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Influence of herbicides and felling, fertilization, and prescribed fire on longleaf pine establishment and growth through six growing seasons

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Abstract Recovery of longleaf pine (*Pinus palustris* P. Mill.) is necessary to arrest the decline of many associated plants and animals, and the establishment of longleaf pine on much of its original range requires artificial regeneration and diligence. 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, two prescribed fires [PF], or multi-year vegetation control by herbicidal and mechanical means [IVM]) were applied to container-grown longleaf pine plantings in two studies. In Study 1 (grass dominated), 6-year-old longleaf pine survival was 52% on the F–checks, 78% on the F–PF plots, and averaged 93% on the other four treatment combinations. Longleaf pine trees on the IVM plots (3.4 m) were significantly taller than on the other two vegetation treatments, and trees on the PF plots (1.8 m) were taller than trees on the check plots (1.2 m). In Study 2 (brush dominated), survival averaged 65% across the six-treatment combinations after 6 years. The longleaf pine trees were 4.7 m tall on the IVM plots and averaged 3.9 m tall on the check and PF plots. Fertilization increased P concentrations in the soil and longleaf pine foliage, while fertilization did not significantly affect longleaf pine height growth. Native fertility was not apparently limiting longleaf pine development contrary to prior research recommendations for these soils. In both studies, the IVM treatment reduced early herbaceous competition and the number and height of arborescent plants. The PF treatment reduced arborescent plant height on the grassy site where fires were more intense than on the brushy site.

Keywords Brown-spot needle blight · Container seedlings · Diammonium phosphate · Hexazinone · *Mycosphaerella dearnessii* M. E. Barr · *Pinus palustris* P. Mill. · Sethoxydim · Triclopyr

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Introduction

Recovery of longleaf pine (*Pinus palustris* P. Mill.) within its historical range is necessary to arrest the decline of nearly 200 associated taxa of vascular plants and several vertebrate species (Hardin and White 1989; Outcalt and Sheffield 1996; Brockway et al. 1998). In this effort, the establishment of longleaf pine regeneration has often been difficult partly because it develops little above ground for the first 2–9 years as the root system develops (Wahlenberg 1946). Early growth is characterized by a bunch of needles at the soil surface resembling a clump of grass; hence the term "grass stage" to describe the juvenile period. Grass-stage longleaf pine seedlings are vulnerable to competition by brush and seedlings of other pine species, smothering by dead grass and litter, and brown-spot needle blight infection (caused by *Mycosphaerella dearnessii* M. E. Barr.) (Wahlenberg 1946; Croker and Boyer 1975, Kais et al. 1986). Prescribed fire can relieve the longleaf pine seedlings from these stresses and improve seedling survival (Grelen 1983) because grass-stage seedlings tolerate low intensity fires. Once the seedlings have a well developed root collar (about 2.5-cm diameter), they are able to initiate height growth (Wahlenberg 1946). Even after emergence from the grass stage, continued vegetation management may be necessary because brush can still outgrow young longleaf pine seedlings (Haywood 2000; Haywood and Grelen 2000; Haywood et al. 2001). When prescribed fire is used, a series of burns is recommended because the benefits of a single prescribed fire can be transitory (Haywood 1995; Brockway and Outcalt 2000), and an aggressive prescribed fire program over several decades may be required to restore pine-grassland communities (Waldrop et al. 1992).

Although recommended, fire is not a panacea for managing longleaf pine stands. Fire can destroy seedlings during and emerging from the grass stage, and later, the use of fire can adversely affect stand yield and soil properties (Wahlenberg 1946; Bruce 1951; Boyer 1983; Boyer and Miller 1994; Haywood 2002). If land managers are reluctant to use fire because of these or other reasons, an alternative system would be intensive site preparation followed by planting longleaf pine container stock and post-plant vegetation control (Nelson et al. 1985; Barnett 1989; Loveless et al. 1989; Haywood 2000; Ramsey and Jose 2004). Yet, total competition control is not necessary (Nelson et al. 1985); reducing plant cover to about 50% is sufficient to insure early emergence from the grass stage (Haywood 2000).

When plants were controlled, 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 in a factorial design, and two studies were included to show how major differences in competing vegetation might influence treatment responses—the understory of one was dominated by grasses and the other brush. The objectives were to determine how fertilization (Yes or No) in combination with vegetation treatments (check, prescribed fire, and intensive vegetation control) influenced (1) longleaf pine seedling survival and height growth, (2) incidence of brown-spot needle blight, (3) foliar and soil nutrition, and (4) competing plant cover, productivity, and stature. Results pertain to the establishment of longleaf pine on medium textured soils throughout its native range in the southern United States.

Methods

Study sites

The study sites are within the humid, temperate, coastal plain and flatwoods province of the West Gulf Region of the southeastern United States (McNab and Avers 1994). Mean January and July temperatures are 8°C and 28°C, respectively (Louisiana Office of State Climatology 2002). Annual precipitation averages 1525 mm with more than 965 mm during the 250-day growing season, which is from 10 March to 15 November (the late winter and fall dates with a 50% probability of a freeze).

The site for Study 1 was located 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, thermic Plinthaquic Paleudult) and Malbis fine sandy loam (fine-loamy, siliceous, thermic Plinthic Paleudult) complex (Kerr et al. 1980). The water table is high and fluctuates throughout the year because of a fine textured horizon or fragipan that restricts drainage. A natural pine and mixed hardwood forest cover was clearcut harvested in the mid 1980's, and the site was sheared and windrowed in 1991. The low cover of herbaceous and scattered arborescent vegetation that developed after windrowing was prescribed fired in March 1993 and 1996. The vegetation was rotary mowed in late 1996, and the site was open native grassland before plot establishment.

Study 2 was established on two soil complexes on the KNF that are better drained than the Study 1 site. One complex (92°36′ W, 31°6′ N at 55 m above sea level) is comprised of Ruston fine sandy loam (fine-loamy, siliceous, thermic Typic Paleudult), Malbis fine sandy loam, and Gore very fine sandy loam (fine, mixed, thermic Vertic Paleudalf) soils with a slope of 1 to 10% (Kerr et al. 1980). The other complex (92°38′ W, 31°8′ N at 66 m above sea level) is comprised of Beauregard, Malbis, and Gore soils with a slope of 1–5%. A closed-canopy, loblolly pine (*Pinus taeda* L.) and hardwood forest occupied Study 2. Both complexes were clearcut harvested in 1996 and were roller drum chopped and prescribed fired in August 1997. By the third growing season, the six most widely distributed arborescent competitors were eastern baccharis (*Baccharis halimifolia* L.), American beautyberry (*Callicarpa americana* L.), sweetgum (*Liquidambar styraciflua* L.), loblolly pine, winged sumac (*Rhus copallinum* L. var. *latifolia* Engl.), and blackberry (*Rubus* spp.).

Both studies are suitable sites for restoring loamy dry-mesic upland longleaf pine forests (Turner et al. 1999). The Beauregard, Malbis, and Ruston soils have been reported to be deficient in P for growing pine trees (Tiarks 1983; Burton 1984; Haywood and Tiarks 1990), and P probably limits pine growth on the Gore soil as well.

Study establishment

The research plots were established in December 1996 for Study 1 and October 1997 for Study 2. In both studies, six fertilization–vegetation treatment (FERT–VT) combinations were assigned in a randomized complete block factorial design (Steel and Torrie 1980). The 24 research plots per study (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. In Study 1, blocking was based on drainage, and the blocks were established parallel to existing windrows. In Study 2, blocking was based on soil type (two blocks on each soil complex) and topographic location within each complex.

Container-grown longleaf pine seedlings were planted in both studies. Container longleaf pine seedlings are recommended over bareroot seedlings (Barnett 1989), and container seedlings survive better in the first growing season than bareroot stock under drought conditions. Forest Service personnel grew the seedlings using the best current practices (Barnett et al. 2002). For Study 1, the seedlings were started in April 1996 with a Mississippi seed source, and the 48-week-old seedlings were planted in March 1997 using a punch of the correct size for the root plug. For Study 2, the seedlings were started in May 1997 with a Louisiana seed source, and the 28-week-old seedlings were planted in November 1997.

The two fertilization levels per block were as follows: (NF) No fertilizer applied and (F) broadcast 200 kg/ha diammonium phosphate (36 kg/ha N and 40 kg/ha P) in May 1997 in Study 1 and June 1998 in Study 2. The fertilizer rate was based on a preliminary nutrition trial with planted longleaf pine seedlings (Burton 1984). The three vegetation treatments (VT) per block were as follows: Check-no management activities after planting, (PF) Prescribed fire-plots were burned twice with prescribed fire in the first six growing seasons, and (IVM) Intensive vegetation management—herbicides were applied after planting for herbaceous and arborescent plant control, and arborescent re-growth was hand felled. This formed six FERT–VT combinations: NF–check, NF–PF, NF–IVM, F–check, F–PF, and F–IVM.

The first prescribed fire in Study 1 was in May 1998 or 14 months after planting. Consumption of available fuels varied. The F–PF plots burned cleaner and more intensely than the 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 prescribed fire was in May 2000. The available fine fuels were living foliage and 1-h time-lag dead fuels (Haywood 1995), which were sampled before firing on four randomly selected 0.2-m^2 subplots per PF plot. Samples were dried at 80°C for 72 h in a forced-air oven to determine moisture content and ovendried 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, the May-2000 fires consumed 4130 kg/ha of available fine fuels on the NF–PF plots and 4690 kg/ha of fuels on the F–PF plots, and they generated a Byram's fire intensity (Haywood 1995) of 300 kJ/s/m on the NF–PF plots and an intensity of 430 kJ/s/m on the F–PF plots. Such high fire intensities are typical in grass dominated rough (Haywood 2002).

The first prescribed fire in Study 2 was delayed until the third growing season (June 2000) or 31 months after planting because of a lack of grass development and subsequent poor fuel bed conditions. In June 2000, available fine fuels averaged

1440 kg/ha, but only half of the fuel was consumed. A Byram's fire intensity (Haywood 1995) of 60 kJ/s/m was generated across all PF plots. A wildfire in January 2003 burned Blocks 3 and 4, but the longleaf pines survived because this species commonly endures high fire intensities (Haywood 2002). Blocks 1 and 2 were prescribed fired the second time in May 2003. The fires consumed 1224 kg/ha of available fine fuels on the NF–PF plots and 800 kg/ha of fuels on the F–PF plots, and they generated a Byram's fire intensity (Haywood 1995) of 55 kJ/s/m on the NF–PF plots and an intensity of 14 kJ/s/m on the F–PF plots. Such low intensities are within the range recommended for wintertime fuel reduction. Crown scorch averaged 25% on blocks 1 and 2.

In Study 1, the grass sod on the IVM plots was rotary tilled in December 1996 before planting in March 1997. Sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) 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) 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. In Study 2, no tillage was necessary and only hexazinone was banded in April 1998 and 1999 because not enough bluestem grasses were present to require using sethoxydim. For both studies, triclopyr (3,5,6-trichloro-2-pyridinyloxyacetic acid) 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.

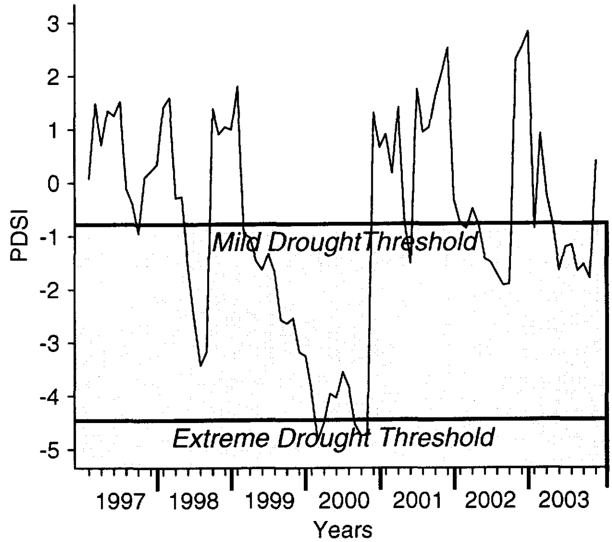
Climatic conditions

Palmer Drought Severity Index (PDSI) values for central Louisiana were obtained from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html, April 2005). Based on PDSI, drought conditions occurred 48% of the time in central Louisiana from 1997 through 2003 (Fig. 1). Study 1 was planted in March 1997, and 1997 was a relatively drought-free year. Study 2 was planted in November 1997, and May through August of the 1998 growing season was in mild to severe drought. Drought conditions again prevailed from February 1999 through October 2000 with conditions becoming severe to extreme during 2000. In 2001, climatic conditions were more normal, but mild to moderate drought conditions redeveloped in 2002 and 2003.

Sampling and chemical analysis

Longleaf pine survival counts and height measurements were taken annually after the first six growing seasons. In Study 1, heights were measured with a calibrated rod to the nearest cm through three growing seasons, and to the nearest 3 cm thereafter. Seedling foliage was examined to determine the extent of brown-spot needle blight to the nearest percent when heights were measured. Herbaceous plant cover within a 0.5-m radius of each longleaf pine seedling was annually estimated to the nearest percent. Cover was quantified as the percentage of the 0.5-m radius circle shaded by herbaceous vegetation when the sun was directly overhead.

Fig. 1 Palmer Drought Severity Index Values (PDSI) for central Louisiana from 1997 through 2003



In Study 2, pine height measurements and brown-spot needle blight estimates were taken after the second through sixth growing seasons because severe drought conditions in 1998 suppressed longleaf seedlings development in the first growing season (Fig. 1). Herbaceous plant cover estimates were taken after the second and third growing seasons.

In both studies, living aboveground herbaceous and woody vegetation in the understory plant community were collected in June 1998 and again in April 2000 on a 0.2-m^2 subplot located in center of each quarter and in the middle of each measurement plot. The aboveground biomass samples were dried at 80°C for 72 h in a forced-air oven to determine ovendried mass. Also in Study 2, competing arborescent plants (trees, shrubs, and blackberry [*Rubus* spp.]) and woody vines were surveyed in April 2000 on five 4-m^2 subplots that were superimposed over the 0.2-m^2 subplots. This survey was done prior to clipping in April 2000; the arborescent plant stems were counted at groundline to determine stocking and heights were recorded. In October 2001, competing arborescent plants and woody vines were inventoried on the 4-m^2 subplots and stocking and heights were recorded in both studies.

The average height of all longleaf pine trees might not be the best indicator of fertilization and vegetation treatment effects because longleaf pines often emerge from the grass stage at different ages, and comparing height of only the emerged trees is not very helpful once the majority of trees have done so (Haywood 2002). Therefore, the longleaf pine population was subdivided into quartiles and heights were compared among the tallest 25%, middle 50%, and shortest 25% of the population.

Samples of the upper 15 cm of mineral soil were collected with a soil probe in August 2003 in Study 1 and in May 2002 in Study 2. Five samples were collected per plot in an "x" pattern, with a sample taken in the center of each quarter and in the middle of each measurement plot at equal distance from the surrounding pine trees. After air-drying, samples were ground in a soil mill and sieved through a 2 mm screen before percent C and N was determined with a LECO CNS-2000 gas analyzer. Mehlich-3 extractable P (mg/kg of soil) was determined with a

Hewlett-Packard 8453 Colorimetric Spectrophotometer. The cmol/kg of soil for Ca, K, Mg, and total cation exchange capacity (CEC) were determined with a Perkin-Elmer 2100 Atomic Absorption Spectrophotometer. The pH of a 10 g soil/20 ml deionized water sample was measured with a Beckman-Coulter pH probe.

Longleaf pine needle samples were collected from current-year flushes in the upper third of the tree crown during January 2003 in Study 1 and January 2004 in Study 2. Samples were taken from five trees per plot. The sample trees were from the upper quartile of the population and they were selected near where the individual soil samples were collected. More than 100 fascicles per 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 the concentration of Ca, K, Mg, and P. The same analytical equipment used for the soil analyses was used for the foliar analyses.

Data analysis

By study, longleaf pine seedling percent survival, percent of longleaf in the grass stage (the seedling was no more than 12 cm tall), total height, percent brown-spot needle blight, and percent herbaceous plant cover were compared between fertilization levels and among vegetation treatments using a repeated measures randomized complete block design model ($\alpha = 0.05$) (SAS Institute Inc. 1985). For stand age (AGE) and interaction-with-age effects, the Huynh-Feldt correction was used in tests of significance. The analyses were done for all longleaf pine and for the tallest 25%, middle 50%, and shortest 25% of the population. Percentages were arcsine transformed before analysis (Steel and Torrie 1980).

By study, competing plant variables were analyzed using a randomized complete block design model ($\alpha = 0.05$) (SAS Institute Inc. 1985)—ovendried mass of herbaceous and arborescent plants and woody vines in June 1998 and April 2000, stocking and total height of arborescent plants in April 2000 (Study 2 only) and October 2001, and stocking of vines in October 2001. Likewise, nutrition variables for soils and longleaf pine foliage were analyzed using a randomized complete block design model ($\alpha = 0.05$) (SAS Institute Inc. 1985). For soils, this was percent C and N; mg/kg of Mehlich-3 extractable P; cmol/kg of Ca, K, Mg, and CEC; and pH. For foliage, this was percent N and g/kg of Ca, K, Mg, and P. Number of stems and nutrition concentrations were logarithmically transformed [Log (Y)] to equalize variances and percentages were arcsine transformed before analysis (Steel and Torrie 1980). For all analyses, if there were significant differences among vegetation treatments, mean comparisons were made using Duncan's Multiple Range Tests ($\alpha = 0.05$).

Results

Longleaf pine survival and disease

In Study 1, longleaf pine survival was similar among all FERT–VT combinations after the first growing season and ranged from 95 to 99% (Fig. 2). Despite planting in the early growing season (March 1997), high survival occurred because container stock was used (Barnett 1989), and moisture conditions were generally normal

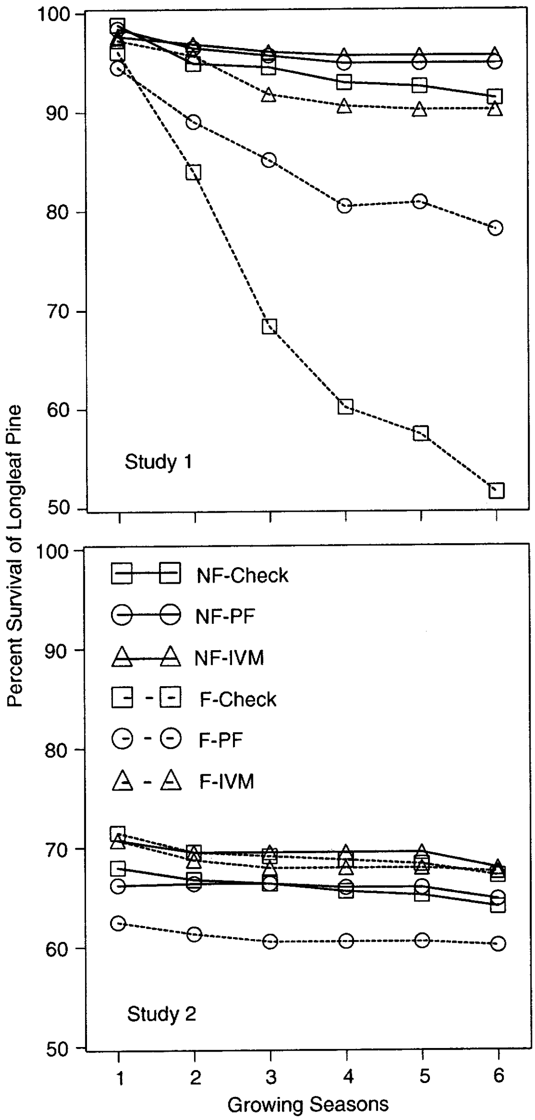


Fig. 2 Percent survival of planted longleaf pines through six growing seasons on two studies in central Louisiana: fertilization levels were F–fertilized and NF–nonfertilized and vegetation treatments were check, prescribed fire (PF), and intensive vegetation management (IVM)

during the first growing season (Fig. 1). However, by the second growing season, survival on the F–check and F–PF plots was lower than on the other four FERT–VT combinations (Fig. 2), which was expressed as a significant AGE-by-FERT-by-VT interaction (Table 1).

In Study 1, fertilization increased herbaceous plant productivity (Table 2), and greater competition coupled with drought during the second growing season (Fig. 1) might have resulted in significantly poorer survival where herbaceous vegetation was not controlled on fertilized plots (Table 1). The IVM treatment reduced competition compared to the check (Table 2) and negated the adverse effect of fertilization, which is why survival was not adversely affected by fertilization on the F–IVM plots (Fig. 2).

Table 1 By study, degrees of freedom, probabilities of a greater *F*-value and error mean squares for percent longleaf pine survival, percentage of pines in the grass stage, total height (m) of all longleaf pine trees from ages 1 through 6 years; and percent competing plant cover for ages 1 through 6 years in Study 1 and ages 2–3 years in Study 2

Sources in the repeated measures analyses	df	$P > F$[a]			
		Pine survival (%)	Grass-stage (%)	Pine total height (m)	Herbaceous plant cover (%)
Study 1					
Block effect	3	0.2044	0.6286	0.6542	0.2394
Fertilization (FERT)	1	<0.0001	0.0345	0.0625	0.0010
Vegetation treatments (VT)	2	0.0033	<0.0001	<0.0001	0.0108
FERT × VT interactions	2	0.0065	0.7328	0.3426	0.0019
Error mean square	15	0.03443[c]	0.05363[c]	0.16064	0.00734[c]
Within subjects[a]					
Stand age (years)	5	<0.0001	<0.0001	<0.0001	<0.0001
Age × blocks	15	0.5457	0.3453	0.7767	0.3637
Age × FERT	5	<0.0001	0.0023	0.0359	<0.0001
Age × VT	10	0.0007	<0.0001	<0.0001	<0.0001
Age × FERT × VT	10	0.0236	0.8981	0.3025	0.0022
Error (time) mean square	75	0.00331[c]	0.00800[c]	0.03108	0.00282[c]
Study 2					
Block effect	3	0.0164	0.0257	<0.0001	<0.0001
FERT	1	0.8634	0.2216	0.3531	0.8632
VT	2	0.1428	0.0008	<0.0001	<0.0001
FERT × VT interactions	2	0.4429	0.2993	0.8929	0.8927
Error mean square	15	0.00120[c]	0.01531[c]	0.17332	0.00749[c]
Within subjects[a]					
Stand age (years)	5[b]	<0.0001	<0.0001	<0.0001	0.0007
Age × blocks	15[b]	0.0046	<0.0001	0.0006	0.3813
Age × FERT	5[b]	0.9821	0.4586	0.4488	0.1691
Age × VT	10[b]	0.0889	<0.0001	<0.0001	<0.0001
Age × FERT × VT	10[b]	0.5809	0.7080	0.8572	0.4274
Error (time) mean square	75[b]	0.00064[c]	0.00385[c]	0.01279	0.00199[c]

[a]For age and interactions-with-age effects, the Huynh–Feldt correction was used in tests of significance

[b]On Site 2, respective degrees of freedom for total height were 4, 12, 4, 8, 8, and 60 and for herbaceous plant cover were 1, 3, 1, 2, 2, and 15 for Stand Age, Age × Blocks, Age × FERT, Age × VT, Age × FERT × VT, and Error (time) mean square sources

[c]Percentages were arcsine transformed before analysis

Table 2 In Study 1, (A) ovendried mass of herbaceous and woody vegetation in the second growing season, total ovendried mass of vegetation in the fourth growing season, stocking and height of arborescent plants and stocking of vines after five growing seasons and (B) degrees of freedom, probabilities of a greater *F*-value and error mean squares from the analyses of variance

Analysis sources/variable values		June 1998			April 2000	October 2001		
		Herbaceous plants (kg ha^{-1})	Arborescent plants and vines (kg ha^{-1})	All competing vegetation (kg ha^{-1})	All competing vegetation (kg ha^{-1})	Arborescent stems (ha^{-1})	Arborescent plant height (m)	Woody vine stems (ha^{-1})
(A)								
Fertilization (FERT)								
No (NF)		1467	85	1552	2653	17751	0.71	17298
Yes (F)		1958	156	2114	2637	23599	1.00	30848
Vegetation treatments[a] *(VT)*								
Check		2820a	209a	3029a	2392b	22796a	1.25a	24094a
PF		530c	60a	590c	2281b	31013a	0.66b	12603a
IVM		1787b	93a	1880b	3263a	8217b	0.66b	35523a
FERT–VT combinations								
NF–Check		2456	204	2660	2762	19522	1.03	18163
NF–PF		592	39	632	2462	28407	0.52	13962
NF–IVM		1353	13	1365	2735	5684	0.59	19769
F–Check		3183	215	3398	2021	26070	1.47	30024
F–PF		468	81	549	2100	33978	0.81	11244
F–IVM		2222	173	2395	3790	10749	0.73	51276
(B)								
Analysis source	*df*	*P > F-value*						
Block effect	3	0.1734	0.5412	0.2755	0.2086	0.0670	0.7651	0.1420
FERT	1	0.0011	0.3589	0.0049	0.9517	0.0421	0.0096	0.3039
VT	2	<0.0001	0.2630	<0.0001	0.0129	0.0012	0.0002	0.4227
FERT × VT interaction	2	0.0091	0.6975	0.0458	0.0283	0.8204	0.4794	0.4427
Error mean square	15	88394.92	33629.1304	174647.23	392646.13	0.34980[b]	0.05778	0.97295[b]

[a] Vegetation treatments are prescribed fire (PF) and intensive vegetation management (IVM): within columns, treatment means followed by the same letter are not significantly different based on the Analysis of Variance and Duncan's Multiple Range Test ($\alpha = 0.05$)

[b] Stocking means were logarithmically transformed [Log (*Y*)] to equalize variances

By the third growing season in Study 1, survival on the F–check plots was poorer than on all others, and continued to decrease through age 6 years (Fig. 2). Survival also decreased on the F–PF plots, while it changed little on the NF–check, NF–PF, NF–IVM, and F–IVM plots. After six growing seasons, survival was 52% on the F–check plots, 78% on the F–PF plots, and averaged 93% on the other four FERT–VT combinations.

In Study 2, longleaf pine survival after the first growing season ranged from 62 to 72% among the FERT–VT combinations (Fig. 2). Drought the first growing season (1998) probably adversely affected survival (Fig. 1). The weakest seedlings most likely died in the first year, because survival was little influenced during the extensive and severe 1999–2000 drought of the second and third growing seasons. Fertilization and the vegetation treatments did not influence survival, but there was a small albeit significant decrease in survival with age (Table 1). After 6 years, survival averaged 65% across Study 2.

In Study 1, percent of brown-spot needle blight differed significantly between fertilization levels and among vegetation treatments, but the percentage of needles infected never averaged more than 4% in a given year on any of the FERT–VT combinations. Although some individual seedlings were severely infected with brown-spot needle blight, the overall low level of infection was too minor to influence stand development (Croker and Boyer 1975). Normally, the incidence of brown-spot needle blight increases over time if longleaf pine is present or nearby (Cordell et al. 1989). Study 1 had longleaf pine present before harvest in the mid 1980's and in the adjacent woodlands, whereas loblolly pine and hardwood forest surrounded Study 2. As a result, brown-spot needle blight was less a factor in Study 2 than in Study 1.

Longleaf pine emergence from the grass stage

In Study 1, 24% of the longleaf pine seedlings emerged from the grass stage after two growing seasons on the IVM plots while the other two vegetation treatments had almost no emergence (Fig. 3). This resulted in a significant AGE-by-VT interaction (Table 1). After three growing seasons, 85% of the seedlings had emerged from the grass stage on the IVM plots, 20% on the PF plots, and 11% on the check plots. These trends continued, and after 6 years, 99% of the longleaf pines had emerged on the IVM plots, 96% on the PF plots, but only 80% on the check plots.

In Study 1, fertilization adversely influenced emergence from the grass stage (Table 1 and Fig. 3). After three growing seasons, emergence averaged 32% on the F plots and 45% on the NF plots. However, after 6 years, there were no significant differences between fertilization levels, which was expressed as a significant AGE-by-FERT interaction (Table 1). Emergence averaged 95% on the NF plots and 89% on the F plots after six growing seasons.

In Study 2, most of the seedlings had emerged from the grass stage by the end of the second growing season (Fig. 3). Emergence occurred although drought conditions were worse in the second growing season than in the first growing season (Fig. 1). Apparently, once the seedlings were established, soil moisture was not limiting height growth despite the drought. In addition, the weakest longleaf pine seedlings likely died in the first growing season and this probably favored a greater percentage-of-emergence among the surviving trees.

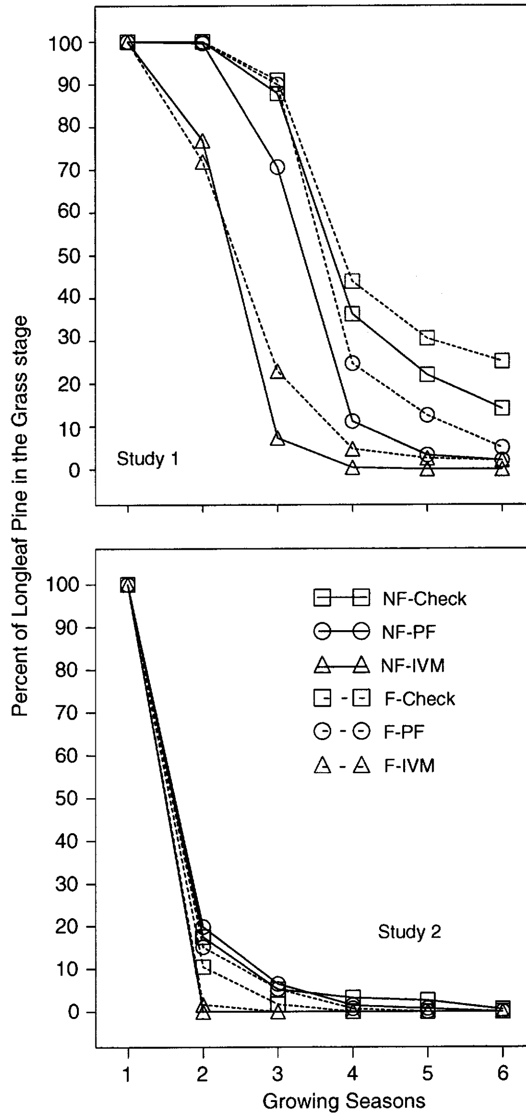


Fig. 3 Percent of longleaf pine in the grass stage through six growing seasons on two studies in central Louisiana: fertilization levels were F–fertilized and NF–nonfertilized and vegetation treatments were check, prescribed fire (PF), and intensive vegetation management (IVM)

Nevertheless, there were significant vegetation treatment differences in Study 2 (Table 1). After 2 years, 99% of the longleaf pines on the IVM plots, 82% on the PF plots, and 86% on the check plots had emerged (Fig. 3). There were no vegetation treatment differences after 6 years, and emergence was nearly 100%. This resulted in a significant AGE-by-VT interaction (Table 1). Fertilization did not significantly influence emergence in Study 2.

Longleaf pine height growth

For all longleaf pine trees in Study 1, VT, AGE, AGE-by-FERT, and AGE-by-VT interactions significantly affected height growth (Table 1). Height was significantly influenced by VT between the first and second growing seasons, but the differences in height were not apparent until after three growing seasons (Fig. 4). After three growing seasons, longleaf pine trees on the IVM plots were 0.5 m tall, while trees averaged 0.1 m tall on the check and PF plots. After 6 years, longleaf pine trees on the IVM plots (3.4 m) were significantly taller than trees on the other two vegetation treatments, and trees on the PF plots (1.8 m) were significantly taller than on the check plots (1.2 m).

In Study 1, fertilization did not significantly influence total height (Table 1). By the fourth growing season, an AGE-by-FERT effect was evident, and these trends continued through six growing seasons (Fig. 4). At age 6 years, the pines were taller on the NF–IVM and NF–PF plots (2.9 m average) than on the F–IVM and F–PF plots (2.4 m average) with no differences between the NF–check and F–check plots (1.2 m average) (Fig. 4).

In Study 1, VT ($P < 0.0001$), AGE ($P < 0.0001$), and an AGE-by-VT interaction ($P < 0.0001$) significantly influenced height of the tallest 25% of the longleaf pine trees, but there was not an AGE-by-FERT effect ($P = 0.1624$) (Fig. 4). After six growing seasons, the tallest 25% of the trees on the IVM plots were 4.6 m tall and averaged 2.8 m tall on the check and PF plots.

In Study 1, trends in total height among the middle 50% of the longleaf pine trees were similar to trends in total height for all trees (Fig. 4). After six growing seasons, middle trees on the IVM plots (3.6 m) were significantly taller than middle trees on the other two vegetation treatments, and middle trees on the PF plots (1.9 m) were significantly taller than trees on the check plots (1.1 m). Fertilization did not significantly affect total height of the middle 50% of the trees ($P = 0.1309$), and the significant AGE-by-FERT effect that occurred among all longleaf pine trees was not evident ($P = 0.1070$).

In Study 1, trends in height growth among the shortest 25% of the longleaf pine trees demonstrated the greatest variation with significant FERT ($P = 0.0019$), VT ($P < 0.0001$), FERT-by-VT ($P = 0.0015$), AGE ($P < 0.0001$), AGE-by-FERT ($P = 0.0002$), AGE-by-VT ($P < 0.0001$), and AGE-by-FERT-by-VT ($P < 0.0001$) responses (Fig. 4). However, this was the subpopulation of trees of least interest.

In Study 2, VT, AGE, and an AGE-by-VT interaction significantly affected height growth of all longleaf pine trees (Table 1). After two growing seasons, trees on the IVM plots averaged 0.7 m tall, while trees averaged 0.4 m tall on the check and PF plots (Fig. 4). These height differences continued to develop, and after six growing seasons, the longleaf pine trees averaged 4.7 m tall on the IVM plots and 3.9 m tall on the check and PF plots. Fertilization did not significantly affect tree height.

In Study 2, the pattern of fertilization and vegetation treatment responses were the same among the tallest 25% of trees as for all longleaf pines (Fig. 4)—VT ($P < 0.0001$), AGE ($P < 0.0001$), and an AGE-by-VT interaction ($P < 0.0001$). The tallest 25% of trees were 5.6-m tall on the IVM plots and averaged 5.2-m tall on the check and PF plots after six growing seasons. In addition, the pattern of fertilization and vegetation treatment responses were the same among the middle 50% and shortest 25% of the trees as for all longleaf pine trees (Fig. 4).

Herbaceous plant cover

In Study 1, herbaceous plant cover was significantly affected by FERT, VT, AGE, FERT-by-VT, AGE-by-FERT, AGE-by-VT, and AGE-by-FERT-by-VT

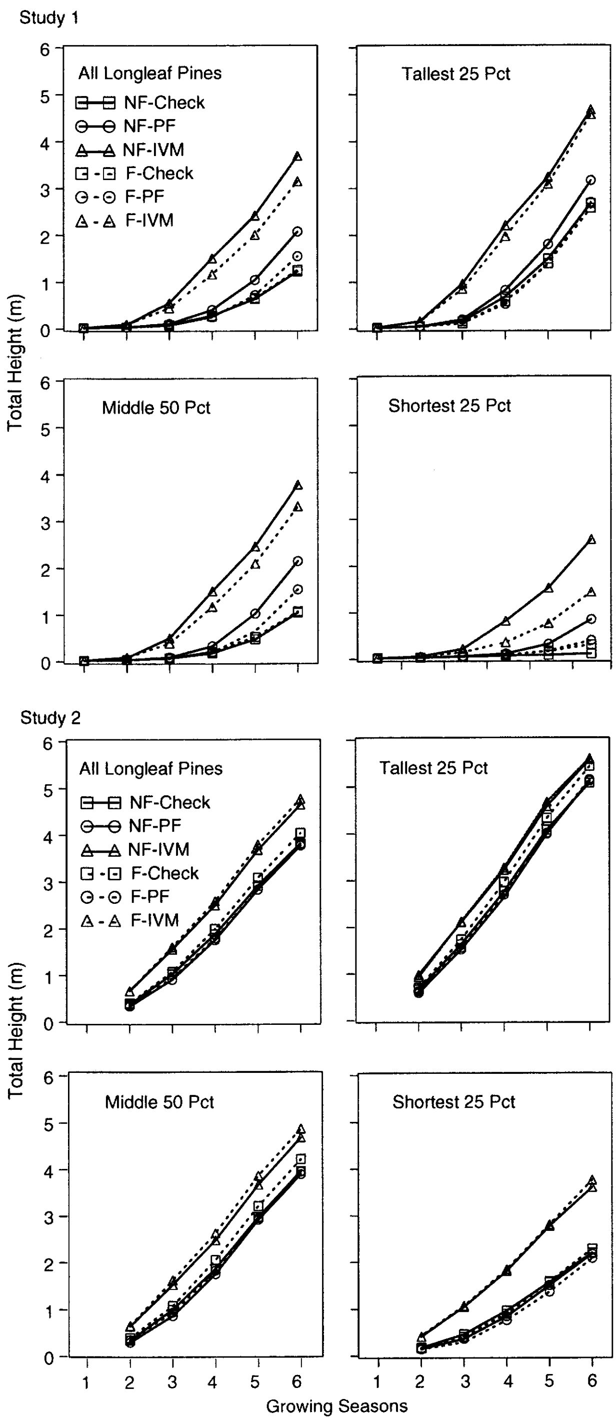


Fig. 4 Total height of longleaf pine trees through six growing seasons on two studies in central Louisiana: fertilization levels were F–fertilized and NF–nonfertilized and vegetation treatments were check, prescribed fire (PF), and intensive vegetation management (IVM)

interactions (Table 1). This variation in responses occurred because the vegetation treatments were not applied every growing season.

In the first growing season in Study 1, the IVM treatments significantly reduced herbaceous plant cover, and the F-IVM plots (40% cover) had more herbage cover than the NF–IVM plots (26% cover) (Fig. 5). The other four FERT–VT combinations had similar cover (88% average).

In the second growing season in Study 1, the first prescribed fire was conducted and the IVM treatments were reapplied. Both PF and IVM significantly reduced herbaceous plant cover (PF 79% and IVM 60% cover) compared to the check (91% cover) (Fig. 5). The IVM treatments were more effective than the PF treatment at reducing herbaceous plant cover within a 0.5-m radius of the pine trees. Over the whole plot, however, PF reduced herbaceous plant productivity more than applying herbicides (530 kg/ha vs. 1787 kg/ha, respectively) because the PF treatment consumed vegetation over the whole plot while the herbicides were applied to a 0.9-m wide strip centered over the rows of planted longleaf pine seedlings (Table 2).

In Study 1, neither herbicides nor fire was applied in the third growing season, and cover estimates ranged from 91 to 94% across all FERT–VT combinations (Fig. 5). The second prescribed fire was applied in the fourth growing season and significantly reduced herbaceous plant cover on the PF plots compared to the other two vegetation treatments (56% vs. 87% on average, respectively). The second fire was more intense than the first fire, and it reduced herbaceous plant cover more than the first fire. The F–check plots (77% cover) had less herbaceous plant cover than did the

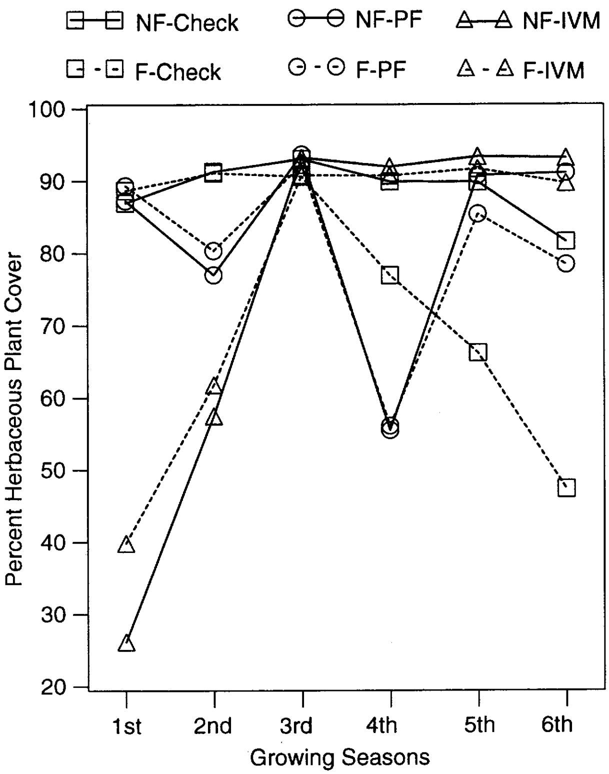


Fig. 5 Percent herbaceous plant cover in Study 1 (the grassy site): fertilization levels were F–fertilized and NF–nonfertilized and vegetation treatments were check, prescribed fire (PF), and intensive vegetation management (IVM)

NF–check, NF–IVM, and F–IVM plots (91% average) after four growing seasons. The F–check plots continued to lose herbaceous plant cover through the sixth growing season as the arborescent vegetation grew taller and shaded the plots (Table 2). By age 6, the F–check plots had 47% herbaceous plant cover, which was significantly less than the other five FERT–VT combinations (87% average) (Fig. 5). The slight decrease in herbage cover between ages 5 and 6 years on the NF–check and F–PF plots occurred because woody vegetation was increasing in stature (Table 2).

In Study 1, the IVM plots by year 5 had the lowest stocking of arborescent plants, and plant stature on the IVM plots was comparable to stature on the PF plots (Table 2). As a result, the IVM plots had 92% herbaceous plant cover at age 6, which was similar to cover on the NF–PF plots (91%)(Fig. 5). Herbaceous plant cover averaged 72% on the F plots and 89% on the NF plots after six growing seasons.

In Study 2, herbaceous plant cover was estimated only in the second and third growing seasons. For these 2 years, VT, AGE, and an AGE-by-VT interaction significantly affected cover (Table 1). The check plots had 73 and 68% cover after the second and third growing seasons, respectively. The prescribed fire applied in the third year reduced herbaceous plant cover from 73% after two growing seasons to 54% after three growing seasons. Herbicide applications stopped in the second growing season, so herbage cover increased from 44% after two growing seasons to 53% after three growing seasons on the IVM plots. After 3 years, the check plots had significantly greater herbaceous plant cover than the PF and IVM plots. Prescribed fire significantly reduced herbage cover in the year of the fire, and stopping the IVM treatments allowed the herbage to recover.

Competing plant productivity and stature

In Study 1, herbaceous plant productivity averaged 1712 kg/ha in the second growing season, whereas arborescent plant productivity averaged only 121 kg/ha (Table 2). As a result, the ovendried mass of all vegetation followed the same pattern as for herbaceous vegetation. Fertilization significantly increased total plant productivity by 36%. Both the PF and IVM treatments significantly reduced total plant productivity. Prescribed fire was more effective at reducing ovendried mass than the IVM treatments because the plots were broadcast burned while the herbicides were applied in 0.9-m strips over the planted rows of pine. However, a significant FERT-by-VT interaction resulted because productivity was greater on the NF–PF plots than on the F–PF plots a month after the first prescribed fire (Table 2), which might reflect the differences in fuel consumption between these two treatment combinations.

During the fourth growing season and before the second prescribed fire in Study 1, the FERT-by-VT interaction nullified a general fertilization effect, and the two fertilization levels had similar production (Table 2). The F–check and F–PF plots produced less total aboveground biomass than the NF–check and NF–PF plots because the increasing stature of arborescent plants on the fertilized plots was beginning to shade out the herbaceous vegetation, and the 0.2-m^2 subplot was too small to collect a representative sample of the overtopping arborescent plants. There was more competing vegetation on the F–IVM plots (3790 kg/ha) than on the other five

FERT–VT combinations (2416 kg/ha average), and the F–IVM plots were probably most productive because the arborescent plants had been controlled leaving the herbaceous plants free to respond to nutrient amendment.

After 5 years, arborescent plant stocking was significantly greater on the F plots compared to the NF plots in Study 1 (Table 2). Among vegetation treatments, stocking was less on the IVM plots (8217 stems/ha) than on the check and PF plots (26,905 stems/ha average). Fertilization significantly increased arborescent plant height, and both PF and IVM significantly reduced arborescent plant height compared to the checks. There were no significant interactions for arborescent plant stocking or height. Woody vines numbered over 24,000/ha, but neither fertilization nor vegetation treatments significantly affected vine stocking.

In Study 2, first year competing plant productivity did not significantly differ between fertilization levels or among vegetation treatments (Table 3). On average, herbaceous plants (2172 kg/ha) comprised 87% of the total ovendried mass sampled. In the third growing season, herbaceous plant productivity averaged 1306 kg/ha, and there were no significant differences between fertilization levels or among treatments.

However, in the third growing season, arborescent plant stocking and heights were significantly affected by vegetation treatment in Study 2 (Table 3). The IVM treatments reduced stocking by 73% and height by 28% compared to the other two vegetation treatments. At the end of the fourth growing season, IVM reduced stocking by 46% and height by 23% compared to the other two vegetation treatments. Prescribed fire had no significant effect on stocking or height 16 months after the fire. After four growing seasons, fertilization significantly increased arborescent plant height by 21%. Woody vine stocking was not significantly affected by fertilization or vegetation treatments.

Soil nutrition

In Study 1, P concentration was 48% greater on the F plots than on the NF plots after six growing seasons (Table 4). Vegetation treatment did not affect P levels, and the P concentration was still well below the estimated sufficiency threshold of 5 ppm for soils on all treatment combinations (Blevins et al. 1996).

In Study 2, concentration of P in the soil was 224% greater on the F plots than on the NF plots 4 years after fertilizer application, and fertilization raised the P concentration above the sufficiency threshold of 5 ppm (Blevins et al. 1996) (Table 4). Vegetation treatment significantly influenced soil P, and the check plots had 46% more soil P than the average for the other two vegetation treatments. The cmol/kg of soil for Ca and K were significantly lower on the F plots than on the NF plots.

There were no VT effects on soil Ca or K in either study (Table 4), and neither fertilization nor vegetation treatment affected the other soil variables in either study. For Study 1, the averages were 5.44 pH, 1.2% C and 0.05% N, 0.38 cmol/kg Mg, and 3.87 cmol/kg CEC. For Study 2, the averages were 5.25 pH, 1.7% C and 0.06% N, 0.30 cmol/kg Mg, and 3.01 cmol/kg CEC.

Foliar nutrition

In Study 1, foliar P concentration on the NF plots was below the sufficiency threshold of 0.8 g/kg, for longleaf pine (Blevins et al. 1996) (Table 5). Fertilization significantly increased foliar P concentration, but the concentration was just at the

Table 3 In Study 2, (A) ovendried mass of herbaceous and woody vegetation in the first growing season, herbaceous ovendried mass and arborescent plant stocking and height in the third and fourth growing seasons, and woody vine stocking in the fourth growing season and (B) degrees of freedom, probabilities of a greater *F*-value, error mean squares from the analyses of variance

Fertilization and vegetation treatments		June 1998			April 2000			October 2001		
						Arborescent plants		Arborescent plants		
		Herbaceous plants (kg ha^{-1})	Arborescent plants and vines (kg ha^{-1})	All competing vegetation (kg ha^{-1})	Herbaceous plants (kg ha^{-1})	Stems (ha^{-1})	Height (m)	Stems (ha^{-1})	Height (m)	Woody vines stems (ha^{-1})
(A)										
Fertilization (FERT)										
No		1818	400	2218	1320	22487	0.53	23064	0.86	15591
Yes		2525	242	2767	1292	32331	0.64	32042	1.04	15490
Vegetation treatments[a] (VT)										
Check		2752a	297a	3049a	1363a	34472a	0.67a	38055a	1.07a	13203a
PF		2298a	483a	2781a	1331a	37932a	0.61a	27121a	0.98a	25276a
IVM		1464a	182a	1646a	1244a	9823b	0.46b	17483b	0.79b	11226a
(B)										
Analysis source	*df*	*P > F-value*								
Block effect	3	0.1035	0.4148	0.0873	0.0057	0.0378	0.2534	0.0393	0.7488	0.0057
FERT	1	0.4349	0.1286	0.5492	0.8599	0.1627	0.0608	0.1000	0.0295	0.5273
VT	2	0.4963	0.0702	0.4182	0.7562	<0.0001	0.0139	0.0005	0.0274	0.1030
FERT × VT interaction	2	0.5490	0.9934	0.5642	0.5944	0.7080	0.8346	0.0986	0.9380	0.8974
Error mean square	15	4651071.6	57892.079	4803854.2	149108.180	0.35737[b]	0.01739	0.25142[b]	0.03478	0.28028[b]

[a] Vegetation treatments are prescribed fire (PF) and intensive vegetation management (IVM); within columns, treatment means followed by the same letter are not significantly different based on Duncan's Multiple Range Tests (α = 0.05)

[b] Stocking means were logarithmically transformed [Log (*Y*)] to equalize variances

Table 4 By study, (A) P concentration and cmol/kg of Ca and K in the surface mineral soil 6 years after fertilization in Study 1 and 4 years after fertilization in Study 2 and (B) degrees of freedom, probabilities of a greater *F*-value, and error mean square from the analyses of variance

		P (mg/kg)	Ca (cmol/kg)	K (cmol/kg)
(A) Study and treatments				
Study 1				
Fertilization (FERT)				
No		1.49	0.93	0.053
Yes		2.20	0.87	0.055
Vegetation treatments[a] (VT)				
Check		1.97a	0.83a	0.057a
PF		1.68a	1.04a	0.053a
IVM		1.88a	0.83a	0.052a
Study 2				
FERT				
No		1.61	1.13	0.066
Yes		5.22	0.82	0.033
VT[a]				
Check		4.32a	1.06a	0.053a
PF		3.24b	0.99a	0.052a
IVM		2.68b	0.88a	0.044a
(B) Degrees of freedom, probabilities of a greater F value, and error mean square				
Analysis source	*df*	*P > F-value*		
Study 1				
Block	3	0.8633	0.1315	0.3662
FERT	1	0.0283	0.4208	0.5739
VT	2	0.7311	0.3560	0.6233
FERT × VT interaction	2	0.3988	0.4683	0.4698
Error mean square	15	0.14747[b]	0.11478[b]	0.09073[b]
Study 2				
Block	3	0.0016	0.0761	0.3337
FERT	1	<0.0001	0.0267	0.0011
VT	2	0.0033	0.5420	0.4048
FERT × VT interaction	2	0.5788	0.5294	0.8387
Error mean square	15	0.04360[b]	0.13451[b]	0.18670[b]

[a] Vegetation treatments are prescribed fire (PF) and intensive vegetation management (IVM); within columns, treatment means followed by the same letter are not significantly different based on Duncan's Multiple Range Tests ($\alpha = 0.05$)

[b] Nutritional variables were logarithmically transformed before analysis

sufficiency threshold after six growing seasons. Foliar P concentration was significantly greater on the PF and IVM plots (0.73 g/kg average) than on the check plots (0.65 g/kg), but there was not a significant FERT-by-VT interaction.

In Study 1, fertilization also significantly increased foliar K concentration by 17%, but the K concentration was above the sufficiency threshold of 3 g/kg without fertilization (Blevins et al. 1996) (Table 5). Percentage of foliar N was significantly greater on the check plots than on the PF plots, and N was intermediate on the IVM plots. Foliar Ca and Mg were not affected by fertilization or vegetation treatment; foliar Ca and Mg averaged 1.5 and 1.2 g/kg, respectively.

In Study 2, fertilization significantly increased the foliar P concentration by 16%, but the concentration was just above the sufficiency threshold of 0.8 g/kg P after six growing seasons (Blevins et al. 1996) (Table 5). Vegetation treatments did not significantly affect foliar N or the concentrations of P, K, Ca, and Mg. Foliar Ca and Mg averaged 1.7 and 0.93 g/kg, respectively.

Table 5 By study, (A) P and K concentrations (g/kg) and percentages of N in the longleaf pine foliage 6 years after fertilization and (B) degrees of freedom, probabilities of a greater *F* value, and error mean square from the analyses of variance

		P (g/kg)	K (g/kg)	N (%)
(A) Study and treatments				
Study 1				
Fertilization (FERT)				
No		0.60	4.49	0.91
Yes		0.80	5.25	0.87
Vegetation treatments[a] (VT)				
Check		0.65b	4.65a	0.92a
PF		0.72a	4.77a	0.85b
IVM		0.74a	5.20a	0.90ab
Study 2				
FERT				
No		0.70	5.65	0.93
Yes		0.81	5.69	0.91
VT[a]				
Check		0.75a	5.55a	0.93a
PF		0.76a	5.97a	0.91a
IVM		0.73a	5.49a	0.92a
(B) Degrees of freedom, probabilities of a greater *F* value, and error mean square				
Analysis source	*df*	*P > F-value*		
Study 1				
Block	3	0.0593	0.0031	0.0160
FERT	1	<0.0001	0.0015	0.0614
VT	2	0.0142	0.0727	0.0387
FERT × VT interaction	2	0.7491	0.4071	0.5536
Error mean square	15	0.007412[b]	0.009842[b]	0.02589[b]
Study 2				
Block	3	0.0007	0.0032	<0.0001
FERT	1	<0.0001	0.7860	0.6033
VT	2	0.3444	0.2019	0.6784
FERT × VT interaction	2	0.5899	0.3756	0.0747
Error mean square	15	0.003101[b]	0.008513[b]	0.02552[b]

[a] Vegetation treatments are prescribed fire (PF) and intensive vegetation management (IVM); within columns, treatment means followed by the same letter are not significantly different based on Duncan's Multiple Range Tests ($\alpha = 0.05$)

[b] Nutritional concentrations were logarithmically transformed and percentages were arcsine transformed before analysis

Discussion

When a site is open grassland or a longleaf pine seed source is not present in the overstory, the best option for reestablishing longleaf pine is removal of the woody vegetation, site preparation, and planting. Through the mid-20th Century, however, land managers had serious problems establishing nursery grown longleaf pine regeneration; so, many managers favored loblolly and slash pine (*P. elliottii* Engelm.) 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; Schmidtling 1987; Outcalt 1993).

Survival was good in the two current studies despite the drought due to planting container stock of good quality (Barnett 1989). Likewise, there was not a disease problem, which likely contributed to the timely initiation of height growth on all treatments (Kais et al. 1986) as well as the strong response to IVM treatments in both studies (Derr 1957).

Intensive vegetation management was the most beneficial treatment in both studies although total plant control was never achieved and competing plant cover was very different between the two studies. In other work, Haywood (2005) found that competition from herbaceous vegetation had a greater adverse effect on longleaf pine height development than competition from arborescent vegetation. In Study 1 (the grassy site), the IVM treatment averaged 46% season-long herbaceous plant cover in the 2 years that herbicides were applied with no residual effect on plant cover (Fig. 5); this supports the position that about 50% plant control early in the rotation is sufficient to boost longleaf pine height growth (Haywood 2000). Prescribed fire reduced herbaceous cover to 77% in the second growing season and 55% in the fourth growing season, which was apparently not sufficient to boost longleaf pine height growth.

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 height although fertilization raised soil P concentrations above the estimated sufficiency threshold of 5 ppm in Study 2 and the foliar concentration of P to the sufficiency threshold of 0.8 g/kg in both studies (Blevins et al. 1996) (Tables 4 and 5). Thus, the fertility amendments recommended in prior studies for these soils deserve reconsideration.

The failure of the seedlings to respond to nutrient amendment might have to do with the 1998 through 2000 drought. Jose et al. (2003) determined that N fertilization shifted C allocation to the seedling shoot with adverse consequences under drought conditions. In addition, fertilization might favor lateral root development, which if detrimental to taproot development, 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. In Study 1, fertilization increased total competing plant productivity in the second growing season and arborescent plant stocking and height by the fifth growing season. In Study 2 (the brushy site), competing plants grew taller on the F plots. The larger plants were probably more competitive for nutrients, water, and sunlight with the planted longleaf pine trees than the shorter plants on the NF plots.

The IVM treatment negated the adverse effect of fertilization on longleaf pine survival (Fig. 2), suggesting that intensive vegetation management might insure better longleaf pine survival on sites inherently richer in nutrients than those studied here (Ramsey et al. 2003). Although survival might be better with plant control, fertilization in combination with either the IVM or PF treatment adversely affected longleaf pine height growth over time in Study 1 (the grassy site) because the adverse effect of more competition on the F plots was greater than the positive effect of plant control (Fig. 4).

Management implications

Two years of vegetation control with herbicides was the best treatment for increasing height growth of planted longleaf pines. Since herbicides are often used in southern US forestry, this option might be broadly accepted where threatened and endangered plants are not growing. However, in later years, needle cast has smothered the herbaceous plants on the IVM plots (Haywood, personal observation), and if pine-grassland habitat is the management objective, fire will have to be introduced at some point (Waldrop et al. 1992) and stocking controlled to arrest the decline in associated herbaceous vegetation. Fortunately, fire can be introduced into sapling size stands without serious longleaf pine mortality, although some loss in post-burn height growth is likely (Haywood 2002). Native fertility is not limiting longleaf pine growth on these sites, and fertilization is probably not worthwhile on similar soils contrary to earlier recommendations.

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