095	0.0241	0.0796	0.0016	0.5394	0.0099	0.2004
FERT	1	0.5537	<0.0001	0.0091	0.0004	0.0056	0.8454	0.0135
VT	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
FERT × VT interaction	2	0.1922	0.0061	0.0765	0.0288	0.6003	0.5761	0.2409
Error mean square	15	0.01539	0.00238	0.00577	0.00863	0.01581	0.00690	236.8613

[a] Within columns, fertilization or vegetation treatments and interactions followed by a different letter are significantly different based on Duncan's Multiple Range Tests ($\alpha = 0.05$) and *df*—degrees of freedom. Percentages were arcsine transformed before analysis, except for total plant cover because total cover on Checks exceeded 100%. However, transformation of data did not change the interpretation of results in the other analyses

Grass cover increased after the wildfire on Check and IVM plots by 15 and 16 percentage points, respectively, while grass cover on PF plots changed little and was 36% seven months after the wildfire (Tables 5, 6). However, the increase in grass cover on the previously unburned Check and IVM plots was not as great as at a different study site after a wildfire (Haywood 2009a). There was a significant interaction after the wildfire (Table 6). Grass cover was greater on the NF-Check and NF-PF plots than on the NF-IVM plots whereas grass cover was greater on the F-PF plots than on the F-Check and F-IVM plots.

Forb cover increased on all six FERT-VT combinations from 2% before the wildfire to 13% after the wildfire (Tables 5, 6). This increase in forb cover was comparable to the forb cover response following a wildfire at another study site (Haywood 2009a).

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 7 months after the wildfire

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
Fertilization (FERT)							
No (NF)	24	30	15	10b[a]	16b	5	77
Yes (F)	19	20	12	21a	33a	6	93
Vegetation treatments (VT)							
Check	14b	22	12	30a	32	6	101a
Prescribed fire	15b	36	14	12b	20	4	86ab
Intensive vegetation management	35a	19	14	5b	23	6	68b
FERT-VT interaction							
NF-Check		33a					
NF-Prescribed fire		39a					
NF-Intensive vegetation management		19b					
F-Check		10c					
F-Prescribed fire		32a					
F-Intensive vegetation management		19b					

Analysis of variance	*df*[a]	Probability > *F*-value[a]						
Block effect	3	0.0709	0.6324	0.0752	0.0505	0.4950	0.0009	0.4295
FERT	1	0.5943	<0.0001	0.0608	0.0482	0.0085	0.1842	0.0647
VT	2	0.0393	<0.0001	0.2832	0.0095	0.2439	0.3372	0.0150
FERT × VT interaction	2	0.7224	0.0005	0.4018	0.6411	0.1818	0.2772	0.6754
Error mean square	15	0.06262	0.00322	0.00416	0.03993	0.02628	0.00481	402.43117

[a] Within columns, fertilization or vegetation treatments and interactions followed by a different letter are significantly different based on Duncan's Multiple Range Tests ($\alpha = 0.05$) and *df*—degrees of freedom. Percentages were arcsine transformed before analysis, except for total plant cover because total cover on checks exceeded 100%. However, transformation of data did not change the interpretation of results in the other analyses

After the wildfire, understory tree cover decreased on Checks by 18 percentage points, decreased by 6 percentage points on IVM plots, but increased slightly on PF plots by 2 percentage points (Tables 5, 6). Shrubs decreased on Checks by 11 percentage points but increased on PF and IVM plots by an average of 7 percentage points. These outcomes were similar to changes in tree and shrub cover following a wildfire at another study site (Haywood 2009a).

Longleaf pine survival was disproportionately affected by the wildfire across the six FERT-VT combinations, and there was a significant FERT-VT interaction affecting the change in survival following the wildfire ($P = 0.0036$). Survival decreased the most on F-IVM plots by 38% but only by 5% on NF-IVM plots. Across vegetation treatments, survival decreased the least on PF plots by 1%, Checks by 14%, and IVM plots by 21% (Tables 3, 7).

Table 7 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 and the analyses of variance with stocking adjusted for survival in January 2009

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)
Fertilization (FERT)							
No		7.3	0.67	30.7	2339a[a]	15.7a	71.8a
Yes		7.3	0.69	31.0	1390b	9.6b	43.1b
Vegetation treatments (VT)							
Check		6.5b	0.53b	22.8b	1302b	6.9c	29.7c
Prescribed fire		6.6b	0.57b	23.8b	2295a	13.1b	54.6b
Intensive vegetation management		8.9a	0.94a	46.0a	1997a	18.7a	91.8a
Analysis of variance	*df*[a]	Probability > *F*-value					
Block effect	3	0.5537	0.3451	0.4574	0.3924	0.3401	0.3418
FERT	1	0.7589	0.6953	0.8994	<0.0001	0.0009	0.0014
VT	2	<0.0001	<0.0001	<0.0001	0.0012	0.0001	<0.0001
FERT × VT interaction	2	0.3214	0.9363	0.8613	0.2066	0.1030	0.1049
Error mean square	15	0.43223	0.01091	36.94933	191,788.70	15.58242	398.23989

[a] Within columns, fertilization or vegetation treatments followed by a different letter are significantly different based on Duncan's Multiple Range Tests ($\alpha = 0.05$) and *df*—degrees of freedom

The wildfire killed more of the smaller pine trees than the larger pine trees. Before the wildfire, average pine tree height, basal area, and volume were 6.0 m, 0.59 dm^2, and 24 dm^3 of stemwood per tree, respectively, in September 2006 (Table 3). However, mortality following the wildfire shifted average tree height, basal area, and volume upward to 6.4 m, 0.63 dm^2, and 26 dm^3 of stemwood per tree, respectively, in the September 2006 record.

The disproportionate loss of smaller pine trees plus an extra growing season of growth resulted in the average longleaf pine tree size being much greater 7 months after the wildfire than after the tenth growing season (Tables 3, 7). However, longleaf pine trees on NF plots where still similar in stature to pine trees on F plots, and trees averaged 7.3 m tall, with 0.68 dm^2 in basal area, and 31 dm^3 of stemwood per tree across all six FERT-VT combinations (Table 7). There were significantly more pine trees on NF plots compared to F plots, and as a result, longleaf pine basal area and volume per hectare remained significantly greater on NF plots than on F plots 7 months after the wildfire.

Vegetation treatments still affected longleaf pine stature and production (Table 7). Longleaf pines on IVM plots were significantly taller and had greater basal area and volume per tree than pine trees on Check and PF plots. There were significantly fewer pine trees on Checks than on PF and IVM plots. However, because of the large decline in tree survival on IVM plots, longleaf pine basal area and volume per hectare decreased on IVM plots by 3.7 m^2 and 7.2 m^3/ha, respectively, from the end of the tenth growing season until 7 months after the wildfire (Tables 3, 7). During this period, basal area and volume per hectare increased by 1.5 m^2 and 11 m^3/ha on PF plots, and volume per hectare increased by 2 m^3/ha on Checks. Nevertheless, IVM plots still had significantly more basal area and volume per hectare than Check or PF plots, and PF plots still were significantly more productive than Checks 7 months after the wildfire (Table 7). There were no significant interactions influencing longleaf pine stature or production after the wildfire.

Discussion

When a site is a grass savanna or a sufficient longleaf pine seed source is not present in the overstory, a good option for reestablishing longleaf pine is removal of the woody vegetation, site preparation, and planting. Through the mid-twentieth century, however, land managers had serious problems establishing nursery grown longleaf pine regeneration; therefore, many managers favored loblolly and slash pines over longleaf pine (Croker 1987). Despite past favoritism, longleaf pine might be potentially as productive as loblolly or slash pine by age 20–25 years on some sites provided there is good survival, an absence of brown-spot needle blight, and initiation of height growth in the first several growing seasons after planting (Derr 1957; Shoulders 1985; Kais et al. 1986; Schmidtling 1987; Outcalt 1993).

Survival was 75% through 10 growing seasons. Although drought conditions occurred 44% of the time in central Louisiana from 1997 through 2007, severe to extreme drought conditions only developed in 1998–2000 (Fig. 1), and apparently, drought conditions were not serious enough to influence survival. In addition, there was a strong response to IVM treatments as reported in other work (Pessin 1944; Derr 1957; Nelson et al. 1985; Schmidtling 1987; Haywood 2000, 2005; Ramsey et al. 2003).

Understory herbaceous vegetation is very competitive with longleaf pine seedlings (Haywood 2005). PF plots had greater percentages of grass and forb cover (Table 5) and less pine growth than IVM plots (Table 3) after 10 growing seasons. The reduced pine growth on Checks was likely from competition with brush that was overtopping and crowding the seedlings and from smothering by falling litter (Haywood 2007).

Based on Burton's (1984) work, 200 kg/ha of diammonium phosphate (36 kg/ha N and 40 kg/ha P) was broadcast in the first growing season, which was greater than the 28 kg/ha P rate recommended by Blevins et al. (1996). Nevertheless, fertilization did not influence tree growth and stature although fertilization raised foliar concentration of P to the sufficiency threshold of 0.08% (Blevins et al. 1996) through six growing seasons (Haywood 2007) and was still higher than for unfertilized foliage through 10 growing seasons (Table 4). In other work, 35–47-year-old longleaf pine failed to respond to repeated applications of diammonium phosphate on Ruston (fine-loamy, siliceous, semiactive, thermic Typic Paleudults) and Smithdale (fine-loamy, siliceous, subactive, thermic Typic Hapludults) fine sandy loam soils with or without control of understory vegetation (Haywood 2009b). In addition, although fertilization level and vegetation treatment influenced foliar N, K, Ca, and Mg during the course of this study, concentrations of these nutrients were sufficient for longleaf pine after 10 growing seasons on all six FERT-VT combinations (Table 4), based on suggested sufficiency levels of 0.95, 0.30, 0.10, and 0.06% for N, K, Ca, and Mg, respectively (Blevins et al. 1996).

The failure of longleaf pine seedlings to respond to nutrient amendment might have to do with severe drought conditions in 1998 through 2000 (Fig. 1). Jose et al. (2003) determined that N fertilization shifted C allocation to seedling shoots and away from roots that would have adverse consequences under severe drought conditions as occurred in this study in the second through fourth growing seasons. In addition, fertilization might favor lateral root development (Ramsey et al. 2003), which if detrimental to taproot development

(Sword Sayer et al. 2009), would limit the ability to access deeper soil moisture during drought (Ramsey et al. 2003).

Competition might explain the lack of response to nutrient amendment as well. Fertilization increased total competing plant production in the second growing season, arborescent plant stand density and height by the fifth growing season (Haywood 2007), and increased understory arborescent plant cover in the tenth growing season (Table 5). The greater competition on the F plots during the course of this study might have reduced pine growth and adversely affected pine survival and production (Table 3). Despite the lack of response by longleaf pine to fertilization in this study, other fertilization regimes might be successful and deserve further study, such as those recommended by Blevins et al. (1996) and more intensive fertilization regimes as studied by Anderson and Johnsen (2009).

On a nearby site, initiating prescribed burning in 6–7-year-old longleaf pine plantings resulted in a decrease in total height on biennially prescribed burned plots compared to Checks (Haywood 2009a). However, the fires applied in May in Haywood's (2009a) study were more intense than the ones on NF-PF plots in this study. The delay in initiating prescribed burning in Haywood's (2009a) study and the differences in fire intensity between the two studies might partly explain the differences in how fire affected total height growth of longleaf pine trees when comparing NF-Check and NF-PF plots herein (Fig. 2) to the Checks and biennially prescribed burned plots at another study site (Haywood 2009a).

Prescribed fire might be causing important physiological changes in the upper crown and roots of longleaf pine trees. In additional work at this site, the loss of lower crown foliage and limbs following prescribed burning shifted the percentage of total leaf area into the upper crown relative to the lower crown, increased the net photosynthetic rate, and reduced root starch concentration as trees rapidly re-established leaf area on PF plots compared to Check or IVM plots (Sword Sayer and Haywood 2009).

Prescribed burning reduced understory vine cover and increased grass and forb cover compared to the other two vegetation treatments, and reduced arborescent cover compared to Checks. Without prescribed fire, falling litter on Check and IVM plots was smothering grasses, understories on Checks were almost completely shaded by arborescent vegetation, and vegetation control on IVM plots had allowed vines to capture additional space. Before the wildfire, it was observed that large, high climbing vines on longleaf pine trees on Check and IVM plots helped to form a midstory capable of catching falling litter that could have acted as ladder fuels adjacent to the tree bole during the wildfire. In addition, the 91% cover of understory arborescent vegetation on Checks also likely added to the problem of ladder fuels (Brockway et al. 2009).

Average available fuel loads on prescribed burned plots in this study was 8,489 kg/ha in 2005 on a dry weight basis, which was similar to the fuel load of plots prescribe burned in May 2005 at another study site (Haywood 2009a). Available fuel on PF plots in this study was estimated to have a caloric content of 4,254 kcal/kg based on Hough's (1969) caloric values for live and dead herbaceous plants, live and dead grass, hardwood leaves, and scrub litter and Wiegert and Monk's (1972) caloric value for longleaf pine litter. This translated into a caloric content of 36×10^6 kcal/ha on PF plots in 2005. 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. However, Wiegert and Monk (1972) also reported that forest floor detritus in a 13-year-old longleaf pine stand had a caloric content of 48×10^6 kcal/ha with an estimated dry weight of 11,800 kg/ha. Therefore, based on Hough's (1969) caloric values for vine and hardwood foliage and litter and Wiegert and Monk's (1972) caloric value for longleaf pine litter, the caloric content of fuels on Check and IVM plots was estimated to be 4,446 kcal/kg before the wildfire. With an estimated dry weight of 11,800 kg/ha, fuels on Check and IVM plots might have had a caloric content of 53×10^6 kcal/ha. This suggests that Check and IVM plots might have had 33–47% greater caloric content than PF plots on the day of the wildfire based on Wiegert and Monk's (1972) work and the estimates herein. The greater amount of heat that would have been released and the laddering of fuels on the heretofore unburned plots might be chief reasons Check and IVM plots suffered 18% mortality after the wildfire while PF plots only had a 1% loss of pine trees. 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; Ferguson et al. 1960) and mortality of shallow roots that would have developed beneath and within the 10-year-old O-horizon on Check and IVM plots (Brose and Wade 2002; O'Brien et al. 2007). In addition, fire might weaken longleaf pine trees, making them susceptible to attacks by insects and pathogens (Ferguson et al. 1960; 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).

The increase in forb cover following the wildfire on all treatments was similar to the increase in forb cover reported by Brockway and Outcalt (2000) and Haywood (2009a). Overall, total understory cover shifted to a higher percentage of herbaceous vegetation and less arborescent and woody vine cover (Tables 5, 6).

Conclusions

Intensive vegetation management was the best treatment for increasing height growth of planted longleaf pines. Since herbicides are often used in the southern United States, this option might be broadly accepted where threatened and endangered plants are not a concern. However, in later years, needle cast will smother herbaceous plants on unburned areas. If rich and productive herbaceous plant communities are one management objective, fire will have to be introduced at some point (Waldrop et al. 1992; Hiers et al. 2007). In addition, longleaf pine stand density will have to be controlled to arrest the decline in herbaceous vegetation in later years because changes in understory herbage production are inversely related to pine basal area (Grelen and Enghardt 1973; Grelen and Lohrey 1978; Wolters 1982).

Based on the foliar concentration of P, the F plots should be refertilized (Blevins et al. 1996). However, lack of individual longleaf pine tree response and the increase in understory arborescent vegetation following application of diammonium phosphate at the beginning of the study indicates that another diammonium phosphate application would not be beneficial as was the outcome in Haywood's (2009b) work. Since the other foliar nutrients were sufficient for longleaf pine (Blevins et al. 1996), another application of diammonium phosphate would not be worthwhile.

Although the wildfire affected understory cover differently on each vegetation treatment, this wildfire had an overall rejuvenating effect in the herbaceous plant community where fire was excluded for 11 years and showed that common herbaceous plants can recover after only one fire. Fortunately, fire can be introduced into sapling to small pole stands, although 10–40% of the longleaf pine trees might be killed (Ferguson et al. 1960; Haywood 2009a). The possible mortality of too many overstory trees cautions for the careful reintroduction of prescribed fire when it has been excluded for long periods, and a mechanical pre-fire treatment might be needed before the reintroduction of prescribed fire (Brockway et al. 2009).

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