Influence of fertilization, weed control, and pine litter on loblolly pine growth and productivity and understory plant development through 12 growing seasons

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Abstract: On a silt loam soil in central Louisiana, three cultural treatments were applied to a seedling loblolly pine (*Pinus taeda* L.) plantation. The treatments were in a 2 × 2 × 2 factorial design: (1) no fertilization or a broadcast application of 177 kg N/ha and 151 kg P/ha; (2) no herbicides applied or broadcast or spot applications of hexazinone, sulfometuron methyl, or glyphosate herbicides and felling as required to control competing vegetation during the first three growing seasons; and (3) no litter applied or broadcast application of pine litter to form a 10 to 15 cm layer in the first growing season. Through 12 growing seasons, the fertilization or herbicide treatment significantly increased stand growth (α = 0.05), and these two treatments had an additive effect (no treatments, 209 m^3/ha; fertilization, 328 m^3/ha; herbicide, 280 m^3/ha; fertilization and herbicide, 362 m^3/ha). However, because litter application probably had a minor fertilization effect, the fertilizer and litter combination produced the greatest yield (370 m^3/ha). The herbicide and litter combination adversely affected pine survival, and so applying all three treatments was no more effective than fertilization alone. The loblolly pine overstory was the dominant factor influencing the long-term development of the understory.

Résumé : Trois traitements culturaux ont été appliqués dans une plantation de pins à encens (*Pinus taeda* L.) établie sur un loam limoneux du centre de la Louisiane. Les traitements ont été appliqués selon un dispositif factoriel (2 × 2 × 2) : (1) avec ou sans application à la volée de 177 kg N/ha et 151 kg P/ha; (2) avec ou sans applications à la volée ou localisées d'hexazinone, de méthyle de sulfometuron ou de glyphosate et abattage si requis pour maîtriser la végétation compétitrice pendant les trois premières saisons de croissance; et (3) avec ou sans application à la volée de litière de pin pour former une couche de 10 à 15 cm lors de la première saison de croissance. Pendant 12 saisons de croissance, la fertilisation ou les herbicides ont significativement augmenté la croissance du peuplement (α = 0,05) et ces deux traitements ont eu un effet additif (aucun traitement : 209 m^3/ha, fertilisation : 328 m^3/ha, herbicides : 280 m^3/ha, fertilisation et herbicides : 362 m^3/ha). Cependant, parce que l'application de litière a probablement eu un léger effet fertilisant, la fertilisation combinée à l'application de litière a donné le rendement le plus élevé (370 m^3/ha). Les herbicides combinés à l'application de litière ont eu un effet néfaste sur la survie du pin et, par conséquent, l'application des trois traitements n'était pas plus efficace que la fertilisation seule. Un étage dominant de pin à encens était le facteur dominant dans le développement à long terme du sous-étage.

[Traduit par la Rédaction]

Introduction

Herbicides are widely and successfully used for vegetation control in loblolly pine (*Pinus taeda* L.) plantations (Schultz 1997). However, on sites where herbaceous plants are the primary competitors with planted pine seedlings, herbicides are not the only vegetation management method available to alleviate competition for light, water, and nutrients. One option is to mulch the newly planted seedlings where herbicide use is restricted and labor for continual weeding is scarce. Mulches and crop residues are widely used in agriculture, although to a lesser extent in forestry, throughout the world to suppress weed development, retain moisture, and reduce erosion and sedimentation (Crutchfield et al. 1985; Sood and Sharma 1985; Walker and McLaughlin 1989; McDonald and Helgerson 1990; Gupta 1991; Sanderson and Cutcliffe 1991; Mayhead 1992; Schroth et al. 1992; Mahajan and Kanwar 1993; Haywood 1999, 2000). Although mulching is a costly practice in the southern United States, where we conducted this study, it is a practical treatment in regions of the world with low labor costs.

Where the application of mulches is cost prohibitive, an alternative on forest sites may be to manage forest floor litter so to keep it relatively intact even when the overstory trees are harvested. This would be possible if litter was allowed to accumulate before harvest and herbicide or mechanical means were used to control the midstory or unmerchantable trees and shrubs, followed by careful har-

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vesting practices and post-harvest shredding of debris (Koch and McKenzie 1976). This management option may be well suited to short-rotation forestry on intensively managed pine sites where possible losses in site productivity (Haywood 1994*a*; Haywood and Tiarks 1995; Tiarks and Haywood 1996) could be mitigated by the beneficial retention of a soil-covering mulch.

If necessary, certain soil-active herbicides can be applied over mulch or crop litter to provide additional weed control (Crutchfield et al. 1985). The litter intercepts and retains a portion of the applied herbicides, but the first significant rain after application washes much of the soil-active herbicides, such as hexazinone and sulfometuron methyl, into the soil where they are 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. Efficacies of herbicides that are not soil active, such as glyphosate, are little influenced by surface litter.

On nutrient-poor sites competing vegetation may limit nutrient availability to pine seedlings (Haywood and Tiarks 1990). On these sites, fertilization may result in greater root, total height, and diameter growth of loblolly pine (Schmidtling 1984; Gent et al. 1986; Allen 1987; Haywood and Tiarks 1990; Brissette and Tiarks 1991; Jokela et al. 2000). Other cultural treatments such as herbicide application along with fertilization may further increase seedling growth.

In this study, fertilizer, litter, and herbicide applications were administered in a 2 × 2 × 2 factorial combination (Cochran and Cox 1957), for a total of eight vegetation management regimes, in a newly planted loblolly pine stand. Haywood et al. (1997) and Sword et al. (1998) reported on early results from this study. Another report is warranted, however, because loblolly pine is noted for its rapid rate of growth from seedling to pole size (Schultz 1997), and stand dynamics alter how loblolly pine trees respond to treatments at young ages (Haywood and Tiarks 1990; Zutter and Miller 1998; Jokela et al. 2000). To examine vegetation responses over time, we report how treatments influenced growth of loblolly pine from ages 6 to 12 years, and the effects of treatments on understory vegetation through 11 growing seasons.

Methods

Study area

The study area is within the humid, temperate Coastal Plain and Flatwoods province of the Western Gulf region of the southern United States (McNab and Avers 1994). The climate is subtropical with mean January and July temperatures of 8 and 28 °C, respectively (Louisiana Office of State Climatology 1999). 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 spring and fall dates with a 50% probability of a frost).

The study site, located on the Kisatchie National Forest in central Louisiana (92°40′W, 31°10′N) at 75 m above sea level, is a gently sloping (1% to 3%) Beauregard silt loam (Plinthaquic Paleudult, fine silty, siliceous, thermic) (Kerr et al. 1980). Although it is phosphorus deficient, this soil is best suited for forest management (Tiarks 1982; Shoulders and Tiarks 1983). Drainage is adequate, and slope is sufficient so that ponding does not interfere with tree growth. Pimple or mima mounds of better-drained soil are present. To avoid soil differences, the plots were established in the intermound areas. The vegetation, consisting of grasses, forbs, and scattered hardwood and pine seedlings, was mowed and treated with herbicides in September 1987 (Haywood et al. 1997).

Plot description and planting

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

Treatments

The eight treatment combinations were randomly assigned in each block in a 2 × 2 × 2 factorial randomized complete block design (Cochran and Cox 1957). The three cultural treatments were as follows:

(1) Fertilization: 135 kg 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; Shoulders and Tiarks 1983).

(2) Herbicide application: Annual postplant applications of herbicides for mostly herbaceous plant control in the first through third growing seasons (1989–1991). Hexazinone (1.12 kg/ha) and sulfometuron methyl (0.21 kg/ha) broadcast applied in April 1989 and 1990. Spot applications of 1% glyphosate in aqueous solution were needed to primarily control bluestem grasses (*Andropogon* spp. and *Schizachyrium* spp.). In April 1991, glyphosate (1.55 kg/ha) and sulfometuron methyl (0.39 kg/ha) were broadcast applied beneath the loblolly pine limbs followed by felling of volunteer woody competitors greater than 2.5 cm diameter at breast height (DBH).

(3) Litter application: Pine litter broadcast over the plot surface to form a 10 to 15 cm litter layer. After planting the loblolly pine seedlings, litter was applied monthly between December 1988 and April 1989 to maintain a 10–15 cm depth. After litter application, four 1.25 m × 1.25 m sections of the litter layer were randomly sampled from within the central measurement area of each plot, oven-dried, and analyzed using standard methods (John 1970; Isaac and Kerber 1971; Powers et al. 1981). Results showed that 37 t/ha (ovendried mass) of litter had been applied, and it contained 200 kg N, 11 kg P, 13 kg K, 23 kg Mg, 114 kg Ca, and 1 kg Na on a per hectare basis. Some of the litter was still present in the third growing season.

In the factorial design, the eight treatment combinations were (1) control, no treatment, (2) herbicide application only, (3) litter application only, (4) herbicide and litter application, (5) fertilization only, (6) fertilizer and herbicide application, (7) fertilizer and litter application, and (8) fertilizer, herbicide, and litter application.

Measurements

Within each measurement plot, total height and DBH of all surviving loblolly pines were measured after the 6th, 8th, 10th, and 12th growing seasons. These data were used to calculate outside-bark volume per tree using Baldwin and Feduccia's (1987) equation.

In September of the 11th growing season, understory trees, shrubs, blackberry canes (*Rubus* spp.), and woody vines competing with the planted loblolly pines were inventoried on five 4.0-m^2 subplots per measurement plot. A 4.0-m^2 subplot was placed within the center of each quarter and in the middle of each measurement plot. The inventory included number of stems for trees, shrubs, blackberry canes, and woody vines. Also, total height and mean crown width were measured to the nearest 3 cm for trees, shrubs, and blackberry canes. There were no stems greater than 5 cm DBH.

Within the center of each 4.0-m^2 subplot, a 0.22-m^2 quadrat was established for evaluating herbaceous vegetation. At each quadrat, herbaceous species were inventoried, and the herbaceous vegetation was clipped to groundline, dried at 80 °C, and weighed to determine productivity.

Data analysis

A repeated measures 2 × 2 × 2 randomized complete block design was employed to analyze the data collected at ages 6, 8, 10, and 12 years. Main effects were fertilization, herbicide, and litter, which were all considered fixed. For age and interaction-with-age effects, the Huynh–Feldt correction (Huynh and Feldt 1976) was used in tests of significance. In our case, the correction made miniscule differences in the probabilities (Table 1). All tests of significance were at $\alpha = 0.05$. Analyses were conducted independently for mean tree total height, mean tree volume, and volume per hectare.

For understory vegetation, a randomized complete block design model was used to test treatment effects on the dried mass of herbaceous plants; number of understory trees, shrubs, blackberry canes, and woody vines; and total height and crown width of the trees, shrubs, and blackberry canes during the 11th growing season.

Table 1. Degrees of freedom, probabilities of a greater *F* value, and error mean squares for loblolly pine total height (metres), outside-bark volume (cubic decimetres/stem), and productivity based (cubic metres/stem) on the repeated measures 2 × 2 × 2 factorial randomized complete block design analysis for ages 6, 8, 10, and 12 years.

		P >*F*		
Analysis source	df	Total height	Volume per tree	Volume per hectare
Between subjects				
Block (B)	2	0.950	0.206	0.317
Fertilization (F)	1	0.0001	0.0001	0.0001
Herbicide (H)	1	0.0001	0.0001	0.002
Litter (L)	1	0.071	0.016	0.594
Interactions				
F × H	1	0.394	0.386	0.064
H × L	1	0.088	0.717	0.519
F × L	1	0.425	0.410	0.028
F × H × L	1	0.235	0.417	0.148
Error mean square	14	1.009	1006.238	1427.352
Within subjects*				
Age (A)	3	0.0001	0.0001	0.0001
Interactions				
A × B	6	0.0001	0.003	0.001
A × F	3	0.0001	0.0001	0.0001
A × H	3	0.021	0.0001	0.476
A × L	3	0.011	0.080	0.316
A × F × H	3	0.001	0.015	0.0001
A × H × L	3	0.041	0.490	0.426
A × F × L	3	0.155	0.640	0.692
A × F × H × L	3	0.674	0.857	0.601
Error mean square	42	0.019	65.926	85.412

*For age and interactions-with-age effects, the Huynh–Feldt correction (Huynh and Feldt 1976) was used in tests of significance. In our case, the correction made miniscule differences in the probabilities.

Results

Loblolly pine

Total height

From the 6th through 12th growing seasons, the fertilization and herbicide main effect treatments significantly increased loblolly pine total height (Table 1). Litter application was beneficial at age 6, but was indistinguishable from controls by age 12 (Fig. 1). This loss in effect was expressed as an age × litter interaction (Table 1).

The significant age × herbicide × litter interaction (Table 1) occurred because the litter treatment was losing effectiveness over the 6-year period and the herbicide and litter combination remained as effective as applying herbicides alone (Fig. 1).

Age also influenced the relationship between fertilization and herbicide treatments. The difference in height between the fertilization treatment and controls increased from 1.3 m at age 6 to 1.8 m after 12 growing seasons (Fig. 1). However, the difference in height of trees on the herbicide treatment and controls decreased from 1.5 m at age 6 to 1.4 m after 12 growing seasons. Thus, a significant age × fertilization × herbicide interaction occurred (Table 1), in which the use of herbicides was of greater benefit at age 6, but fertilization was more beneficial by age 10 (Fig. 1).

After 12 growing seasons, trees were taller on the four fertilization treatments than on the four unfertilized treatments (Fig. 1). The three best treatment combinations were fertilization and litter, fertilization and herbicide, and all three main effects together. Total height averaged 16 m among these three treatment combinations.

Volume per tree

Although the gain in volume from applying litter decreased from 8 dm^3/tree at age 6 to 7 dm^3/tree after 12 grow-

Fig. 1. Total height (metres) of loblolly pine from the 6th through 12th growing seasons: control, no treatment; L, litter application only; H, herbicide application only; HL, herbicide and litter application; F, fertilization only; FL, fertilizer and litter application; FH, fertilizer and herbicide application, and FHL, fertilizer, herbicide, and litter application.

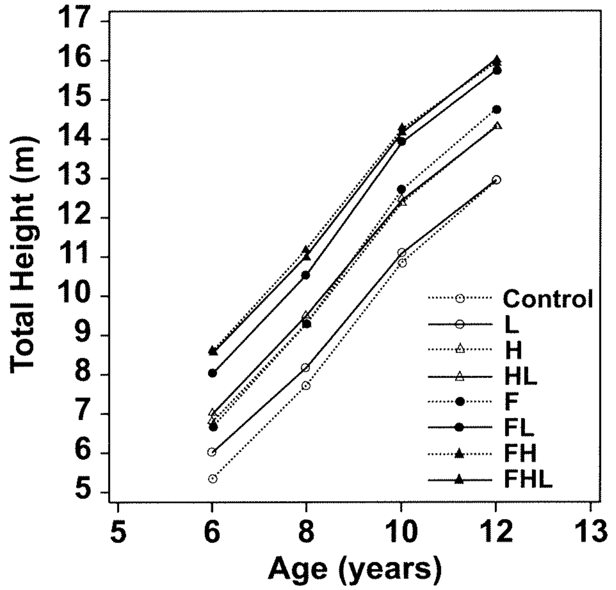
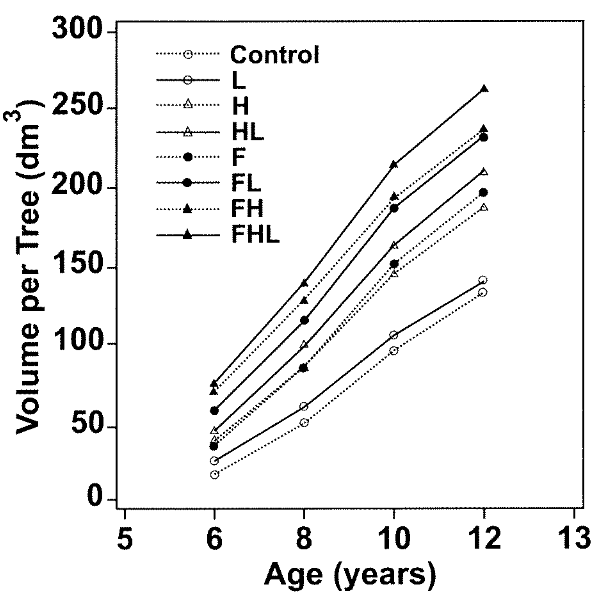


Fig. 2. Outside-bark volume per tree (cubic decimetres) of loblolly pine from the 6th through 12th growing seasons: control, no treatment; L, litter application only; H, herbicide application only; HL, herbicide and litter application; F, fertilization only; FL, fertilizer and litter application; FH, fertilizer and herbicide application; and FHL, fertilizer, herbicide, and litter application.



ing seasons, litter application was still having a positive effect on stem volume (Table 1, Fig. 2). Volume per tree was also significantly affected by the other two main effect treatments, with fertilization having the greatest influence on stem volume by age 12.

Table 2. (A) Loblolly pine survival after 12 growing seasons and (B) degrees of freedom, probabilities of a greater *F* value, and error mean square from the analysis of variance.

(A) Loblolly pine survival.

Treatment	Survival (%)
Control, no treatment	94
Herbicide (H)	89
Litter (L)	90
H and L	76
Fertilization (F)	99
F and H	91
F and L	94
F, H, and L	78

(B) Degrees of freedom, probabilities of a greater *F* value, and error mean square.

Analysis source	df	$P > F$
Block	2	0.823
F	1	0.285
H	1	0.001
L	1	0.005
Interactions		
F × H	1	0.454
F × L	1	0.801
H × L	1	0.094
F × H × L	1	0.933
Error mean square	14	131.862

A significant age × fertilization × herbicide interaction occurred because the use of herbicides resulted in more volume per tree at age 6, but fertilization was more beneficial by age 10 (Table 1, Fig. 2). As with total height, volume per tree was best on the fertilizer and litter, fertilizer and herbicide, and fertilizer, herbicide, and litter treatments. However, since litter was still having a positive effect on volume at age 12, stem volume was greatest when all three treatments were applied.

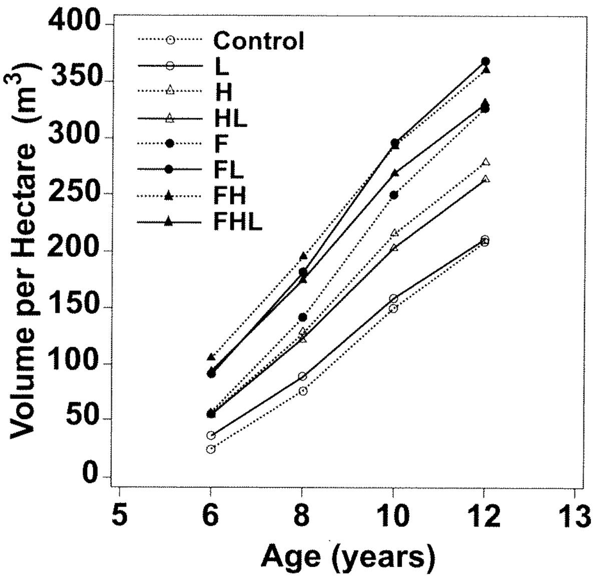
Survival and volume per hectare

Overall survival of planted loblolly pine trees was 89% after 12 growing seasons (Table 2), which decreased only slightly from the 91% survival rate after five growing seasons (Haywood et al. 1997). Fertilization did not influence survival. Both the litter and herbicide treatments resulted in a significant reduction in survival. Most importantly, the two treatments together had an additive adverse effect, and survival averaged 76% when both treatments were applied.

The fertilization and herbicide main effect treatments significantly increased loblolly pine volume per hectare (Table 1). By age 8, all four of the fertilized treatments were more productive than the four nonfertilized treatments, and the influence of fertilization on productivity continued to increase through age 12, which was expressed as a significant age × fertilization interaction (Table 1, Fig. 3).

There were differences in how the herbicide and litter applications influenced volume per hectare that were not solely due to the adverse effect of these two treatments on survival, which was expressed as a herbicide × litter interaction (Ta-

Fig. 3. Outside-bark volume per hectare (cubic metres) of loblolly pine from the 6th through 12th growing seasons: control, no treatment; L, litter application only; H, herbicide application only; HL, herbicide and litter application; F, fertilization only; FL, fertilizer and litter application; FH, fertilizer and herbicide application; and FHL, fertilizer, herbicide, and litter application.



ble 1). At age 6, applying only litter increased pine volume but litter alone was not effective after 12 growing seasons; litter no longer demonstrated a residual weed control effect (Haywood 1999, 2000) (Fig. 3). As a result, herbicide application by age 12 was more beneficial than the herbicide–litter treatment combination. On the fertilized plots, 6-year-old loblolly pine was more productive on the herbicide treatment than if litter was applied. By age 10, however, this relationship was reversed, and after 12 growing seasons, the fertilized–litter plots had slightly more volume than the fertilized–herbicide plots.

There was an age × fertilization × herbicide interaction affecting pine yield (Table 1). At age 6, loblolly pine productivity was nearly twice as much on the fertilized–herbicide plots than if only a single treatment was applied, and the fertilized-only and herbicide-only plots had similar volumes (Fig. 3). After 12 growing seasons, loblolly pine productivity was greater on the two fertilized treatments than on the two nonfertilized treatments, but volume was still greatest on the fertilized–herbicide plots.

The two best treatments were the fertilizer–herbicide and fertilizer–litter combinations, which averaged 366 m^3/ha after 12 growing seasons (Fig. 3). The litter and herbicide combination resulted in the poorest survival (Table 2), and the fertilizer–herbicide–litter combination had a yield similar to that of applying only fertilizer (Fig. 3). These two treatments averaged 330 m^3/ha after 12 growing seasons.

Understory vegetation

After 11 growing seasons, understory trees averaged 1967 stems/ha across all treatments. There were no statistical differences among treatments for number of tree stems, mean total tree height, or mean tree crown width (Table 3).

Number of shrubs per hectare and stature were significantly less on plots treated with herbicides, although these chemicals were primarily used to control herbaceous vegetation in the first three growing seasons (Table 3). On the herbicide-treated plots, the number of shrubs was 4448 stems/ha, with stature averaging 0.5 m and a crown width of 0.3 m, and on the untreated plots the number of shrubs was 10 705 stems/ha, with stature averaging 0.8 m and a crown width of 0.4 m.

The dried mass of herbaceous vegetation averaged only 29 kg/ha after 11 growing seasons across all treatments (Table 4). In the third growing season, this site produced 680 kg/ha of herbage (Haywood et al. 1997). Despite the general decrease in herbaceous plant production, the litter-treated plots produced significantly more herbage than the untreated plots. Also, litter application was associated with the greatest herbaceous plant production when neither fertilizer nor herbicides were applied.

Conversely, the herbicide-treated plots produced significantly less herbage than the untreated plots. Herbicides had the greatest adverse effect on herbaceous plant production when either applied with fertilizer or without the application of litter.

There were significantly more blackberry canes on the unfertilized plots than on the fertilized plots (Table 4). Unfertilized canes numbered 6383 stems/ha and were 0.8 m tall with a crown width of 0.3 m. Fertilized canes numbered 1281 stems/ha and were 0.4 m tall with a crown width of 0.2 m. Woody vines numbered 7331 stems/ha after 11 growing seasons with no statistical differences among treatments.

After 11 growing seasons, the most common and widely distributed understory plants were shrubs, specifically waxmyrtle or southern bayberry (*Myrica cerifera* L.), shining sumac (*Rhus copallina* L.), Elliott's blueberry (*Vaccinium elliottii* Chapm.), and arrowwood (*Viburnum dentatum* L.). The most common and widely distributed trees and woody vines were blackgum (*Nyssa sylvatica* Marsh.), water oak (*Quercus nigra* L.), Carolina jessamine (*Gelsemium sempervirens* (L.) Ait. f.), Japanese honeysuckle (*Lonicera japonica* Thunb.), cat greenbrier (*Smilax glauca* Walt.), small greenbrier (*Smilax smallii* Morong.), and poison-oak (*Toxicodendron toxicarium* (Salisb.) Gillis). Blackberry canes were also common. No herbaceous plants were common enough on any of the treatments to remark upon.

Discussion

Loblolly pine

The application of fertilizers was the most beneficial treatment through 12 growing seasons whether applied alone or in combination with other treatments, a finding supported by Jokela et al. (2000). Allen (1987) reported that ameliorating phosphorus deficiencies at time of planting might elevate site indices by 2.5 to 4.5 m or more at 25 years of age. These sustained responses from a single phosphorus application are possible on nutrient-deficient soils because the applied phosphorus becomes a significant part of the site's total phosphorus capital, and thus phosphorus availability can remain elevated for decades.

Table 3. (A) Least-square means for the number of stems, mean height, and crown width of understory trees and shrubs after 11 growing seasons and (B) degrees of freedom, probabilities of a greater F value, and error mean squares from the analysis of variance.

(A) Least-square means.

	No. of stems (ha^{-1})		Height (m)		Crown width (m)	
Treatment	Trees	Shrubs	Trees	Shrubs	Trees	Shrubs
Control, no treatment	1977	9 225	2.9	0.9	1.5	0.46
Herbicide (H)	30	7 084	0.5	0.4	0.3	0.24
Litter (L)	2142	12 026	1.7	0.8	1.1	0.45
H and L	859	5 107	3.0	0.6	1.7	0.31
Fertilization (F)	1483	15 814	1.1	0.9	0.6	0.46
F and H	5581	2 306	0.1	0.3	0.1	0.19
F and L	1687	5 754	1.9	0.6	1.1	0.33
F, H, and L	1977	3 295	0.6	0.4	0.4	0.29

(B) Degrees of freedom, probabilities of a greater F value, and error mean squares.

		$P > F$*					
		No. of stems		Height		Crown width	
Analysis source	df	Trees	Shrubs	Trees	Shrubs	Trees	Shrubs
Block	2	0.4271	0.8227	0.3668	0.2103	0.4000	0.2016
F	1	0.3880	0.2074	0.2023	0.2371	0.2366	0.4298
H	1	0.9684	0.0033	0.3123	0.0029	0.3506	0.0088
L	1	0.9255	0.6903	0.4407	0.8670	0.3840	0.8525
Interactions							
F × L	1	0.5674	0.5816	0.9995	0.6702	0.9557	0.6973
F × H	1	0.3409	0.1456	0.7151	0.8306	0.6823	0.8219
L × H	1	0.7945	0.5987	0.2810	0.1151	0.4257	0.1752
F × L × H	1	0.5818	0.1519	0.2773	0.8966	0.3257	0.5289
Error means square	14	0.7941†	0.3857†	2.2780	0.0531	0.8061	0.0159

*Probabilities are significant in determining main and interaction treatment effects at $\alpha = 0.05$.
†Number of stems per hectare was logarithmically transformed before analysis.

Tiarks (1983) reported that phosphorus fertilization on a Beauregard soil caused significant gains in slash pine (*Pinus elliottii* Engelm. var. *elliottii*) stand yields through at least 13 growing seasons. On a Malbis sandy loam soil in northern Louisiana, phosphorus fertilization resulted in greater individual volumes for 11-year-old loblolly pines, but fertilization did not increase total stand yields (Haywood and Tiarks 1990). Similarly, Haywood and Burton (1990) reported that phosphorus fertilization at planting increased the mean size of 12-year-old loblolly pine across five distinct subsoil textures, but total stand yield was confounded by the effect of soil type on stand survival as well as the quality of site preparation.

Some of the original applied litter was still present in the third growing season providing some benefit to the loblolly pine trees (Haywood et al. 1997). Once the pines in our study developed enough crown to begin shedding sufficient amounts of dead needles, the trees were mulching themselves on a yearly basis, masking any residual weed-control effect (Haywood 1999, 2000) by the 12th growing season.

The herbicide and litter combination in this study was less successful than herbicides alone because the litter no longer demonstrated a residual weed control effect and these two treatments together resulted in the lowest survival. Although we anticipated some chemical injury, the sharp reduction in survival on the herbicide and litter plots was surprising. However, litter reduced soil temperature and root growth (Haywood et al. 1997), and less root development when herbicides were applied may have resulted in more pine seedling injury than anticipated.

Of greater interest were the high pine yields when both fertilizer and litter were applied. These results suggested that the fertility effect of adding litter was insufficient to overcome the inherent nutrition deficiency common on Beauregard silt loam sites (Tiarks 1982; Shoulders and Tiarks 1983). However, the fertilizer application was able to overcome these deficiencies, and perhaps the litter provided a further slow-release fertilization effect.

Herbicide applications primarily for the control of herbaceous vegetation in the first three growing seasons after planting effectively increased individual loblolly pine size and stand productivity. In another 10-year-old stand of loblolly pine planted on a different grass-dominated Beauregard silt loam site, herbaceous weed control was also shown to increase loblolly pine stature and volume per hectare (Haywood 1994*b*). On a Malbis sandy loam soil in northern Louisiana, herbaceous weed control resulted in greater loblolly pine volume per hectare through 11 growing seasons, but the pine trees were of similar size on the weeded and unweeded plots, and the important difference was stand stocking (Haywood and Tiarks 1990). In our present study, herbaceous weed control was associated with

Table 4. (A) Least-square means for the ovendried mass of herbaceous plants and number of understory blackberry canes and woody vines after 11 growing seasons and (B) degrees of freedom, probabilities of a greater *F* value, and error mean squares from the analysis of variance.

(A) Least-square means.

Treatment	Dried mass of herbaceous plants (kg/ha)	No. of blackberry canes (ha^{-1})	No. of woody vines (ha^{-1})
Control, no treatment	4	4 118	7 248
Herbicide (H)	12	4 942	7 248
Litter (L)	89	11 531	7 248
H and L	41	4 942	7 577
Fertilization (F)	36	1 855	7 248
F and H	4	988	2 800
F and L	42	988	16 638
F, H, and L	5	1 290	2 636
Significant two-way interactions			
F × L			
No F and no L	8		
No F but L	65		
F but no L	20		
F and L	24		
H × L			
No L and no H	20		
No L but H	8		
L but no H	65		
L and H	23		
F × H			
No F and no H	46		
No F but H	27		
F but no H	39		
F and H	4		

(B) Degrees of freedom, probabilities of a greater *F* value, and error mean squares.

		$P > F$*		
Analysis source	df	Dry mass of herbaceous plants	No. of blackberry canes	No. of woody vines
Block effect	2	0.4283	0.9149	0.5916
F	1	0.6700	0.0102	0.6656
L	1	0.0242	0.5084	0.7259
H	1	0.0298	0.3088	0.0815
Interations				
F × L	1	0.0200	0.1615	0.9145
F × H	1	0.0497	0.8074	0.2499
L × H	1	0.0241	0.9707	0.4064
F × L × H	1	0.5956	0.5029	0.4853
Error means square	14	0.6628†	0.8986†	1.2550†

*Probabilities are significant in determining main and interaction treatment effects at $\alpha = 0.05$.
†Number of stems per hectare was logarithmically transformed before analysis.

poorer survival among the planted pines, in contrast to the results of Haywood and Tiarks (1990). However, we used herbicides to control herbaceous weeds, and some pine mortality can be expected when herbicides are used, whereas Haywood and Tiarks (1990) hoed to remove herbaceous plants.

Periodic gains in stand yields associated with just herbaceous weed control were evidently maintained from ages 6 through 12 years (Fig. 3). On two southeastern United States Paleudult sites, Miller et al. (1995) also showed a positive yield response to four annual herbaceous weed control treatments that did not decline in importance from age 5 to 8 years. However, Zutter and Miller (1998) had different results for loblolly pine planted on a poorly to somewhat poorly drained flatwoods site in southeastern Georgia. Their pine stands were significantly more productive with herbaceous weed control, but growth gains were declining from ages 6 to 11 years. In 10 plantations across the southeastern

United States, Jokela et al. (2000) also reported declining yield differences from the fifth to eighth growing season when comparing untreated and first-year herbicide-treated plots.

Miller et al.'s (1995) untreated plots averaged 40.4 m^3/ha and the herbicide-treated plots averaged 86.1 m^3/ha after eight growing seasons (Miller et al. 1995). On three Paleudult sites in the southeastern United States, Jokela et al. (2000) found that 8-year-old loblolly pine stands averaged 36.1, 47.9, 43.0, and 55.4 m^3/ha on the untreated control, fertilized, herbaceous plant control, and fertilized and weeded treatments, respectively. Our yields from comparable treatments were 76.7, 142.6, 127.3, and 195.1 m^3/ha on the untreated control, fertilizer, herbicide, and fertilizer and herbicide plots, respectively, after eight growing seasons (Fig. 3).

Understory vegetation

Over time, the decrease in herbaceous plant production was no doubt related to smothering of understory vegetation by the continual needle cast and increasing competition from the overstory loblolly pine for sunlight, water, and nutrients (Grelen 1976; Grelen and Lohrey 1978). Likewise, the greater stature and number of blackberry canes on the unfertilized plots compared with the fertilized plots were also related to greater competition from the larger fertilized pine trees (Lay 1977). Litter application was no longer influencing the understory plant community because the original applied litter had decayed and the pine trees on all treatments were mulching themselves. The pattern of understory tree and shrub development after 11 years was similar to the findings in the third growing season (Haywood et al. 1997). Herbicides affected the number and stature of shrubs but not understory trees. However, tree seedlings were only scattered on the site at the beginning of the study. Thus, the chemical treatments were selected to primarily control herbaceous vegetation, although they were evidently effective on shrubs as well.

Although each of the treatments influenced vegetative composition in the understory through 11 growing seasons, the overstory of pure loblolly pine was apparently the dominant factor influencing the development of the understory. This should continue to be the case in the future (Miller et al. 1999).

Conclusions

Originally, we proposed that on clear-cut sites litter and logging debris could be shredded and dispersed as mulch in which pine seedlings could be planted followed by release of the planted seedlings with herbicides if needed. Our findings indicate that if mulching were done alone it would not have a lasting benefit. However, if logging debris has to be reduced to plant the site, then mulching by shredding and dispersing debris is a no-harm alternative if control burning cannot be practiced or may cause environmental harm (Tiedemann et al. 2000). More importantly, if fertilizers are also applied, mulching can be a very successful management strategy.

Herbaceous weed control increased per tree volume and final yields per hectare, and there was no reason to preserve litter if herbicides were being applied for this purpose. The combination of fertilization and herbaceous plant control was as successful a management strategy as fertilization and litter retention.

Clearly, however, fertilization was the most successful single application alternative on this nutritionally deficient Paleudult site. So, if funding constraints limit managers to applying one ameliorative treatment, fertilization is the best choice on nutrient deficient soils.

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