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677 South Segoe Rd., Madison, WI 53711 USA

Site Preparation and Fertilization Effects on Growth of Slash Pine for Two Rotations

A. E. Tiarks* and J. D. Haywood

ABSTRACT

Two **replicated site preparation studies were used to examine the effect of management on pine height and volume growth in the next rotation on Paleudults. Treatments included no tillage, flat disking, bedding, and fertilization. The first rotation of planted slash pine (*Pinus elliottii* Engelm. var. *elliottii*) *was* measured for 15 yr on one site and 20 yr at the other, harvested, and replanted without additional tillage. The second rotations were measured for 10 yr. At one site, 100 kg ha-' P was applied to each rotation as a treatment variable. At one site, disking before the first rotation increased pine heights. Bedding before the first rotation increased pine heights at both sites. In the second rotation, the response was reversed, with pines planted on beds being the shortest. The P fertilization increased heights in both rotations hut did not affect response to tillage. The P as well as N, applied only at age 7 in the second rotation, had a negative effect on the second rotation's volume, probably because of increased competition from shrubs and other understory plants. Across both sites and for all treatments, 10-yr-old slash pines averaged 7% less in height and 24% less in volume in the second rotation. These differences are statistically significant. Analysis at age 10 from both rotations indicates stable foliar concentrations of P and Ca, declining K, and increasing Mn and Al.**

While several pine species are native to the southern Coastal Plain, the sustainability of short-rotation pines on the more infertile soils in the area is of concern. Declines in growth of natural pine stands have been reported in Alabama and Georgia (Bechtold et al., 1991; Ruark et al., 1991). Reductions in growth ranged from 3 to 3 1% , but the factors responsible for these declines were not identified.

In Australia, the productivity of the second compared with the first rotation of an introduced species, radiata pine (*Pinus radiata* D. Don), has been reported to be less (Keeves, 1966), the same (Gentle et al., 1986), or more (Squire et al., 1985). Identified or suspected causes of changes in productivity include damage from site preparation burning (Keeves, 1966), nutrient depletion (Squire et al., 1985), and weather conditions at time of planting (Boardman, 1978). When the same site is used to compare productivity between successive rotations, difficulties may arise because of variations in genotype, establishment techniques, and weather (Squire et al., 1985). However, using the same site does eliminate variation in the soil and site. Because of the above studies, declines due to specific management practices (Keeves, 1966) have been corrected, leading to increased productivity (Squire et al., 1985).

To compare the productivity of two rotations of southern pine, we utilized two studies that had been established to measure the effect of disking and bedding on the growth of slash pine (Haywood, 1983; Tiarks, 1983). By clearcutting and replanting the same plots, we were able to compare the growth of one rotation with another. We have previously reported the results of one of the studies (Haywood, 1994), which showed a modest decline in the productivity of slash pine and a dramatic decline in loblolly pine (*P. taeda* L.). Unfortunately, no soil or foliage samples were collected on the original study, nor was fertilizer applied as a treatment. A nearby

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study of only slash pine that is also in the second rotation did have fertilizer as a treatment and some soil and plant samples were available from both rotations. Slash pine was used in the second study because it outperforms loblolly on low-fertility sites (Haywood et al., 1990) and responds well to fertilization and other management practices (Haywood et al., 1994).

Disadvantages of using existing studies to compare productivity between rotations include: (i) size of plots and treatments used are fixed by the initial study design, (ii) changes in weed competition associated with some treatments may confound comparisons between rotations, and (iii) uncontrolled factors such as genetics, quality of planting stock, and climate may differentially influence productivity in the two rotations. Advantages include: (i) the statistics are available from the first rotation showing the variation between plots because of soil and microsite differences and (ii) multirotation effects of treatments can be evaluated.

METHODS

Study Sites

The two study areas are located in Rapides Parish, Louisiana, within 1 km of each other. Study 1 is on Beauregard (fine-silty, siliceous, thermic Plinthaquic Paleudult), and Caddo (fine-silty, siliceous, thermic Typic Glossaqualf) silt loam soils while Study 2 ispredominately Beauregard. These soils are acidic, have low natural fertility with an average site index base age 25 of 20 m, and are common in flatwoods of the West Gulf Coastal Plain (Kerr et al., 1980). The Caddo soil occurs on the lower parts of the level to slightly sloping landscape, is poorly drained, and may have a perched water table at or just below the surface during extended periods from December through February (Haywood et al., 1990). The Beauregard occurs on slightly higher parts of the landscape, is moderately well drained, and has a winter water table between 45 and 70 cm. The two soils are very similar in surface horizon characteristics and response to site treatments including fire and tillage.

On both sites, the natural longleaf pine (P. *palustris* Mill.) and hardwood growth was clear-cut harvested in the 1920s. After harvesting, a cover of bluestem (*Andropogon* spp. and ***Schizachyrium*** spp.), scattered post oak ***(Quercus stellata*** Wangenh.), and southern bayberry *(Myrica cerifera* L.) developed. The cover was maintained in this open-range condition by periodic burning. Before plot establishment and tree planting, the areas were again cut and burned to reduce the woody and grass vegetation.

Plot Establishment, Treatments, and Planting

Both studies were established in the 1960s to evaluate disking and bedding as mechanical site preparation methods (Table 1). Study 1 was established to compare three site preparation treatments in a randomized complete block design with four replications. Replications were located based on surface drainage. Each of the 12 plots measures 44 by 33 m. Rows were spaced 2.4 m apart and seedlings were 1.8 m apart within rows but only the center 100 trees of a plot were used as measurement trees. Study 2 was established as a randomized complete block design with three site preparation treatments and four replications. Each of the 12 main plots were split into four subplots that were 18 by 22 m, with fertilizer treatments applied to the subplots. Row spacing was 3.0 m and seedling spacing 1.8 m within rows. Tree measurements were made on the 24 trees located in the center of each subplot.

Table 1. Tie of treatment application and sampling (s) of soil and foliage from two rotations of two studies.

		Study 1		study 2	
Month	Year	Age	Operation	Age	Operation
		yr		yr	
July	1960		burn		
Oct.	1960		disk		
July	1961		disk		
Sept.	1961		bed		
Feb.	1962	0	plant		
Oct.	1967				disk
Oct.	1967				bed
Sept.	1967				P and Ca applied
Nov.	1968				bum
Feb.	1969			0	plant
June	1974			6	soil s
Oct.	1974	13	thinned		
Aug.	1979			11	foliage s
June	1982			14	soil s
Aug.	1983	22	harvest	15	harvest
Oct.	1983		burn		bum
Feb.	1984	0	plant	0	plant
May	1984			0	P applied
May	1991			8	N applied
Mar.	1993	9	foliage s		
Feb.	1994			10	foliage s
June	1994	11	soil s	11	soil s

In Study 1, the site preparation treatments were: (i) burn only – all plots were burned in 1960 to facilitate planting, (ii) burn-disk – following burning, plots were treated with an offset disk harrow in the fall of 1960 and again in July 1961 to control established grass competition, and (iii) burn-disk-bed – following burning and disking, beds averaging 0.50 m from furrow to crest before settling were formed in September 1961 by making two passes with a bedding harrow. The beds were 0.22 m tall after 17 yr and 0.20 m after 33 yr. Graded, nursery-grown, bare-root, 1-O slash pine seedlings were hand planted in February 1962. The plots were thinned from 1684 trees ha-' to 854 trees ha^{-1} after the 13th growing season.

In Study 2, the three site preparation treatments were: (i) burn only – no mechanical site preparation, (ii) disk only – no burning, and (iii) bed only – no burning or disking. The plots were established in the fall of 1967. The fertilizer treatments applied to one of four subplots of each main plot were: (i) no fertilizer, (ii) 100 kg P ha^{-1}, (iii) 1120 kg lime ha-' and (iv) a combination of P and lime. The amendments were applied after the burning but before mechanical site preparation so the P and lime were mixed into the soil only on the disked or bedded plots. Slash pine seedlings similar in quality to those used in Study 1 were hand planted in February 1969.

In 1983, both study sites were clear-cut harvested and the plots replanted the next year. Table 1 gives an outline of the treatment applications and time of soil and plant samplings. Logging equipment was not allowed on the plots. After harvest, both study areas were prescribed burned to reduce logging residue and facilitate planting. The disked or bedded plots were not retreated mechanically so the influence of the initial site preparation treatments could be evaluated during the second rotation.

In February 1984, the plots on both sites were hand planted with slash pine seedlings similar in quality and probably better genetically to those used in the first rotation. The seedlings were planted at the original spacing between stumps in the original planting rows.

Study 1 was managed to keep the competition in the two rotations approximately the same. During the first rotation, grasses were the initial principal competitors with the pine trees, although woody competitors were present. During the second rotation, all plots in Study 1 were rotary mowed yearly between the rows of pine trees to control the size of woody competitors. Woody vegetation was cut down within the planted rows during the ninth growing season.

In Study 2 the competition was allowed to change in response to the treatments so no competition control or fire was applied to any of the plots. Where no P had been applied, the competition was mostly grasses in both rotations, but on plots that had received P, the amount of woody competition gradually increased during the first rotation and was much greater in the second.

The lime applied to the first rotation of Study 2 had no effect on pine growth so that treatment was replaced with a N application of 56 kg ha-' applied as NH_4NO_3 in the beginning of the eighth growing season of the second rotation. The rate of N was based on pine response to N on nearby Beauregard soils (Shoulders and Tiarks, 1983).

Measurements and Data Analysis

For Study 1 in the first rotation, total height measurements were taken at ages 1 to 10, 13, 15, and 20 yr and in the second rotation, total heights were taken yearly. For Study 2, total height measurements were taken at ages 1 through 5, 7, and 10 yr for both rotations and at age 13 for the first. For both studies and in both rotations, height poles were used to measure tree heights for the first seven growing seasons and a clinometer was used to measure tree heights thereafter. Diameter at breast height was measured on all trees at age 10 in both studies and rotations. The age 10 diameter and total height data were used to calculate outside-bark total stem volumes (Lohrey , 1985).

Foliar samples were collected from Study 1 in March of age 9 only in the second rotation. In Study 2 foliage was collected in June of the 1 1th growing season of the first rotation and in February at the end of the 10th growing season of the second rotation (Table 1). The samples were collected from the upper one-third of the crowns of five dominant and codominant trees per plot. The samples were oven dried at 70°C for 24 h, weighed, and ground in a Wiley mill. After H_2SO_4/$CuSO_4 \cdot H_2O$ digestion, N and P were determined by NH_4 probe (Powers et al., 1981) and colorimetry (John, 1970). Atomic absorption spectrophotometry was used to determine K, Ca, Mg, Mn, and Al in the digests (Isaac and Kerber, 1971). In the first rotation, samples were discarded after analysis so the foliage from the two rotations were analyzed at different times.

A composite of 10 subsamples was collected from the surface 10 cm of each plot of Study 1 in the 11th growing season of the second rotation for nutrient analysis. At the same time, soil samples were also collected from around the plots from similar soils but where pine, hardwood, and grass species established naturally before the study was installed. The soil samples were analyzed for available P using Mehlich 3 (Mehlich, 1984) extract and for exchangeable bases by extracting with 1 *M* NH_4OAc (Thomas, 1982).

Surface soil samples were taken from Study 2 in the 14th growing season of the first rotation and in the 11th year of the second rotation. After measuring pH in water and available P using Bray P2 (Olsen and Sommers, 1982), samples were discarded so the samples from the two rotations were analyzed at different times. In the sixth growing season of the first rotation of Study 2, soil samples were collected from the 0- to 3-, 3- to 9-, 9- to 18-, and 18- to 36-cm depths on the bum-only plots. This sampling by depth was repeated 20 years later in the 11th growing season of the second rotation. On these samples, organic carbon (OC) was determined by the Walkley-Black method (Nelson and Sommers, 1982) and exchangeable K, Ca, and Mg as above. These samples were also used to measure total P by digestion with $HClO_4$ (Olsen and Sommers, 1982), organic P by ignition (Saunders and Williams, 1955), and P in fractions (Jackson, 1958). The profile samples from Rotation 1 had been saved so these were analyzed at the same time as the samples from Rotation 2.

In June 1994, soil strength was measured using a recording penetrometer equipped with a 30" conical tip 10 mm^2 in area. All the slash pine plots were measured for Study 1 but only the unfertilized split plots within each of the three site preparation treatments were measured for Study 2. In both studies an entire block was measured in a day to minimize interblock changes in soil water content that would affect soil strength. Within each plot, six transects were made from the tree row halfway to the next row. The resistance was recorded every 0.1 m horizontally and every 0.015 m vertically. The transect readings were averaged by plot and this average was used to compare differences between site preparation treatments for each depth and distance from the row using analysis of variance.

Pine height and volume data for Study 1 were analyzed by analysis of variance using a split plot in time model (Steel and Torrie, 1980) with rotation as the main plot effect and site preparation as the subplot effect. The foliage data from samples collected in 1993 were analyzed by simple analysis of variance with the three treatments and four blocks. For the soil data from Study 1, a fourth treatment of no trees, representing the nearby areas, was added and a preplanned comparison of outside plots vs. plots was tested with analysis of variance.

Pine height and volume, concentrations of nutrients and Al in foliage, soil pH, available P by Mehlich 3 extraction, and exchangeable Ca for Study 2 were analyzed by a split plot in time and space model (Steel and Torrie, 1980) with rotation as the main plot, mechanical site preparation as the subplot, and fertilization as the sub-subplot. Data from the soil collected at the different depths in both rotations of Study 2 were also tested by a split-plot model with rotation as the main plot and depths as the subplots.

RESULTS

Pine Growth

In Study 1 at age 10 and across all treatments, the average height of the pines in the second rotation was 10% shorter than in the first rotation (Table 2). The volume in the second rotation was 85.6 $m^3 ha^{-1}$ or about 62 % of the volume in the first rotation. These differences are significant at the 0.02 and 0.01 probability levels (Table 3). While the differences between rotations was greater on the mechanically prepared plots than on the burn-only plots, the rotation x site preparation interaction term is not significant.

In Study 2, the pines on plots that were not mechanically prepared or fertilized were about the same height at age 10 in both rotations, while the volume was 19% greater. The disking and bedding increased pine growth in the first rotation and had a negative effect in the second (Table 2), leading to a rotation x site preparation treatment interaction of statistical significance at the 0.035 probability level for height and at the 0.091 probability level for volume (Table 3). Thus, averaged across all site preparation treatments, the volume on the unfertilized plots was the same in both rotations.

The differences in heights between pines on disked or bedded plots and those on bum-only plots throughout

Table 2. **Heights and volume of 10-yr-old slash pine in two rotations of two studies as affected by site preparation and fertiliition treatments.**

Study	P	N†	Rotation 1 Burn‡	Rotation 1 Disk	Rotation 1 Bed	Rotation 1 Average	Rotation 2 Bum	Rotation 2 Disk	Rotation 2 Bed	Rotation 2 Average
	— kg ha^{-1} —					Height, m				
1			9.8	9.8	10.5	10.0	9.1	8.9	9.0	9.0
						8 .8	8.7		8.2	8.5
2	0	0	8.5	9.8	9.3	8 .9	a.2	8.7	7.6	8.0
2	100	56†	9.4	9.2	9.9	9.7	9.3	8.9	9.1	9.1
2	100		8.3		9.3	8.9	8.2	8.1	7.6	8.0
						Vdume, m^3 ha-’				
1										
2	0	0	133.9 64.7	128.5 74.0	154.8 82.9	139.0 73.9	93.0 77.0	83.3 70.3	80.7 73.3	85.6 73.5
2	0	56†	71.4	85.2	84.6	80.4	60.5	68.2	67.0	65.2
2		0								
2	100 100	56†	103.2 91.6	104.9 109.4	101.4 100.4	100.8 102.8	80.5 79.4	77.3 79.8	76.0 77.0	77.9 78.7

† Lime was applied at 1120 kg ha-’ in the first rotation only. The N fertilizer treatment was applied only in the second rotation at the beginning of the eighth growing season.
‡ The burning was repeated between the first and second rotation but the mechanical site preparation treatments were applied only at the beginning of the first rotation.

the two rotations is shown in Fig. 1. In both studies, pines on bedded plots were taller in the first rotation. However, the early advantage in height maximized at age 10 when pines on bedded plots were 0.7 m taller. By age 13, the effect of bedding had decreased to 0.4 m for Study 1 and 0.3 m for Study 2. This was the last measurement before the thinning of Study 1 and the clear-cutting of Study 2. The thinning done on Study 1 seems to have allowed the effect of bedding to recover, so that by age 20, the trees on bedded plots were 0.6 m taller than those on bum-only plots. In the second rotation, the heights of the pines in the bedded plots on both studies were shorter, with the greatest difference of 0.6 m occurring at ages 5 and 7 yr for Study 2.

In Study 1, the disking never affected the heights in the first rotation, but pines on disked plots were 0.3 m shorter than pines on bum-only plots at age 7 in the second rotation (Fig. 1). In Study 2, the effect of disking was intermediate between no mechanical site preparation and bedding throughout the two rotations.

In Study 2, the application of 100 kg ha-’ of P prior to planting of each rotation increased the height of the pines at age 10 (Table 2). In the first rotation, response to the P averaged 0.8 m across all site preparation methods. In the second rotation, the response to P averaged 0.6 m on plots not receiving N. In the first rotation, the P fertilization alone increased volume by 26.9 m^3 ha^{-1} on the bum-only plots, 35.4 m^3 ha^{-1} on the disked plots, and 18.5 m^3 ha-’ on the bedded plots. However, in the second rotation, P fertilization only increased volume by 4.4 m^3 ha^{-1} across all site preparation plots not receiving N.

The 50 kg ha^{-1} of N fertilizer was applied only at the beginning of the eighth growing season of the second rotation. Lime had been applied at the beginning of the first rotation to the plots that later were treated with N.

Table 3. Analysis of variance tables used for testing the effects of rotations and treatments on the pine growth of the two studies and soil properties in Study 2. The values are probabilities of greater *F* by chance and the error terms used to test the effects.

Source	df	Study 1 Height	Study 1 Volume	Study 2 Height	Study 2 Volume	Study 2 Soil pH	Study 2 Bray P2
				$P > F$ value			
Block	3	0.085	0.395	0.187	0.242	0.026	0.886
Site Prep (S)	2	0.118	0.298	0.787	0.373	0.267	0.342
EMS = error (a)	6	(0.113)	(193.8)	(0.498)	(194.3)	(0.0192)	(1.437)
Phosphorus (P)	1	–	–	0.001	0.001	0.147	0.001
Nitrogen (N)	1		–	0.124	0.991	0.001	0.628
P × N	1		–	0.769	0.777	0.514	0.725
EMS = error (*b*)	27			(0.286)	(241.1)	(0.0145)	(0.365)
Rotation (R)	3	0.022	0.012	0.088	0.001	0.001	0.0065
EMS = error (c)		(0.338)	(557.8)	(0.270)	(45.1)	(0.0040)	(0.367)
R × S	2	0.259	0.137	0.035	0.091	0.823	0.528
EMS = Error (*d*)	6	(0.251)	(231.1)	(0.305)	(91.3)	(0.0121)	(0.734)
R × P	1		–	0.720	0.001	0.511	0.001
R × N	1		–	0.042	0.054	0.102	0.830
R × P × N	1			0.154	0.147	0.762	0.634
S × P	2			0.170	0.183	0.650	0.214
S × N	2		–	0.948	0.774	0.002	0.264
S × P × N	2		–	0.510	0.330	0.846	0.141
R × S × P	2			0.245	0.811	0.293	0.802
R × S × N	2			0.975	0.302	0.461	0.564
R × S × P × N	2			0.505	0.803	0.887	0.175
EMS = Error (*e*)	27			(0.223)	(107.2)	(0.0054)	(0.377)

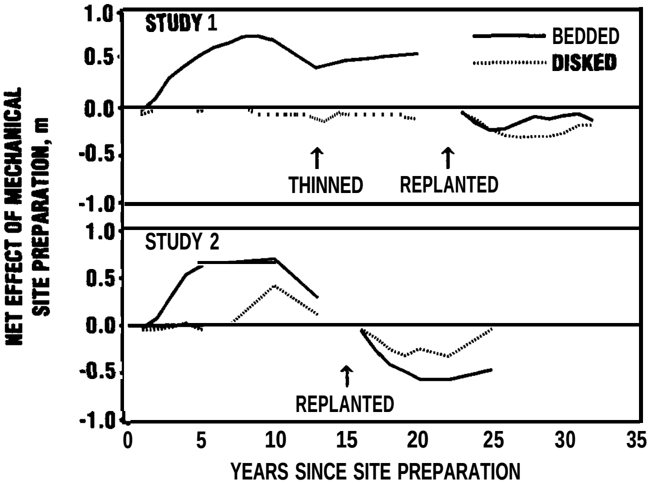

Fig. 1. The net effect of disking or bedding on the total height of slash pine compared with no mechanical site preparation on two studies for two rotations.

The pine heights in the first rotation were not affected by the liming treatment (Table 2) nor were there differences in the first 7 yr of the second rotation (data not shown). Thus the effects on these plots is assigned only to the N treatment. After three growing seasons, the N decreased pine volume by 16.5 m^3 ha-' on the burn-only plots without P and decreased volume hy 1.1 $m^3 ha^{-1}$ on burn-only plots fertilized with P. This effect was not significant as a main effect (Table 3), but the rotation x N interaction is significant. As N was not applied to the first rotation, the effect must be due to the N applied in the second rotation.

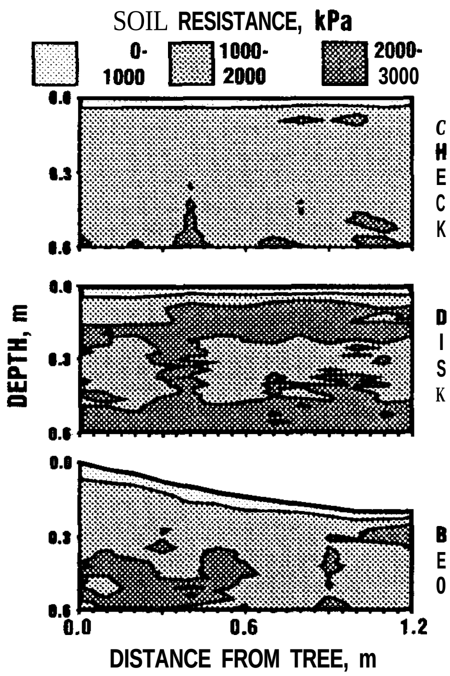

Fig. 2. Soil strength, measured by penetrometer, on burn-only (top), disked (middle), and bedded treatments (bottom) measured 33 yr after site preparation. Each value is an average of six transects made on each of four blocks.

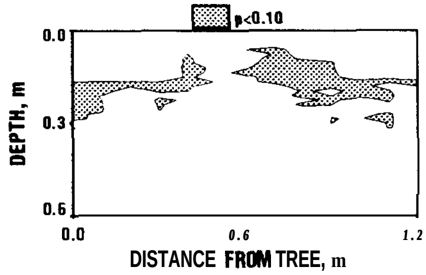

Fig. 3. Locations within row and soil profile where the soil strength in disked plots is significantly ($P = 0.10$) greater than in burn-only or bedded plots.

Soil Strength

The site preparation treatments applied to Study 1 in 1960 and 1961 had little effect on mean soil strength in 1994. The soil strength averages for the soil to a depth of 0.6 m were 1670, 1930, and 1750 kPa for the check, disking, and bedding treatments, respectively. However, the treatments did impact the pattern of soil strengths (Fig. 2). On the burn-only plots, soil strengths exceeded 2000 kPa in only small volumes of soil. On disked plots, soil strength exceeded 2000 kPa in about one-half the soil above the 0.3-m depth. These values are statistically significant at the 0.1 probability level (Fig. 3). In the cells where significant differences occurred, the soil strength of the check and bedded plots were 1630 and 1620 kPa while the disked plots were 2290 kPa. Bedding also increased the amount of soil where resistances exceeded 2000 kPa, but the differences were not significant. On Study 2, the site preparation treatments had no obvious effect on strength patterns nor were the values statistically significant. Resistance values in Study 2 ranged from 1770 kPa for burn-only plots to 1610 kPa for the bedded plots.

Soil Chemistry

The surface soil (15 cm) of Study 1 was sampled only in the 1 lth growing season of the second rotation, so rotational comparisons are not possible for Study 1. Instead, soil was collected from fallowed areas near the plots. In the 1 lth growing season of the second rotation, the Mehlich 3 available P was not affected by disking or bedding and averaged 0.9 mg kg-' on the plots. The P in the soil from the unmanaged areas was slightly higher at 1.2 mg kg-‘, but this difference was not statistically significant. The disking and bedding treatments did not affect the exchangeable bases in the surface soil, averaging 0.054, 0.79, and 0.42 $cmol_c$ kg-' for K, Ca, and Mg, respectively, in soil from the plots. The soil from the unmanaged areas outside the plots had the same amount of K but less Ca and Mg than soil from the plots. The fallowed soil contained 0.52 and 0.28 $cmol_c$ kg-' of Ca and Mg. These values are less than the plot values at the 0.058 and 0.081 probability levels.

In Study 2, the surface soil was sampled at similar times in the two rotations, allowing the statistical comparison of soil chemistry by rotation, site preparation treatment, and fertilization. The pH of the surface soil increased

Table 4. For Study 2, the soil pH and amount of available P (Bray P2) and exchangeable Ca in soil from two rotations of slash pine. Values are averages of four blocks and three site preparation treatments.

P	Nt	pH	Bray P2	Exchangeable Ca
— kg ha^{-1} —			g kg-'	cmol$_c$ kg-'
			Rotation 1	
0	0	4.11	1.2	0.60
0	0t	4.23	1.1	0.66
100	0	4.15	1.9	0.62
100	0†	4.29	1.9	1.00
			Rotation 2	
0	0	4.96	1.1	0.79
0	56t	5.02	1.1	1.22
100	0	4.96	3.1	1.14
100	56†	5.06	5.6	1.41

† Lime was applied at 1120 kg ha-' in the first rotation only. The N fertilizer treatment was applied only in the second rotation at the beginning of the eighth growing season.

from 4.20 at age 13 in the first rotation to 5.00 at age 10 in the second rotation (Table 4). Because the laboratory measurements were made at separate times, the possibility that the differences are due to error cannot be eliminated. The lime applied in the first rotation increased the pH in the first rotation by an average of 0.19 units on the burn-only plots (Table 4), but the increase was only 0.09 units on the disked and bedded plots. The increase in pH from liming is significant at the 0.001 probability level (Table 3). In the second rotation, the pH of the soil from plots treated with lime in the first rotation followed by N in the second was still greater on the burn-only plots but not on the disked or bedded plots. Thus, the site x N term is statistically significant.

The addition of P fertilizer to the plots increased the Bray 2 available P from 1.2 to 1.9 mg kg^{-1} in the first rotation (Table 4). Compared with the first rotation, the available P in soil from the unfertilized plots in the second rotation had not changed significantly. On the fertilized plots the P had nearly doubled or tripled in the second rotation, depending on the N treatment, causing a significant rotation x P interaction (Table 3). Thus, the repeated P fertilization had an accumulative effect on available P.

The effect of rotation and P fertilization on OC and exchangeable K, Ca, and Mg was also tested using soil samples collected from Study 2 in 1974 and 1994 at four depths and analyzed at the same time in 1994 (Table 5). Rotation and P fertilization affected the OC contents significantly in only the 0- to 3- and 3- to 9-cm depths. Without P fertilization, the OC content at 0- to 3 cm decreased from 23 g kg^{-1} in the first rotation to 20 g kg^{-1} in the second. The OC increased in the 0- to *3-cm* layer in plots receiving P fertilizer from 22 to 29 g kg^{-1} during the 20-yr period. In the 3- to 9-cm depth, the OC content decreased during the 20-yr period by 25% in the unfertilized plots but increased by a similar amount in plots receiving P. The year-collected x fertilization interaction term was statistically significant for both depths. The year-collected term at the 18- to 36-cm depth is also statistically significant at the 0.013 probability level, but the actual differences in OC are small.

On plots not receiving P fertilizer, the exchangeable K decreased during the 20-yr period (Table 5). The differences were significant at all depths, but the greatest decrease was from 0.082 to 0.051 cmol$_c$ kg-' in the 0- to 3-cm depth. On plots receiving P fertilizer, the amount of K in the surface 9 cm did not change with time. However, at the 18- to 36-cm depth, the loss of K was greater in the fertilizer plots than in the unfertilized ones.

The exchangeable Ca and Mg was lower in the surface 18 cm of soil on unfertilized plots in Rotation 2 than in Rotation 1 (Table 5). The loss of both bases was the greatest in the surface 3 cm but was still significant in the 9- to 18-cm layer during the 20-yr period. The P fertilization treatment increased the amount of Ca and

Table 5. For Study 2, the amount of organic carbon (OC) and exchangeable bases and probabilities of a greater *F* value for specified effect occurring by chance in different depths of soil treated with P fertilizer and sampled 20 yr apart.

Depth	1974		1994		*P* > *F* value		
	0 P	100 g P kg-'	0 P	100 g P kg^{-1}	Year	P fert.	Y × P
cm							
				OC, g kg-'			
o-3	23	22	20	29	0.2297	0.0414	0.0227
3-9	16	13	12	1.5	0.4639	0.6946	0.0139
9-18	8	8	7	8	0.6301	0.7681	0.5598
18-36	4	4	3	4	0.0138	0.4881	0.1901
				K, cmol$_c$ kg-'			
o-3	0.082	0.102	0.051	0.098	0.0190	0.0001	0.0031
3-9	0.050	0.050	0.029	0.047	0.0027	0.0706	0.0670
9-18	0.033	0.036	0.023	0.029	0.0257	0.0371	0.3457
18-36	0.049	0.048	0.039	0.031	0.0257	0.1961	0.2940
				Ca, cmol$_c$ kg^{-1}			
o-3	1.78	1.73	0.99	2.01	0.0597	0.0272	0.0185
3-9	1.32	1.25	0.73	0.93	0.0066	0.5712	0.2583
9-18	0.98	1.03	0.83	0.81	0.0263	0.8582	0.6589
18-36	0.92	0.96	0.93	0.87	0.1371	0.9140	0.6095
				Mg, cmol$_c$ kg^{-1}			
o-3	0.76	0.73	*0.46*	0.83	0.1841	0.0157	0.0080
3-9	0.58	0.46	0.33	0.41	0.0510	0.5148	0.0204
9-18	0.52	0.49	0.41	0.38	0.0309	0.3968	0.9971
8-36	0.73	0.75	0.79	0.73	0.7688	0.7537	0.5946

Table 6. For Study 2, the amount of P and probabilities of a greater *F* value for specified effect occurring by chance in different fractions in the surface 18 cm of soil treated with P fertilizer and sampled 20 yr apart.

P fraction	1974		1994		$P > F$ value		
	0 P	100 g P kg^{-1}	0 P	100 g P kg-'	Year	P fert.	Y × P
	g kg-'						
Water-extractable	1.5	2.1	0.8	0.9	0.0323	0.0004	0.1233
Al-P	6.0	11.5	4.6	7.1	0.0143	0.0047	0.2226
Fe-P	12.5	18.0	9.1	16.1	0.2919	0.0002	0.2862
Ca-P	3.6	4.1	1.3	3.1	0.0788	0.0454	0.1743
Occluded	7.1	3.9	4.5	6.9	0.61%	0.7827	0.0950
Organic	31.6	38.6	33.2	61.2	0.0241	0.0002	0.0035
Sum of fractions	63.1	78.2	53.5	95.3			
Measured total	68	94	67	112	0.0918	0.0001	0.0021

Mg in the surface 3 cm in the second rotation. However, this effect diminished rapidly with depth so that P fertilization did not change the amount of Ca or Mg retained at the 9- to 18- and 18- to 36-cm depths.

Phosphorus Fractions in Soil

For Study 2, analysis of variance by depth shows the amount of P in the different fractions in the 0- to 3-, 3- to 9-, and 9- to 18-cm depths was affected in similar ways by P fertilization and sample year. However, fertilization and year did not have a significant effect on the P fractions in the soil from the 18- to 36-cm depth. Based on this analysis, the weighted average of the P fractions for the surface 18 cm was used for subsequent analysis and interpretations, which showed that the P fertilizer increased the total amount of P in the soil and that this amount increased after each application (Table 6). The total amount in the soil from unfertilized plots was the same in the two samplings done 20 yr apart. The amount of water-extractable P was only 1.5 mg kg^{-1} in the 1974 sampling from unfertilized plots. The P fertilization increased the amount of water-extractable P in the 1974 sampling collected 5 yr after fertilization. However, in samples collected 10 yr into the second rotation, the amount of water-extractable P in the fertilized and unfertilized soils are the same, and both are lower than in the first rotation. The effect of sampling period is significant at a 0.03 probability level.

The amount of P in the Al-P and Ca-P fractions was lower in the second rotation than in the first and increased with P fertilization (Table 6). The Fe-P and organic fractions were stable with time in the unfertilized soil, but increased with P fertilization. The occluded fraction was not significantly affected by time or P fertilization. The sum of the fractions accounts for 80 to 93% of the P actually measured by the total P method, with the greatest amount of unaccounted for P in the soil from unfertilized plots in the second rotation.

Nutrients and Aluminum in Foliage

The concentrations of N in foliage from Study 2 at age 10 show no increase from the N applied to the second rotation (Table 7). Phosphorus fertilization increased the N concentration in the first rotation but had no effect in the second. Lime rather than N was applied to the N subplots in the first rotation and the N concentrations in the first rotation were reduced by the lime treatment. This change in treatment caused a significant N*X* rotation interaction (Table 8). On plots receiving no fertilizer, the N concentrations decreased from 10.4 to 9.9 g kg^{-1} between rotations. On P-treated plots, the decrease in foliar N was from 11.6 to 10.1 g kg-‘. In the second rotation, the N concentrations are all approaching the critical range of 8 to 10 g kg^{-1} (Pritchett and Comerford, 1983).

The concentration of P in the foliage did not change in the unfertilized plots between rotations (Table 7). The application of 100 kg ha^{-1} of P at the beginning of each rotation significantly increased the P concentration in the foliage at age 10 in both rotations (Table 8) to above the critical range of 0.8 to 0.9 g kg-' (Pritchett and Comerford, 1983). The change in treatment from liming to N fertilization led to a statistically significant N *x*

Table 7. For Study 2, the concentrations of nutrients and Al in foliage of two rotations of slash pine. Values are averages of four blocks and three site preparation treatments.

P	N†	N	P	K	Ca	Mg	Mn	Al
kg ha^{-1}		g kg-'						
	0				Rotation 1			
0	0†	10.4	0.74	5.9	1.1	1.0	0.24	0.30
0		8.5	0.75	5.9	1.1	0.9	0.24	0.28
100	0	11.6	0.98	5.7	1.1	1.0	0.26	0.39
100	0†	10.4	1.03	5.4	1.2	1.0	0.27	0.34
0	0				Rotation 2			
0	56†	10.0 9.9	0.75 0.71	3.5 3.5	1.6	0.9	0.56	0.52
					1.7	0.9	0.48	0.72
100	0	10.1	1.04	3.5	1.9	1.1	0.49	0.60
100	56†	10.2	1.01	3.4	1.9	1.1	0.44	0.57

† Lime was applied at 1120 kg ha-' in the first rotation only. The N fertilizer treatment was applied only in the second rotation at the beginning of the eighth growing season.

Table 8. Analysis of variance tables used for testing the effects of rotations and treatments on concentrations of nutrients and Al in foliage collected at age 10 from Study 2.

Source	df	N	P	K	Ca	Mg	Mn	Al
		$P > F$ value						
Block	3	0.187	0.777	0.441	0.293	0.393	0.098	0.658
Site Prep (S)	2	0.148	0.908	0.540	0.589	0.192	0.108	0.768
EMS = error (a)	6	(0.968)	(0.0116)	(0.359)	(0.0786)	(0.0136)	(0.0096)	(0.0221)
Phosphorus (P)	1	0.001	0.001	0.038	0.017	0.001	0.595	0.592
Nitrogen (N)	1	0.002	0.908	0.200	0.2%	0.068	0.351	0.481
P × N	2:	0.507	0.367	0.152	0.879	0.933	0.789	0.094
EMS = error *(b)*		(1.124)	0.840	(0.180)	(0.0674)	(0.0111)	(0.0250)	(0.0347)
Rotation (R)	1	0.271	(0.0156)	0.001	0.006	0.429	0.008	0.003
EMS = error (c)	3	(0.358)		(0.210)	(0.2182)	(0.0082)	(0.0350)	(0.0205)
R × S	2	0.268	0.663	0.612	0.385	0.536	0.054	0.613
EMS = error *(d)*	6	(0.421)	(0.0179)	(0.177)	(0.1415)	(0.0065)	(0.0093)	(0.0190)
R × P	1	0.006	0.255	0.022	0.205	0.013	0.213	0.148
R × N	1	0.002	0.021	0.619	0.760	0.2%	0.236	0.091
R × P × N	1	0.426	0.532	0.623	0.570	0.265	0.962	0.197
S × P	2	0.358	0.272	0.886	0.593	0.3%	0.702	0.598
S × N	2	0.707	0.947	0.151	0.428	0.562	0.771	0.925
S × P × N	2	0.367	0.769	0.011	0.643	0.028	0.844	0.179
R × S × P	2	0.139	0.532	0.061	0.838	0.413	0.589	0.691
R × S × N	2	0.532	0.265	0.874	0.090	0.160	0.904	0.899
R × S × P × N	2	0.976	0.636	0.022	0.745	0.150	0.508	0.237
EMS = error E	27	1.231	(0.0048)	(0.105)	(0.0717)	(0.0109)	(0.0235)	(0.0318)

rotation interaction, possibly because the N stimulated growth sufficiently to lower the P concentration.

The K concentration in the foliage decreased significantly from 5.9 g kg^{-1} on the unfertilized plots in the first rotation to 3.5 g kg-' in the second (Tables 7 and 8). The P application decreased the K concentration in the first rotation but not in the second. The K concentrations are above the critical range of 2.5 to 3.0 g kg^{-1} for K (Pritchett and Comerford, 1983).

The Ca concentrations were significantly higher in the second rotation than in the first (Tables 7 and 8). In the second rotation, P fertilization increased the Ca concentrations in the foliage, but the lime application applied before the first rotation had no effect on the Ca in the foliage in either rotation. In contrast to Ca, the concentrations of Mg in the foliage did not increase with rotations, but like Ca, Mg concentrations were increased by P fertilization in the second rotation.

The concentrations of both Mn and Al were nearly double in the second rotation compared with the first (Table 7). Since the concentration of Ca in the foliage was also higher in the second rotation, the change in the Ca/Al molar ratio was from 2.5 in the first rotation to 2.1 in the second. Both of these values are much below the 6.2 threshold for 75 % risk suggested by Cronan and Grigal (1995). The site preparation and fertilization treatments did not affect the Al concentrations in the foliage. The Mn foliage concentrations were slightly higher on the disked and bedded plots in the first rotation but lower on these plots in the second. While this small difference is statistically significant, it is probably not biologically important, especially compared with the much greater changes between rotations.

DISCUSSION

A famous detective in fiction once noted that "eliminate all which is impossible, then whatever remains, however improbable, must be the truth" (Doyle, 1927). Fortunately for Sherlock Holmes, he lived in a fictional world and solved created problems with unique solutions. In the real world where these two studies are located, the "truth" is productivity, defined as the measured pine height and volume growth. This growth has been affected by a combination of factors that may have changed between rotations. While many factors may affect productivity and cannot be eliminated as impossible, an evaluation of their potential effects shows it is improbable that these factors materially affect productivity.

Factors that are probably not important in causing any differences in growth between the rotations in these studies include climate, seedling quality, genetics, and weed competition. The most important climatic parameter, rainfall, was not significantly different between the first 7 yr of the two rotations of Study 1 (Haywood, 1994). Seedlings were obtained from the same nursery in both rotations of both studies with only small differences in production and grading techniques. The potential differences in seedling size probably would not affect the size of slash pine by age 10 (Haywood and Barnett, 1994). The local nurseries used mixed seed lots from diverse sources, minimizing chances for changes in genetics. Assuming nursery practices and genetics are improving with time, significant changes would increase the productivity of the second rotation. The competition in Study 1 was managed so it would be as equal as possible in the two rotations. The volume on the second rotation bum-only plots was 31% lower than in the first rotation of Study 1. For Study 2, the amount and type of competition appeared to be the same in both rotations on the burn-only unfertilized plots and volume in the second rotation was 19% higher than in the first. For Study 2 the apparent amount of woody competition was greater on the fertilized plots and probably caused the 12% volume reduction in the second rotation on burn-only P-fertilized plots. However, the increased competition was a direct result of the P fertilizer and costs of weed control will be higher for the fertilization to be effective in multiple rotations.

The negative response to disking and bedding in the second rotation illustrates that what appears to be a neutral to positive practice may lead to productivity losses in the long term. Mechanical treatments such as disking must be done when soil water content is optimal for tillage. As the penetrometer results from Study 1 show, tillage can increase soil strengths that may never recover without expensive tillage under optimal conditions. Soil strengths are highly dependent on the water content of the soil and these measurements were made when the soil water contents were at intermediate levels for the site and any effects of the site treatments on soil water content would be minimized. The soil strengths >2000 kPa are above the range where root penetration is severely reduced (Taylor et al., 1966). While the disking on Study 1 did not reduce slash pine growth in the first rotation, it apparently nullified any positive effects of disking in the first 5 yr (Fig. 1). In the second rotation of Study 1, the heights are the shortest on the disked plots, probably because the higher soil strengths are limiting root growth.

Cultural practices applied at planting may produce dramatic results (Tiarks and Haywood, 1986) that fade by the time of first thinning (Haywood and Tiarks, 1990). In the case of Study 1, results at age 8 were showing a 0.7-m response from bedding and were reported with cautious optimism (Mann and Derr, 1970). Bedding is not now a recommended practice on these sites, based partly on first-rotation results from these two studies (Haywood, 1983; Tiarks, 1983), and on results from other sites (Derr and Mann, 1977; Wilhite and Jones, 198 1). These recommendations were based on data showing a small positive response to bedding that was not economical.

The negative response to bedding in the second rotation may be because the practice confines the pine root system to the soil in the beds, where nutrients have been concentrated. The roots preferentially deplete the nutrients from the beds during the first rotation. In the second rotation, the roots are still confined to the soil volume depleted by the first rotation. This speculation cannot be confirmed by soil analysis because, at these low levels of P, available-P soil tests based on partial extractants are not able to discriminate between sites (Lea et al., 1980). Also, the available-P tests are not useful in predicting growth of pines on unfertilized soils (Ballard and Pritchett, 1975). The P fertilizer, applied on the surface of the beds in the second rotation, should have prevented the small decline in growth. The benefits of the fertilizer were probably masked by the associated increase in competition.

The available P in these soils is very low even by forest soil standards. The Mehlich 3 levels of P in soils from 482 forested plots scattered throughout Louisiana and Mississippi ranged from 1 to 20 mg kg^{-1} (Meier, 1994, personal communication). Compared with this population, the Mehlich P levels of 0.9 to 1.2 mg kg^{-1} on unfertilized plots are in the lower 5 percentile. While the available P in the twice-fertilized soils from Study 2 rank in the top quartile of the larger population, the samples are still below the critical level of 5 to 6 mg kg^{-1} (Lea et al., 1980). Thus, while the low values of available P in the unfertilized plots of both the first and second rotations indicate that the pines would respond to P additions, the tests cannot be used to quantify the effect of P status on changes in pine growth between rotations.

Because of the poor reliability of the available P tests at these low values, changes in the status in the different P fractions may be better indicators of the P regime. While the availability of different fractions of soil P varies with species (Ae et al., 1990) the water-extractable P, Al-P, and Fe-P fractions are thought to be the most available to pines (Gilmore and Matis, 1981). The sum of these fractions in the surface 18 cm of soil decreased from 20.8 mg kg^{-1} in the unfertilized plots in the first rotation to 14.5 mg kg^{-1} in the second. Fertilization had increased the P in these fractions 5 yr after the first application to 3 1.6 mg kg^{-1} but the amount had declined to 24.1 mg kg^{-1} 10 yr after the second application. However, the amount of P in the organic fraction was nearly doubled by the two P applications so the P is being conserved on the site. The organic P fraction is generally related to the level of extractable P (Smeck, 1973), but much of the increase is probably in a relatively inert fraction of organic P (Parfitt, 1980). However, the organic P may be a good indicator of long-term soil fertility (Sharpley and Smith, 1985) as well as an important source of supply to pines either through mineralization or direct utilization by mycorrhizae (Kelly et al., 1983).

The K in the soil and foliage measured in both rotations indicate near-deficiency levels may have developed on these sites. In the fifth year of the first rotation of Study 2, the exchangeable K in the 0- to 3-cm soil depth was slightly above the 0.07 $cmol_c\ kg^{-1}$ measured in a stand on similar soils that did not respond to K fertilization (Shoulders and Tiarks, 1987). Also, the additions of lime did not depress the concentrations of K in the foliage, as has been noted in southern pines on K-deficient sites (Gilmore, 1972). The foliage samples were collected in June of the first rotation and February of the second rotation. Changes in nutrient levels with seasons could be responsible for part of the change in K concentrations (Wells and Metz, 1963). However, the magnitude of the change between rotations is much greater than normally associated with seasonal fluctuations. In the second rotation, the exchangeable K levels of 0.03 to 0.05 $cmol_c\ kg^{-1}$ are only slightly higher than the 0.02 $cmol_c\ kg^{-1}$ where slash pine plantations on similar soils did show a significant response to K fertilization (Shoulders and Tiarks, 1990).

These two studies show that short-rotation slash pine can be maintained if disturbance is minimized and nutrient levels maintained. A severe decline in the growth of slash pine occurred in Study 1, but were minimal in Study 2. If weed control had been combined with the P applications in Study 2, increases in growth would be expected. However, the soil and foliage data indicate that K fertilization would also be beneficial. The soils have little resilience and other nutrient deficiencies may develop, but at these low levels, availability indices are of little value in making fertilizer recommendations. In practice, noticeable losses in growth may occur before deficiencies are identified and corrected.

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