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Fertilization, weed control, and pine litter influence loblolly pine stem productivity and root development

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Application. Development of forest plantations may be delayed or yield expectations curtailed by interference from competing vegetation. Competing vegetation can be controlled with herbicides after crop trees are planted, but herbicide use in public and private loblolly pine plantations may face greater restrictions in the future. Fortunately, there are ways to manage competition which can reduce the need for herbicides. These include litter accumulation as a mulch and fertilization. A combination of broadcasting 177 kg N/ha, 151 kg P/ha, and herbicides was the best treatment for increasing average 5-year-old loblolly pine volume and total stand productivity. However, this treatment combination suppressed all other plant communities. This may or may not be desirable depending on the objectives of the forest manager. For example, the maintenance of forest litter (allowing 37 Mg/ha of forest floor material to accumulate before harvest, careful harvesting practices, and post-harvest shredding of debris), followed by fertilization at planting, should be considered if rapid development of all woody vegetation is the manager's goal rather than loblolly pine productivity alone. Fertilization is an option if the manager wishes to initially increase herbaceous plant cover along with rapid development of all woody vegetation. However, each of the three alternatives will result in progressively less loblolly pine productivity in the following order, fertilizer-herbicide > fertilizer-litter > fertilizer only. Litter was clearly less satisfactory than herbicides for controlling weeds.

Abstract. Following site preparation, three cultural treatments and three open-pollinated loblolly pine (*Pinus taeda* L.) families were studied on a gently sloping Beauregard silt loam in central Louisiana. The treatments were: (1) fertilization (either broadcast application of 177 kg N and 151 kg P/ha or none); (2) herbicide application (either broadcast application of herbicides during the first through third growing seasons, and felling of a few, scattered volunteer hardwood trees greater than 2.5 cm dbh during the third growing season or none); and (3) litter application (either broadcast application of 37 Mg/ha (oven-dried weight) of pine straw over the plots to form a 10 to 15 cm layer or none). The subplot treatment was planting stock, where in November 1988, 28-week-old container-grown loblolly pine seedlings from three open-pollinated families were randomly assigned to planting locations.

Through five growing seasons, fertilization and weed control with herbicides resulted in the greatest loblolly pine productivity, but the use of herbicides severely reduced other vegetation. Applying litter, which was less effective than herbicides as a weed control treatment, increased the presence of blackberry (*Rubus* spp.) when herbicides were not applied. Applying litter resulted in a decrease and fertilization resulted in an increase in the number and length of live lateral roots. Soil temperature was reduced by litter application. Treatment responses were not influenced by loblolly pine family.

Introduction

Herbicides are widely used for vegetation management, but they are not the only vegetation management method available to alleviate the effects of competitors on crops. For example, mulches and crop residues are widely used in agriculture and to a lesser extent in forestry throughout the world to suppress weed seed germination and growth, retain moisture, and reduce erosion and sedimentation (Crutchfield et al. 1985, Gupta 1991, Mahajan and Kanwar 1993, Mayhead 1992, McDonald and Helgerson 1990, Sanderson and Cutcliffe 1991, Schroth et al. 1992, Sood and Sharma 1985, Walker and McLaughlin 1989). Although mulching is a costly practice in the southern United States, where this study was conducted, it is practical in other regions of the world where labor costs are low.

Where the application of mulches is cost prohibitive, an alternative on forest sites may be the management of the existing forest floor to keep it relatively intact even when the stand is harvested. This would be possible if litter was allowed to accumulate before harvest, followed by careful harvesting practices, and post-harvest shredding of debris (Koch and McKenzie 1976). This management option may be suited to short rotation intensively managed stands where maximum fiber production for pulp and small sawlogs is the goal.

In new plantations, successional vegetation can eventually deplete soil moisture which adversely affects the water status of loblolly pine (*Pinus taeda* L.) seedlings (Byrne et al. 1987). On nutrient-poor sites successional vegetation may also limit nutrient availability to pine seedlings (Haywood and Tiarks 1990).

Both, herbicides and mulches of synthetic or natural materials reduce successional plant interference (Haywood 1994b, Haywood and Youngquist 199 1, McDonald and Helgerson 1990), and certain soil-active herbicides can be applied over mulch or crop litter to control weeds (Crutchfield et al. 1985). The litter intercepts and retains a portion of the applied herbicide, but the first significant rain after application washes much of the soil-active herbicide into the soil where it is effective (Ghadiri et al. 1984). As a result, weed control may be better when herbicides are applied where litter has been left in place, but many factors influence the relationship between litter and herbicide efficacy.

Fertilization can result in greater root, total height, and diameter growth of loblolly pine (Brissette and Tiarks 1991, Gent et al. 1986, Haywood and Tiarks 1990, Schmidtling 1984). Other cultural treatments such as herbicide application along with fertilization may further increase seedling growth.

In this study, fertilizer, litter, and herbicide application were administered separately and in a 2 by 2 by 2 factorial combination (Cochran and Cox 1957) to determine the growth of loblolly pine under eight vegetation management regimes and the effects of these treatments on soil temperature and successional vegetation. The possibility of a genetics by treatment interaction was evaluated by using three open-pollinated families of loblolly pine as subplot treatments.

Methods

Study area

The study site is a gently sloping Beauregard silt loam (Plinthaquic Paleudult, fine-silty, siliceous, thermic) in central Louisiana at latitude 31° 10' North and longitude 92" 40' West. The elevation is 75 m. Drainage is adequate and slope is sufficient so that ponding does not interfere with tree growth. Pimple or mima mounds are present. These mounds may number 11 per hectare, occupy about 15% of the site, and are better drained and usually more productive than the surrounding soil. To avoid soil differences, the plots were established in the inter-mound areas. Vegetation, consisting of grasses, forbs, and scattered hardwood and pine seedlings and saplings, was rotary mowed and glyphosate[1] was broadcast over the area in September 1987 as a site preparation treatment to reduce the heavy grass rough which had developed on the site over several years.

Plot establishment

Twenty-four (25 by 25 m) treatment plots were established. Plots contained 10 rows of 10 planted pine trees all spaced 2.5 m apart. The central six rows of six trees were the measurement plot. Plots were grouped into 3 blocks of 8 plots each. Blocking was based on drainage inferred from soil color at 50 cm, and a possible fragipan at 15 to 18 cm in Block 2.

[1] The chemical names are hexazinone (3-cyclohexyl-6-[dimethylamino]-1-methyl-1,3,5-triazine-2,4[1H,3H]-dione), sulfometuron (methyl 2-[[[[(4,6-dimethyl-2-pyrimidinyl) amino]carbonyl]amino]sulfonyl]benzoate), and glyphosate (N-[phosphonomethyl]glycine).

Treatments and planting

Following site preparation, two levels each of three cultural treatments (main effects) and three open-pollinated loblolly pine families (subplot effect) were randomly assigned in each block in a 2 by 2 by 2 factorial split-plot, randomized complete block design (Cochran and Cox 1957). The three cultural treatments were:

(1) ***Fertilization:*** None was applied, or 135 kg N and 15 1 kg P/ha were broadcast-applied as diammonium phosphate in March 1988 followed by 42 kg N/ha broadcast-applied as urea in March 1989. This choice and" rate of fertilizer was based on recommendations for loblolly pine grown on Beauregard silt loam soils (Shoulders and Tiarks 1983).

(2) ***Herbicide application:*** None was applied after site preparation, or annual post-plant applications of herbicides in the first through third growing seasons (1989-1991). Hexazinone (1.12 kg/ha) and sulfometuron (0.21 kg/ha) were broadcast-applied in April 1989 and 1990 followed by spot application of 1% glyphosate in aqueous solution. Glyphosate . (1.55 kg/ha) and sulfometuron (0.39 kg/ha) were broadcast applied beneath the loblolly pine limbs followed by felling of a few, scattered volunteer hardwood trees greater than 2.5 cm diameter at breast height (dbh) in April 199 1.

(3) ***Litter application:*** None was applied, or loblolly pine straw taken from a well maintained seed orchard was broadcast-applied over the plot surface to form a 10 to 15 cm litter layer. After planting the loblolly pine seedlings, additional litter from the orchard was applied monthly between December 1988 and April 1989 to maintain a 10-15 cm depth. In April 1989, four sections of the litter layer each measuring 1.25 by 1.25 m were randomly sampled from within the central measurement area of each plot, oven dried, and analyzed using standard methods (Isaac and Kerber 1971, John 1970, Powers et al. 1981). Results indicated that the litter layer weighed 37 Mg/ha (oven-dried weight) and on a hectare equivalent area contained 200 kg N, 11 kg P, 13 kg K, 23 kg Mg, 114 kg Ca, and 1 kg Na.

In the factorial design, the eight main plot treatment combinations were:

C = Check, no treatment after site preparation
H = Herbicide application only
L = Litter application only
HL = Herbicide and litter application
F = Fertilization only
FH = Fertilizer and herbicide application
FL = Fertilizer and litter application
FHL = Fertilizer, herbicide, and litter application

The subplot treatment was planting stock. The three loblolly pine families used in this study were open-pollinated collections from a first generation loblolly seed orchard in central Louisiana, and were phenotypically selected for superior growth and form. Two of the families originated in Natchitoches Parish, Louisiana, and the third family originated in Walker County, Texas. In November 1988, 28-week-old container-grown loblolly pine seedlings from the three families were planted at a 2.5 by 2.5 m spacing in randomly assigned locations throughout each measurement plot. The border trees were from a single family.

Measurements

Total heights of all surviving loblolly pines were measured monthly between January and October 1989; between March and November 1990; in January and then between March and December 1991; in March, June, September, and November 1992; and in March, June, September, and December 1993. In December 1993, dbh measurements were made. Total height and dbh data collected in December 1993 were used to calculate inside-bark volume per tree (Schmitt and Bower 1970).

Mineral soil temperatures were measured hourly at 0, 15 and 30 cm using thermocouples at five randomly chosen locations in each measurement plot of Block 1. The soil profile was accessed through vertical holes, 20 cm in diameter. Thermocouples, constructed of copper-constantan thermocouple wire (20 gauge), were insulated in 3 cm plastic tubing that was caulked with silicone and installed horizontally into the vertical wall of the soil profile at 15 and 30 cm. The access holes were closed. Thermocouples at 0 cm were soldered to the mid-point of an 8 cm piece of copper wire (12 gauge) and placed at the soil surface-litter layer interface.

On each plot of Block 1, drainage pipe (1.3 cm diameter) was lain 5 cm below the soil surface between the five thermocouple locations and a weather resistant enclosure. Thermocouple wires were run through the drainage pipe and wired in parallel at the enclosure using thermocouple blocks equipped with terminal lugs. A swamping resistor (200 Ohm, 2% tolerance) was inserted into one leg of each thermocouple circuit to compensate for unbalanced resistances (Waldren 1985).

From the eight enclosures on Block 1, mean plot temperatures were transmitted through multipair thermocouple extension cable (4-twisted pair, 20 gauge), that was lain in drainage pipe (1.3 cm diameter) 5 cm below the soil surface, to an Easylogger data acquisition unit equipped with a terminal strip multiplexer (Omnidata International, Inc., Logan, UT). Mean temperatures were recorded hourly after software compensation with an external reference junction (Omega 1992).

In May of the third growing season, the vegetation competing with the planted loblolly pines was measured on five 0.004 ha quadrants per plot. Measurements included current-year herbaceous plant production; number of stems, height, and crown spread of trees (no stems were greater than 5 cm dbh), blackberry, and other shrubs; and number of vine stems.

In July and September 1992, loblolly pine lateral roots were quantified in plots that had received herbicide application (H, HL, FH, and FHL). Soil cores, 30 cm deep, were extracted 0.5 m from the stem of each of two randomly selected loblolly pine trees per family using a metal coring device (Ruark 1985). Cores were stored at 4 °C until processing. Loblolly pine lateral roots (≥ 1 cm long) in O-5,5-15 and 15-30 cm core sections were extracted from soil and organic debris by wet sieving with a 1 mm^2 mesh soil sieve. Roots were stored in 15% ethanol at 4 °C until the number of live and dead loblolly pine lateral roots were quantified based on the guidelines of Vogt and Persson (1991). Lengths of live loblolly pine lateral roots were quantified using an image analyzer (Decagon Devices, Inc., Pullman, WA).

Data analysis

For this factorial experiment, analyses of variance (a, = 0.05) were performed for loblolly pine seasonal total height growth and 5th-year loblolly pine survival, total height, dbh, volume per tree, and volume per hectare using a split-plot randomized complete block design model (Cochran and Cox 1957).

For vegetation competing with the planted pines, a randomized complete block design model was used to test main plot effects on the dried weight of herbaceous plants; number of small trees, blackberry, other shrubs, and vines; and total height and crown spread of small trees, blackberry, and other shrubs (Cochran and Cox 1957). A randomized complete block design model was also used to evaluate the effects of fertilization and litter application on loblolly pine fine lateral root number and length per volume of soil by depth. Treatment effects were tested using the residual mean square as the error term. Soil temperatures were measured in one of the three blocks in the study; therefore, no statistical analyses were performed to verify trends in soil temperatures.

Results and discussion

Above-ground loblolly pine growth and yield

During the first and second growing seasons, several treatments significantly affected seasonal changes in loblolly pine total height (figure 1). In the first growing season, the greatest current annual height growth was on the FL plots (38 cm), followed by the FH (32 cm), F (28 cm) and FHL (27 cm) plots. In the second growing season, the greatest current annual height growth was on the FH (122 cm) and FHL (122 cm) plots followed by the FL (100 cm), H (76 cm), and HL (72 cm) plots. Treatment effects on current annual height growth were consistent in the third through fifth growing seasons. After five growing seasons, loblolly pines were tallest on the FH (7.2 m), FHL (7.0 m), and FL (6.6 m) plots.

After five growing seasons, there was a significant interaction between litter and herbicide application on loblolly pine survival, height, and dbh (Table 1). Litter and herbicide application significantly reduced loblolly pine survival by 9 and 13%, respectively. However, their application together decreased pine survival by 2 1%. Partly because of less intraspecific competition, application of both litter and herbicides resulted in taller trees with greater dbh than application of either herbicide or litter alone.

After five growing seasons, loblolly pine tree and stand volumes were significantly affected by interactions among the three cultural treatments (Table 1). In plots that were not fertilized, tree volumes on the HL plots were 23% larger than on the H plots. However, the non-fertilized HL and H plots produced similar stand volumes (an average of 20.4 m^3/ha), because pine survival was only 76% on the HL plots compared to 93% on the H plots. In contrast, on plots that were fertilized, the FHL plots produced 4% less tree volume and 15% less stand volume than the FH plots. Volume difference between the FHL and FH plots was partly caused by an 11 percentage point difference in survival.

The influence of main plot treatments on stand survival clearly affected the outcome of this study and caused interactions among main effects. However,. all main effects independently affected stand productivity, with the application of either fertilizer, herbicides, or litter increasing stand volumes by 156, 160, and 67%, respectively, when compared to the check treatment (Table 1). Litter was clearly less effective than herbicides.

These loblolly pines stands will probably continue to respond to the initial application of phosphorus fertilizer (Haywood and Tiarks 1990). However, phosphorus sufficiency may not continue beyond the 15th growing season (Pritchett and Gooding 1975), when additional fertilization may be needed. Long-term effects of herbicide and litter treatments on tree growth will depend partly on future stand management practices such as early thinning to encourage stem diameter growth. Without thinning, the benefit of weed control may be lost (Haywood and Tiarks 1990).

After five years, survival was similar among the three open-pollinated loblolly pine families ranging from 89 to 9 1%. There were significant growth

1. Loblolly pine percent survival, average height, dbh, inside-bark volume per tree and volume per hectare by treatment combination after five growing seasons.

Treatment combinations	Degress of freedom	Survival	Total height	Dbh	Volume per tree	Volume per ha
		(%)	(m)	(cm)	(dm^3)	(m^3)
Check, no treatment after site preparation		99	4.0	5.2	4.9	7.8
Herbicide (H) application only		93	5.3	7.9	13.7	20.3
Litter (L) application only		94	4.6	6.4	8.5	13.0
H and L application		76	5.6	8.8	16.9	20.6
Fertilization (F) only		loo	5.3	7.9	12.5	20.0
F and H application		91	7.2	11.8	33.1	48.1
F and L application		98	6.6	10.4	24.2	37.9
F, H, and L application		80	7.0	11.6	31.9	40.7
Analyses of Variance						
		All three families (P > F-value)				
Block effect	2	0.456[1/]	0.288	0.645	0.786	0.319
F main effect	1	.497	.0001	.0001	.0001	.0001
L main effect	1	.003	.012	.004	.003	.031
H main effect	1	.0001	.0001	.0001	.0001	.0001
F x L interaction	1	.386	.911	.891	.448	.460
F x H interaction	1	.771	.794	.972	.034	.129
L x H interaction	1	.038	.018	.027	.014	.001
F x L x H interaction	1	.770	.118	.072	.021	.009
Main plot error mean square	14	97.535	5602.0	183.11	25.724	50.385
Family (Fam)	2	.119	.004	.031	.028	.034
F Fam interaction	2	.615	.552	.711	.873	.987
L x Fam interaction	2	.186	.382	.236	.197	.181
H x Fam interaction	2	.476	.997	.605	.535	.272
F x L x Fam interaction	2	.379	.316	.524	.367	.268
F x H x Fam interaction	2	.961	.764	.851	.955	.837
L x H x Fam interaction	2	.778	.282	.182	.176	.084
F x L x H x Fam interaction	2	.887	.554	.546	.269	.327
Subplot error mean square	32	72.361	680.1	43.250	7.060	21.435

[1/] Probabilities are considered significant in determining main and interaction treatment effects at α = 0.05.

and yield differences among the three families, but there were no significant interactions among family and cultural treatments. One of the two families from Natchitoches Parish, Louisiana had the greatest average volume at 19 dm^3 per tree and total stand volume at 27.7 m^3 per hectare. The other family from Natchitoches Parish averaged 18 dm^3 per tree and yielded 26.3 m^3 hectare. The pine family from Walker County, Texas was significantly smaller than the two families from Louisiana, with an average volume per tree of 17 dm^3 and a stand volume of 24.1 m^3 per hectare.

Loblolly pine lateral root growth and soil temperature

The visual separation of pine roots from those of the natural vegetation on this site could not be done accurately. Although the importance of interspecific root competition and its effect on lateral root demography is recognized, lateral root growth was quantified only on plots that were treated with herbicides in this study. Fertilization significantly increased the number and length of live loblolly pine lateral roots in soil cores sampled in July and September 1992 (Table 2). Beauregard silt loam soils are typically nutrient-deficient (Shoulders and Tiarks 1983, Tiarks 1982), so a larger root system and more fine root growth were expected in response to fertilization at planting.

In July 1992, litter application did not significantly affect the occurrence or length of loblolly pine lateral roots as the soil depth increased to 30 cm (Table 2). However, in September, the HL and FHL plots averaged significantly fewer lateral roots of shorter length at the 5-15 cm depth than the H and FH plots indicating that the presence of litter reduced root development at that depth regardless of fertility.

The influence of pine litter application on root distribution was also demonstrated by Bilan (1960) who found that mulching with pine litter caused the roots of 2-year-old loblolly pine to be concentrated in the upper 7.5 cm of non-fertilized soil. Similarly, although not statistically significant, we found that mulching with pine straw increased the number and length of lateral roots in the 0 to 5 cm depth on plots that were not fertilized.

In July 1992, the number of roots in the 0 to 5 cm depth was significantly affected by, an interaction between litter and fertilizer application (Table 2). A similar effect was observed in September 1992 (P = 0.09 18). Litter application on the fertilized plots (FHL) reduced the number of roots in the 0 to 5 cm depth when compared to the FH treatment (Figure 2). This response to litter application was not observed on the non-fertilized plots. At the time this root growth response was observed, trees on the fertilized plots were 43 percent taller than those on plots that were not fertilized (Figure 1).

Soil temperatures at 0, 15, and 30 cm, exhibited similar seasonal trends. In general, soil temperatures were reduced by litter and fertilizer, either applied alone or in combination (Figure 3). However, this effect was only consistently observed on plots that were also treated with herbicides where plant cover was consistently low.

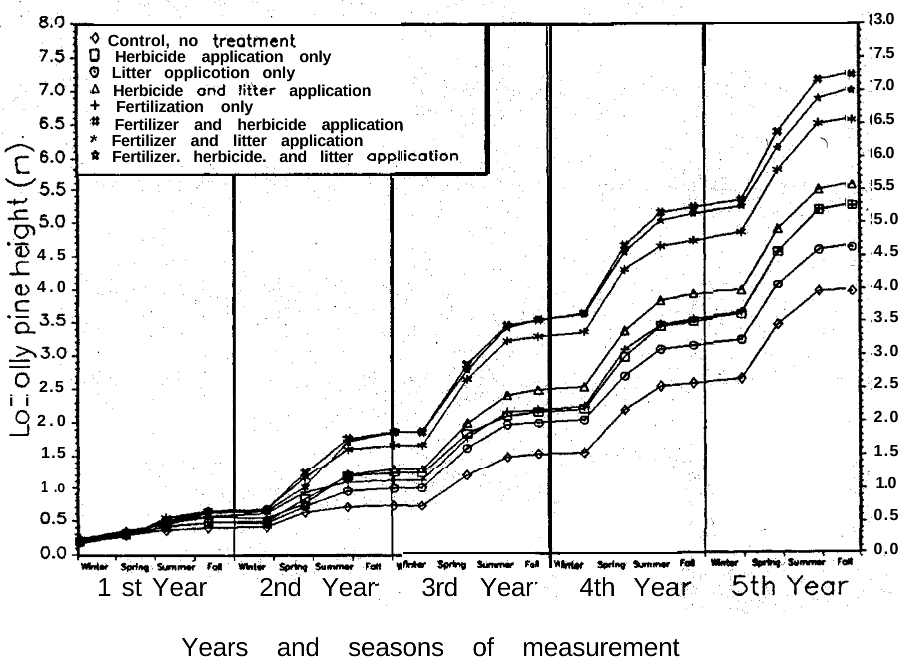

Figure I. Loblolly pine height growth over the first five growing season in response to treatment.

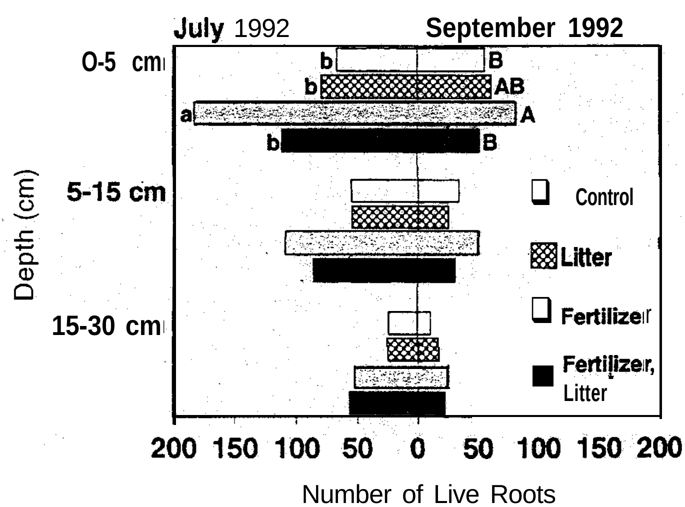

Figure 2. Mean number of live loblolly pine lateral roots per dm^3 in 0–5, 5–15, and 15-30 cm sections of soil cores in response to litter and herbicides. Significant interactions between litter and fertilization were detected at the O-5 cm depth. Within the same month, means associated with different lower and upper case letters at the O-5 cm depth are significantly different at $\alpha = 0.05$ and 0.10, respectively, by the LSD test.

Table 2. Number and length per dm^3 of soil of live loblolly pine lateral roots at O-5, 5-15 and 15–30 cm in July and September 1992 (the fourth growing season) in response to litter and fertilizer application on plots treated with herbicides.

Treatment combinations	Degrees of freedom	July 1992 O-5 cm	July 1992 5–15 cm	July 1992 15–30 cm	September 1992 0–5 cm	September 1992 5-15 cm	September 1992 15-30
Number per dm^3							
Herbicide only		66.6	55.4	24.0	55.6	33.7	10.8
Plus litter (L)		79.4	54.9	25.3	61.1	25.0	17.0
Plus fertilization (F)		182.5	108.9	52.2	82.0	50.6	24.4
Plus F and L		111.5	86.3	56.9	51.4	30.7	21.9
Analyses of variance				(P > F-value)			
Block	2	0.358[1/]	0.079	0.066	0.001	0.024	0.0002
L	1	.147	.222	.713	.237	.013	.617
F	1	.0004	.0001	.0005	.440	.013	.014
L × F	1	.038	.246	.829	.092	.160	.243
Error mean square	66	156.0	141.5	231.4	46.5	40.8	50.0
Length (cm/dm^3)							
Herbicide only		115.7	100.3	42.4	162.4	121.9	33.0
Plus L		146.7	101.6	37.4	241.6	72.8	45.9
Plus F		235.5	197.4	80.3	155.5	161.7	54.9
Plus F and L		175.9	142.6	67.2	182.0	109.2	77.1
Analyses of variance				(P > F-value)			
Block	2	0.443	0.875	0.081	0.246	0.844	0.294
L	1	.566	.193	.423	.076	.005	.100
F	1	.004	.001	.004	.261	.032	.014
L × F	1	.072	.173	.718	.372	.924	.658
Error mean square	66	240.6	660.8	445.8	352.7	495.1	395.7

1/ Probabilities are considered significant in determining main and interaction treatment effects at $\alpha = 0.05$.

A strong positive relationship exists between root-zone temperature and the growth of pine roots (Andersen et al. 1986, Brissette and Chambers 1992, Nambiar et al. 1979, Sword 1996). For example, an increase in root-zone temperature from 18 to 23 °C resulted in a 1.8-fold increase in longleaf pine (*Pinus palustris* Mill.) seedling root growth (Sword 1996). In our study, the reduction in soil temperature caused by mulching may have contributed to the negative effect of litter application on root growth.

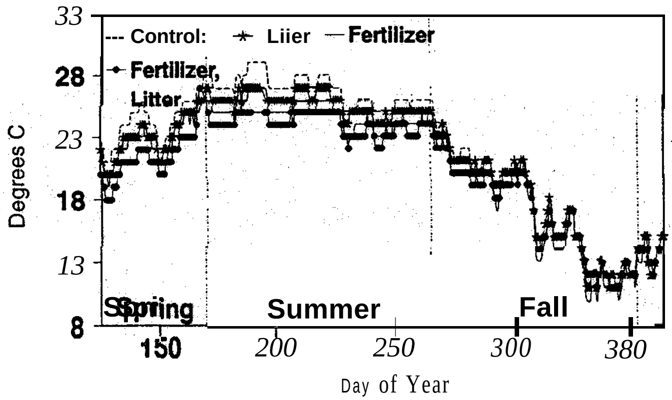

Figure 3. Mean soil temperature at the 30 cm depth on one of three blocks in response to litter and fertilizer application on plots that were treated with herbicides.

Other vegetation-

After three growing seasons, there were significant litter by herbicide interactions affecting both current-year herbaceous plant production and blackberry stocking (Table 3). Both the herbicide and litter treatments reduced herbaceous plant production, but the combination of the two treatments was especially effective. The herbicide treatment reduced the blackberry population, but the litter treatment greatly increased the number of blackberry when herbicides were not applied. The herbicide treatment also significantly reduced the number of shrubs and vines, but the litter and fertilizer treatments had no significant influence on the shrub and vine populations.

These results suggest that less herbicide might be needed for herbaceous plant control on sites with an intact litter layer. As a result, it may be possible to reduce stand establishment costs by minimizing disturbance of the forest floor during harvest and site preparation (Ghadiri et al. 1984).

Interestingly, the stimulation of blackberry growth by litter application corresponded to a reduction in number and length of loblolly pine roots for the July sampling at the 0 to 5 cm depth on the FHL plots (Table 2). The distribution of loblolly pine roots by depth is influenced by competition with other plant species (Fredericksen and Zedaker 1995). In our study, competition between blackberry and loblolly pine roots at the 0 to 5 cm depth may have contributed to the negative effect of litter application on loblolly pine root growth.

Fertilization did not significantly influence herbaceous plant production in the third growing season (Table 3). It was observed that the use of fertilizer greatly increased production in the first two growing seasons (no data collect-

Table 3. Oven-dried weight of current-year herbaceous plant production and number of small hardwood trees, blackberry, other shrubs and vines per hectare after three growing seasons.

Treatment combinations	Degrees of freedom	Oven-dried weight of herbaceous plants	Number per hectare: Hardwood trees	Blackberry	Other Shrubs	Vines
		(kg/ha)	(counts)			
Check, no treatment after site preparation		2,071	3,800	967	4,900	2,517
Herbicide (H) application only		97	567	183	850	3,417
Litter (L) application only		430	2,483	13,767	6,433	9,633
H and L application		17	1,450	83	1,383	2,533
Fertilization (F) only		1,744	950	9,000	4,033	23,200
F and H application		498	650	183	783	1,767
F and L application		492	400	17,817	3,233	10,333
F, H, and L application		91	1,617	1,183	1,217	3,133
			Analyses of variance (P > F-value)			
Block effect	2	0.038[1/]	0.058	0.129	0.811	0.971
F main effect	1	.680	.020	.141	.292	.176
L main effect	1	.0001	.993	.019	.671	.717
H main effect	1	.0001	.080	.0003	.003	.028
F x L interaction	1	.904	.640	.738	.545	.234
F x H interaction	1	.160	.011	.215	.345	.138
L X H interaction	1	.0003	.055	.028	.953	.669
F x L x H interaction	1	.174	.706	.557	.578	.141
Error means square	14	93,608	1,184,449	26,790,194	5,769,985	76,237,917

[1/] Probabilities are considered significant in determining main and interaction treatment effects at $\alpha = 0.05$.

ed). By the third growing season the dead debris was probably suppressing current-year production, as has been the case in other work (Haywood and Thill 1995). Also, the large stature of the loblolly pine saplings on the fertilized plots would have limited light availability at the forest floor by the third year (Figure 1). In addition, fertilization significantly increased the height (0.81 m) and crown spread (1,039 m^2/ha) of blackberry and other shrubs when compared to average height (0.51 m) and crown spread (282 m^2/ha) on non-fertilized plots, thus further limiting the availability ofunderstory light.

There was a herbicide by fertilizer interaction affecting hardwood tree stocking (Table 3). This resulted from large numbers of-hardwoods on the C and L plots with small numbers of hardwoods on the F and FL plots. Light competition on the fertilized plots may have partly caused a reduction in hardwood stocking. Also, greater herbaceous competition in the first two growing seasons might have reduced hardwood development on the fertilized plots (McDonald 1986). Regardless, the high variation in hardwood tree spatial distribution on the site at the beginning of the study, made determining statistical differences difficult.

Conclusions

Fertilization at planting with herbicide applications during the first three growing seasons was the best treatment for increasing loblolly pine height, diameter, volume per tree, and total stand productivity. Since the presence of litter reduced weed cover, there may be less need for herbicides on sites where litter was not destroyed prior to planting pines. However, the presence of a heavy litter layer may modify the growth of roots and their location in the soil.

The use of herbicides to favor pine development will likely suppress the development of all other plant communities on the site. This may or may not be desirable depending on the objectives of the forest landowner. For example, the maintenance of forest litter (allowing the forest floor to accumulate before harvest, careful harvesting practices, and post-harvest shredding of debris) followed by fertilization at planting should be considered if rapid development of all woody vegetation is the management goal rather than principally loblolly pine productivity. Fertilization alone is an option if the management objectives are to at least initially increase herbaceous plant cover along with rapid development of all woody vegetation. However, each of these alternatives will result in progressively less total loblolly pine productivity: fertilizer-herbicide > fertilizer-litter > fertilizer only.

Haywood (1994a) reported growth declines in short-rotation, intensively managed loblolly pine planted on silt loams soils, and the alternatives we tested may also affect the long-term sustainability of loblolly pine plantations. Non-crop vegetation may be important in conserving mineral nutrients by (1) improved extraction and cycling, (2) storage of nutrients in living plants and litter, and (3) nitrogen fixation (Duzan 1994). Since fertilization with or without the litter treatment resulted in the development of non-crop vegetation and acceptable pine productivity, forest manager may want to consider managing successional vegetation rather than trying to eradicate it.

We found that soil temperature was reduced by treatments that produced more cover and shade. Moreover, reduced root growth in response to litter application on FHL plots may have been caused by more aggressive light competition on FHL plots when compared to FH plots. This information suggests that successional vegetation can be manipulated to alter the stand environment and subsequently, above-ground and root growth of young loblolly pine.

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