INTENSIVE MANAGEMENT OF LOBLOLLY PINE DURING ESTABLISHMENT INFLUENCES NUTRITION AND PRODUCTIVITY THROUGH 15 GROWING SEASONS

James D. Haywood, Mary Anne Sword Sayer, and Allan E. Tiarks[1]

Abstract—Three cultural treatments in a 2^3 (yes or no) factorial combination were applied during establishment of a loblolly pine (*Pinus taeda* L.) plantation: phosphorus and nitrogen fertilization at planting, herbicide applications in the first 3 years, and litter application in the first year. Both the herbicide and litter treatments reduced loblolly pine survival. After 12 years, foliar phosphorus concentrations were still greater on the fertilized plots (0.98 g/kg) than on nonfertilized plots (0.73 g/kg), and fertilization had increased soil potassium, carbon, and nitrogen concentrations, probably indirect responses to improving the soil environment and changes in the understory plant community. The fertilization and herbicide treatments resulted in taller loblolly pine trees and greater volume per tree throughout 15 years. The litter treatment was ineffective after 15 years, but the fertilization and litter treatment combination resulted in the greatest loblolly pine volume/ha.

INTRODUCTION

Herbicides are widely used for vegetation control in loblolly pine (*Pinus taeda* L.) plantations (Schultz 1997). However, where herbaceous plants are the primary competitors, herbicides are not the only vegetation management method available to reduce competition for light, water, and nutrients on pine planting sites (Haywood 2000). One option is to mulch or to keep forest floor litter relatively intact even after the overstory trees have been harvested. This is possible if litter is allowed to accumulate before harvest, herbicide or mechanical means are used to control the unmerchantable midstory trees and understory vegetation, and postharvest debris is shredded (Koch and McKenzie 1976). This option may be well suited to short-rotation forestry on intensively managed pine sites where possible losses in site productivity (Haywood and Tiarks 1995) could be mitigated by the beneficial retention of soil-covering mulch.

On sites of low fertility, such as those typically found on the West Gulf Coastal Plain, competing vegetation may limit nutrient availability to pine seedlings (Haywood and Tiarks 1990). On such sites, fertilization can result in greater loblolly pine growth (Allen 1987, Gent and others 1986, Haywood and Tiarks 1990, Jokela and others 2000, Schmidtling 1984). Combinations of cultural treatments such as applying herbicides or mulch with fertilizer may further increase seedling productivity.

In this study, fertilizer, litter, and herbicides were applied in a 2^3 (yes and no) factorial combination (Cochran and Cox 1957) in a newly planted loblolly pine stand. We report on loblolly pine growth and yield, foliar nutrition, and soil chemistry through 15 growing seasons.

METHODS

Study Establishment

The study site is located on the Kisatchie National Forest in central Louisiana (long. 92°40' W., lat. 31°10′ N.) at 75 m above sea level. The soil is a gently sloping (1 to 3 percent) Beauregard silt loam (fine-silty, siliceous, thermic Plinthaquic Paleudult) (Kerr and others 1980). The Beauregard soil is phosphorus (P) deficient (Tiarks 1982) and is well suited for forest management (Kerr and others 1980). Drainage is adequate and slope is sufficient so that ponding does not interfere with tree growth. The cover of grasses, forbs, and scattered hardwood and pine seedlings was rotary mowed and treated with herbicides in September 1987 (Haywood and others 2003).

Twenty-four 24.4- by 24.4-m treatment plots were established and grouped into three blocks of eight plots based on subsoil drainage (Haywood and others 1997). Plots were planted in November 1988, with 28-week-old container-grown loblolly pine seedlings using a planting punch of the correct size for the root plug. Each plot contained 10 rows of 10 planted pine trees spaced 2.44 m apart. The central six rows of six planted pine trees was the measurement plot (0.0214 ha).

The three cultural treatments were randomly assigned in each block in a 2^3 factorial randomized complete block design as follows (Cochran and Cox 1957):

Fertilization (F): 135 kg nitrogen (N)/ha and 151 kg P/ha broadcast as diammonium phosphate in March 1988 followed by 42 kg N/ha broadcast as urea in March 1989. The choice and rate of fertilizer were based on recommendations for loblolly pine grown on Beauregard silt loam soils (Tiarks 1982).

Herbicide application (H): annual post-planting applications of herbicides for mostly herbaceous plant control in the first through third growing seasons (1989 to 1991). Hexazinone [1.12 kg active ingredient (a.i.)/ha] and sulfometuron (0.21 kg a.i./ha) were broadcast in April 1989 and 1990. Spot applications of 1 percent glyphosate in aqueous solution were also applied for bluestem grass (*Andropogon* spp. and *Schizachyrium* spp.) control. In April 1991, glyphosate (1.55 kg a.i./ha) and sulfometuron (0.39 kg a.i./ha) were broadcast beneath the loblolly pine limbs followed by felling of volunteer woody competitors > 2.5 cm diameter at breast height (d.b.h.).

[1] Research Forester, Research Plant Physiologist, and Emeritus Research Soil Scientist, respectively, USDA Forest Service, Southern Research Station, Pineville, LA 71360.

Citation for proceedings: Connor, Kristina F., ed. 2006. Proceedings of the 13th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–92. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 640 p.

Litter application (L): After planting, pine litter was broadcast over the plot surface to form a 10- to 15-cm litter layer. Pine litter was reapplied monthly through April 1989 to maintain the 10- to 15-cm depth. After litter application, four 1.25- by 1.25-m sections of the litter layer were randomly sampled from within the central measurement area of each plot. Samples were oven-dried at 70 °C, ground in a Wiley mill, and sieved through a 2-mm screen before determining the concentration of N by gas analysis. An additional sample was digested in acid before determining concentrations of calcium (Ca), potassium (K), magnesium (Mg), and P by spectrophotography. Results showed that we had applied 37 metric tons/ha (oven-dried weight) of litter, and it contained 200 kg N, 11 kg P, 13 kg K, 114 kg Ca, and 23 kg Mg on a per ha basis. Some of the litter was still present in the third growing season.

In the factorial design, the eight treatment combinations were check (no treatment), L, H, LH, F, FL, FH, and FLH.

Measurements and Analyses

Within each measurement plot, we repeatedly measured the total height of all loblolly pines through 12 growing seasons (Haywood and others 2003) and again after 15 growing seasons using a laser instrument. Tree d.b.h. was measured with a diameter tape. Outside-bark volume per tree for ages 10, 12, and 15 years was calculated with Baldwin and Feduccia's (1987) equation.

In January 2001, foliar samples from the upper crown of half of the loblolly pines per plot were collected, and the needles were oven-dried at 70 °C, ground in a Wiley mill, and sieved through a 2-mm screen before determining percent N using a LECO CNS-2000 gas analyzer. An additional prepared sample was digested in acid before quantifying the concentrations of Ca, K, and Mg using a Perkin-Elmer 2100 atomic absorption spectrophotometer and the concentration of P with a Hewlett-Packard 8453 colorimetric spectrophotometer.

Ten soil samples to a 10-cm depth were randomly collected across each plot in 2002. After air-drying, samples were ground in a soil mill and sieved through a 2-mm screen before determining the percentages of C and N; Mehlich-3 extractable P (mg/kg of soil); and cmol/kg of Ca, K, Mg, and total cation exchange capacity using the same equipment as used in the foliar analyses. Soil pH in 10 g of soil/20 ml deionized water sample was measured using a Beckman-Coulter pH probe.

A repeated-measures 2^3 factorial randomized complete block model was used to analyze loblolly pine total height, volume per tree (dm^3/tree) and volume per ha (m^3/ha) at ages 10, 12 and 15 years to determine if changes in loblolly pine development were still occurring in response to the treatments (SAS Institute 1985). Main effects were F, H, and L, and these were considered fixed effects. For the main effects of age and interaction effects of age, the Huynh-Feldt correction was used in tests of significance. In our study, the correction made minuscule differences in the probabilities. A randomized complete block model was used to test treatment effects on the foliar nutrition variables collected after 12 growing seasons, soil pH and nutrition variables collected after 14 growing seasons, and loblolly pine survival after 15 growing seasons. All tests of significance were at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Loblolly Pine Growth and Productivity

Survival was adversely affected by the H and L treatments at the beginning of the study (Haywood and others 1997), and these adverse effects were still significant after 15 years (table 1). However, despite lower average survival on the H and L plots, all treatment combinations were well stocked. After 15 years, survival among the 8 treatment combinations ranged from 73 to 95 percent (1,230 to 1,604 trees/ha) and averaged 87 percent (1,466 trees/ha).

Both the F and H treatments significantly affected loblolly pine height growth (fig. 1). However, the differences in height from ages 10 to 15 years remained similar between the F plots and the non-F (NF) plots and the H plots and the non-H (NH) plots, which resulted in an insignificant age-F and age-H interaction (table 2). After 15 years, trees on the F plots averaged 18 m tall and on the NF plots 16 m tall; trees on the H plots averaged 17 m tall and on the NH plots 16 m. The early height gains associated with the L treatment (Haywood and others 1997, 2003) faded after 15 years (fig. 1), which was expressed as a significant age-L interaction (table 2). Loblolly pine on both the L and non-L (NL) plots averaged 17 m tall after 15 years.

All three main effect treatments had at least some influence on volume per tree (table 2). However, the F and H plots continued to gain volume compared to the NF and NH plots from age 10 to 15 years, which was expressed as significant

Table 1—Percent survival of loblolly pine after 15 growing seasons, degrees of freedom, probabilities of a greater F-value, and error mean square

Treatments	Survival
	percent
Check	95
Herbicide (H)	87
Litter (L)	89
L and H	73
Fertilization (F)	95
F and H	88
F and L	94
F, L, and H	75

Analysis sources	Degrees of freedom	Probabilities of a greater F-value
Block	2	0.9316
F	1	0.4995
L	1	0.0129
H	1	0.0008
Interactions		
F – L	1	0.5983
F – H	1	0.8206
L – H	1	0.1281
F – L – H	1	0.7059
EMS	14	54.1961

EMS = error mean square.

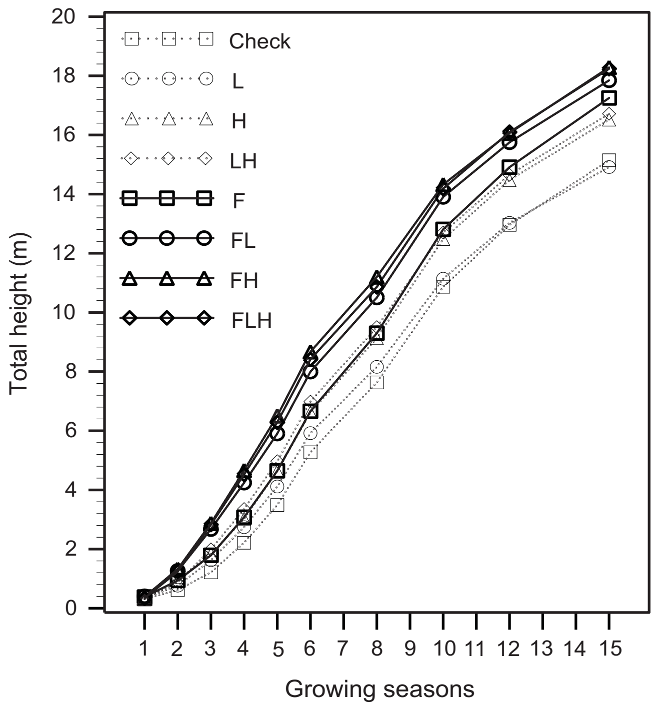

Figure 1—Total height (m) of loblolly pine through 15 growing seasons: Check = no treatment, L = litter, H = herbicides, F = fertilizers were applied.

age-F and age-H interactions. The L plots showed little gain in volume compared to the NL plots over the same period, and as a result there was not a significant age-L interaction. The F, H, and L plots averaged 312, 303, and 284 dm^3/tree; and the NF, NH, and NL plots averaged 232, 241, and 259 dm^3/tree, respectively, after 15 years (table 3).

Loblolly pine volume/ha was influenced by both survival and volume per tree. Although the H treatment reduced survival, the H plots still had significantly more volume/ha than the NH plots (table 2). Litter application also reduced survival, and because it only marginally increased volume per tree, the L treatment had no effect on stand yields after 15 years. Fertilization had the greatest influence on stand yields among the main-effect treatments. The F, H, and L plots averaged 458, 406, and 390 m^3/ha; and the NF, NH, and NL plots averaged 329, 380, and 396 m^3/ha, respectively, after 15 years (table 3). There was an F-H interaction because the H treatment reduced survival on the FH plots; the NF-NH, NF-H, F-NH, and F-H treatment combinations averaged 296, 361, 464, and 451 m^3/ha, respectively, after 15 years. There was also an age-F-H interaction (table 2), because the F-H interaction was only significant between ages 12 and 15 years.

Nutrition

After three growing seasons, we found N dilution in plant tissues as loblolly pine growth responded to fertilization (Sword and others 1998). After 12 years, however, fertilization had

Table 2—Degrees of freedom, probabilities of a greater F-value, and error mean squares for loblolly pine total height, outside bark volume per tree, and volume per ha based on the repeated measures randomized complete block design analyses for ages 10, 12, and 15 years

Analysis sources	Degrees of freedom	Probabilities of a greater F-value[a] Total height	Volume per tree	Volume per ha
		m	*dm^3/stem*	*m^3/ha*
Between subjects				
Block effect	2	0.2860	0.0689	0.1146
Fertilization (F)	1	<0 .0001	<0.0001	<0.0001
Litter (L)	1	0.2577	0.0514	0.9805
Herbicide (H)	1	< 0.0001	0.0002	0.0399
Interactions				
F – L	1	0.5332	0.7572	0.5566
F – H	1	0.0898	0.1559	0.0229
L – H	1	0.4144	0.7354	0.1065
F – L – H	1	0.2450	0.5116	0.2469
Error mean square	14	0.85461	2018.3377	2728.9674
Within subjects				
Stand age (years)	2	<0.0001	<0.0001	<0.0001
Interactions				
Age – Blocks	4	0.0002	0.0005	0.0006
Age – F	2	0.1518	<0.0001	<0.0001
Age – L	2	0.0164	0.4722	0.0839
Age – H	2	0.4272	0.0012	0.7608
Age – F – L	2	0.8594	0.7025	0.7701
Age – F – H	2	0.4581	0.0863	0.0102
Age – L – H	2	0.0063	0.1133	0.9893
Age – F – L – H	2	0.6824	0.7817	0.5613
Error mean square	28	0.01766	46.0567	67.9095

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

Table 3—Least square means for loblolly pine volume per tree and volume per ha after 15 growing seasons

Treatments	Volume per tree	Volume per ha
	dm^3/stem	*m^3/ha*
Check	187	300
Herbicide (H)	252	369
Litter (L)	194	292
L and H	293	354
Fertilization (F)	277	445
F and H	320	471
F and L	304	483
F, L, and H	346	431

no effect on foliar N concentration, suggesting that the direct effect of N amendment on tree growth had subsided between ages 3 and 12 years (table 4). Nevertheless, N nutrition was not the primary factor limiting loblolly pine growth in this study, because foliar N concentrations at ages 3 and 12 years were above the sufficiency level of 11.0 g/kg across all treatments (Allen 1987).

The F treatment significantly increased average foliar P concentration of 3-year-old loblolly pine from 0.9 g/kg to 1.4 g/kg (Sword and others 1998). Unlike foliar N, foliar P concentration continued to be directly affected by P fertilization at planting through 12 years (table 4). The foliar P levels on the NF plots averaged 0.73 g/kg, and those on the F plots averaged 0.98 g/kg, which was still at the sufficiency level of 1.0 g/kg (Allen 1987). Concentrations of Mehlich-3 extractable P in the soil confirmed that after 14 growing seasons, the F plots still had more available soil P than the NF plots (table 5).

Comparison of foliar nutrition at ages 3 and 12 years suggests that the H and F treatments had secondary effects on loblolly pine nutrition and that these effects changed as the stand developed. For example, the H treatment did not affect the foliar P concentration of 3-year-old loblolly pine seedlings (Sword and others 1998), but it significantly increased foliar P concentrations by 7 percent, from 0.83 g/kg to 0.88 g/kg after 12 years (table 4). Although the positive effect of the H treatment on foliar P concentration after 12 years did not result in P sufficiency, this trend suggests that the H treatment influenced site conditions that control loblolly pine foliar P nutrition. As the stand developed, H- and F-induced changes in site conditions also may have resulted in opposing effects on foliar Mg concentration. Specifically, foliar Mg changed from being reduced to being unaffected by the H treatment and from being unaffected to being increased by the F treatment between ages 3 (Sword and others 1998) and 12 years (table 4).

The H treatment also affected soil fertility differently as the stand developed. In the fourth growing season, the H treatment reduced exchangeable K and Mg (Sword and others 1998). After 14 years, however, the H treatment had no effect on exchangeable K and Mg but resulted in significantly less total C by 12 percent, total N by 21 percent, and exchangeable Ca by 27 percent, compared to the NH plots (table 5). However, these reductions in N and Ca supply were not sufficient to affect foliar concentrations of N and Ca.

Table 4—Concentrations of N, P, K, Ca, and Mg in the loblolly pine foliage after 12 growing seasons—degrees of freedom, probabilities of a greater F-value, and error mean squares

Treatments		N	P	K	Ca	Mg
		- - - - - - - - - -	- - - - - - - -	*g/kg*	- - - - - - - -	- - - - - - - - - -
Check		11.9	0.71	3.45	1.56	0.95
Herbicide (H)		11.7	0.74	3.34	1.46	0.92
Litter (L)		12.0	0.69	3.06	1.50	0.91
L and H		11.8	0.78	3.60	1.27	0.94
Fertilization (F)		11.9	0.93	3.53	1.48	1.03
F and H		11.6	0.98	3.55	1.56	0.99
F and L		11.6	0.97	3.80	1.56	1.00
F, L, and H		11.9	1.03	3.87	1.37	0.98
Analysis sources	**Degrees of freedom**	- - - - - - - - - -	- - - - Probabilities	of a greater	F-value - - - -	- - - - - - - - - -
Block	2	0.9844	0.1696	0.0106	0.5335	0.3780
F	1	0.7798	<0.0001	0.0001	0.5932	0.0287
L	1	0.8601	0.1830	0.0890	0.3077	0.5943
H	1	0.8190	0.0042	0.0505	0.2098	0.6607
Interactions						
F – L	1	0.8408	0.2859	0.0111	0.6901	0.9484
F – H	1	0.6940	0.8474	0.2119	0.5348	0.6006
L – H	1	0.6414	0.3407	0.0135	0.2545	0.5869
F – L – H	1	0.5701	0.4736	0.0313	0.7093	0.7247
EMS	14	0.00468	0.00179	0.02268	0.04192	0.00537

N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; EMS = error mean square.

Table 5—Percent of C and N, concentration of Mehlich-3 extractable P, and K, Ca, Mg, and CEC in the soil after 14 growing seasons—degrees of freedom, probabilities of a greater F-value, and error mean squares

Treatments	C	N	P	K	Ca	Mg	CEC
	- - - *percent* - - -		*mg/kg*	- - - - - - - - - - - *cmol/kg* - - - - - - - - - - -			
Check	1.10	0.051	1.56	0.061	0.72	0.28	3.11
Herbicide (H)	0.91	0.041	1.60	0.050	0.52	0.20	2.45
Litter (L)	1.14	0.056	1.71	0.065	0.82	0.34	3.33
L and H	1.01	0.041	1.62	0.054	0.43	0.39	2.38
Fertilization (F)	1.34	0.063	3.28	0.068	0.74	0.38	4.60
F and H	1.19	0.049	8.34	0.073	0.59	0.27	3.86
F and L	1.33	0.062	7.91	0.064	0.89	0.39	4.88
F, L, and H	1.24	0.053	11.07	0.068	0.77	0.28	3.97

Analysis sources	Degrees of freedom	- - - - - - - - Probabilities of a greater F-value			- - - - - - - -			
Block	2	0.5525	0.7747	0.3141	<0.0001	0.7347	0.8951	0.0185
F	1	0.0022	0.0079	0.0094	0.0189	0.1741	0.4648	0.0138
L	1	0.4936	0.4517	0.3639	0.9478	0.3477	0.0674	0.8109
H	1	0.0383	0.0016	0.3260	0.4357	0.0322	0.0919	0.1505
Interactions								
F – L	1	0.7304	0.8967	0.3851	0.3229	0.4124	0.1159	0.9149
F – H	1	0.7597	0.7789	0.3194	0.0780	0.3697	0.1654	0.9838
L – H	1	0.6416	0.9558	0.8049	0.9351	0.6725	0.4121	0.8356
F – L – H	1	0.9483	0.4536	0.8281	0.9699	0.5427	0.3709	0.9584
EMS	14	0.02386	0.00006	24.0868	0.00010	0.04770	0.00682	1.7215

C = carbon; N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; CEC = cation exchange capacity; EMS=error mean square.

Herbicide application during establishment reduced herbaceous and woody competition through the third growing season and herbaceous competition through the eleventh growing season (Haywood and others 1997, 2003). Less competing vegetation and soil C after 14 growing seasons suggested that the H treatment decreased long-term organic matter inputs to the soil from non-pine fine root and foliage turnover. Because organic matter inputs to soil from the forest floor and roots are the primary source of soil N, P, Mg, and Ca (Johnson 1995), we hypothesized that reductions in herbaceous vegetation throughout stand development decreased the supply of N and Ca to the loblolly pine trees.

In contrast, 23 percent more total C, 20 percent more total N, 19 percent more exchangeable K, and 53 percent more cation exchange capacity in the soil were found on the F plots compared to the NF plots after 14 growing seasons (table 5). We attribute this secondary effect of fertilization to greater herbaceous and woody vegetation production, including the planted loblolly pine trees and, subsequently, more organic matter deposition in the soil.

Of particular interest at our study site are trends in foliar and soil K concentrations, as well as among the H, F, and L treatments. After three growing seasons, for example, foliar K was unaffected by the F treatment, averaging 5.4 g/kg across the study site (Sword and others 1998), which is well above the sufficiency value for loblolly pine of 3.5 g/kg (Allen 1987). After 12 years, however, foliar K concentrations were significantly affected by the F treatment (table 4). Specifically, fertilization maintained a sufficient foliar K concentration (3.7 g/kg), while the NF treatment resulted in a foliar K concentration (3.4 g/kg) less than sufficient for optimum loblolly pine growth. As previously stated, we also found that the F treatment significantly increased soil K after 14 years.

After 12 years, neither the L nor H treatments alone affected foliar K levels, but the LH treatment combination improved foliar K so that its concentration was maintained above the sufficiency level of 3.5 g/kg (table 4). Also, only K exhibited a significant response to interactions of the L, H, and F treatments among the foliar mineral nutrients evaluated. Understory vegetation at ages 3 and 10 years was also affected by interactions of the L, H, and F treatments (Haywood and others 1997, 2003). After three growing seasons, for example, herbaceous biomass and the number of hardwood trees and blackberry canes/ha were significantly affected by a two-way interaction between the L and H treatments; and after 10 years, herbaceous biomass/ha was significantly affected by F-L, F-H, and L-H interactions. The K cycle is dominated by hydrologic processes rather than organic matter deposition (Johnson 1995). Therefore, throughfall, interception, and foliar and soil leaching conditions created by the vegetation communities in our study may have controlled the K nutrition of loblolly pine at our study site. Soil pH was unaffected by treatment and averaged 5.3 across the study site (data not shown).

MANAGEMENT RECOMMENDATIONS

Fertilization continues to be the best main-effect treatment in terms of loblolly pine survival, height growth, and volume

(Haywood and others 1997, 2003; table 3). If land managers are able to apply only one treatment, they should fertilize nutritionally deficient silt loam soils. Herbicides were effective in increasing average stem growth, but they were also associated with decreased survival. If comparable survival is expected among treatment options, herbicides are a viable choice, especially on sites where brush is a more important competitor than in this study. Retention of litter becomes less important over time (Haywood and others 1997, 2003; table 2). However, on a fertilized site, litter retention is a no-risk option, and, in fact, among the eight treatment combinations, the FL plots were the most productive (table 3). Therefore, keeping organic matter in place rather than destroying it during harvest, site preparation, and stand establishment is a sound alternative on intensively managed lands.

Fertilization improved the nutritional status of the soil. Increases in P in the foliage and soil were direct effects of fertilization. Other nutritional effects were probably long-term, indirect effects of either modified organic matter deposition to the soil or changes in understory vegetation. A higher level of foliar P among loblolly pines on the F plots was associated with gains in loblolly pine height and volume growth over 15 years (fig. 1, table 3). The benefits from fertilization, however, may not continue. Foliar P levels on the F plots had returned to the sufficiency level of 0.1 percent by growing season 12 (Allen 1987); gains in height from fertilization had also ceased; and 15 years is about as long as a P-fertilizer boost is expected to last (Pritchett and Gooding 1975). If this were a commercial venture, the fertilized stand would need to be thinned and refertilized. The herbicide and litter treatments also affected site quality, often in subtle ways.

LITERATURE CITED

Allen, H.L. 1987. Forest fertilizers nutrient amendment, stand productivity, and environmental impact. Journal of Forestry. 85(2): 37-46.

Baldwin, V.C., Jr.; Feduccia, D.P. 1987. Loblolly pine growth and yield prediction for managed West Gulf plantations. Res. Pap. SO-236. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 27 p.

Cochran, W.G.; Cox, G.M. 1957. Experimental design. 2d ed. New York: John Wiley. 611 p.

Gent, J.A.; Allen, H.L.; Campbell, R.G.; Wells, C.G. 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. Southern Journal of Applied Forestry. 10(3): 124-128.

Haywood, J.D. 2000. Mulch and hexazinone herbicide shorten the time longleaf pine seedlings are in the grass stage and increase height growth. New Forests. 19: 279-290.

Haywood, J.D.; Tiarks, A.E. 1990. Eleventh-year results of fertilization, herbaceous, and woody plant control in a loblolly pine plantation. Southern Journal of Applied Forestry. 14(4): 173-177.

Haywood, J.D.; Tiarks, A.E. 1995. Growth reductions in short-rotation loblolly and slash pines in central Louisiana: 10th year results. In: Edwards, M.B., comp. Proceedings of the eighth biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-1. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 268-274.

Haywood, J.D.; Tiarks, A.E.; Sword, M.A. 1997. Fertilization, weed control, and pine litter influence loblolly pine stem productivity and root development. New Forests. 14: 233-249.

Haywood, J.D.; Goelz, J.C.; Sword Sayer, M.A.; Tiarks, A.E. 2003. Influence of fertilization, weed control, and pine litter on loblolly pine growth and productivity and understory plant development through 12 growing seasons. Canadian Journal of Forest Research. 33: 1974-1982.

Johnson, D.W. 1995. Role of carbon in the cycling of other nutrients in forested ecosystems. In: McFee, W.W.; Kelly, J.M., eds. Carbon forms and functions in forest soils. Madison, WI: Soil Science Society of America: 299-328.

Jokela, E.J.; Wilson, D.S.; Allen, J.E. 2000. Early growth responses of slash and loblolly pine following fertilization and herbaceous weed control treatments at establishment. Southern Journal of Applied Forestry. 24(1): 23-30.

Kerr, A. Jr.; Griffis B.J.; Powell J.W. [and others]. 1980. Soil survey of Rapides Parish, Louisiana. Baton Rouge, LA: U.S. Department of Agriculture, Soil Conservation Service and Forest Service in cooperation with Louisiana State University, Louisiana Agricultural Experiment Station. 86 p.

Koch, P.; McKenzie, D.W. 1976. Machine to harvest slash, brush, and thinnings for fuel and fiber: a concept. Journal of Forestry. 74(12): 809-812.

Pritchett, W.L.; Gooding, J.W. 1975. Fertilizer recommendations for pines in the southeastern coastal plain of the United States. Bulletin 774. Gainesville, FL: University of Florida, Agricultural Experiment Stations, Institute of Food and Agricultural Sciences. 23 p.

SAS Institute, 1985. SAS User's guide: statistics. 5th ed. Cary, NC: SAS Institute. 956 p.

Schmidtling, R.C. 1984. Early intensive culture affects long-term growth of loblolly pine trees. Forest Science. 30(2): 491-498.

Schultz, R.P. 1997. Loblolly pine: the ecology and culture of loblolly pine (*Pinus taeda* L.). Agric. Handb. 713. Washington, DC: U.S. Department of Agriculture, Forest Service: 1-1 to 12-27.

Sword, M.A.; Tiarks, A.E.; Haywood, J.D. 1998. Establishment treatments affect the relationships among nutrition, productivity and competing vegetation of loblolly pine saplings on a Gulf Coastal Plain site. Forest Ecology and Management. 105: 175-188.

Tiarks A.E. 1982. Phosphorus sorption curves for evaluating phosphorus requirements of loblolly pine (*Pinus taeda*). Communications in Soil Science and Plant Analysis. 13(8): 619-631.