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Availability of residual phosphorus fertilizer for loblolly pine

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ABSTRACT

Fertilizing pine plantations with phosphorus has been a common practice on the Coastal Plain since the 1960s. A decision to fertilize a second or subsequent rotation must take into consideration the availability of residual phosphorus fertilizer. We tested the efficacy of phosphorus applied in a first rotation loblolly pine stand to support the growth of the subsequent second rotation stand. Phosphorus rates applied in 1967 at the time of planting of the first rotation were 0, 28 and 56 kg/ha. Retreatments included the application of 45 kg/ha P at midrotation in 1978, and the application of 45 kg/ha P at the beginning of the second rotation in 1991. The field trial had a split-block design with the three initial P rates crossed by five retreatments, and replicated four times. The first rotation 28 kg/ha P treatment had 91% and the 56 kg/ha P treatment 101% of the volume at age 5 of all the treatments fertilized with P in the second rotation. Foliar P levels, in the second rotation, were elevated at age 2 relative to ages 3 and 5, presumably due to effective competition control. Twenty-nine percent, 40% and 75% of the trees fertilized with 28 kg/ha P in 1967, 56 kg/ha P in 1967, and 45 kg/ha P in 1991, respectively, had foliar P concentrations of 0.10% or above at age 3. Based on foliar analyses, we recommend refertilizing stands fertilized with 45 kg/ha P in the first rotation by age 3 in the second rotation.

1. Introduction

Phosphorus fertilization of slash pine (*Pinus elliottii* Engelm.) and loblolly pine (*Pinus taeda* L.) plantations has been an operational practice on the Coastal Plain of the United States since the late 1960s. At least 81,000 ha/year were fertilized with P at establishment in the southeastern United States between 1996 and 2004 (Albaugh et al., 2007; Fox et al., 2007a,b). Which pine stands to fertilize and when to apply phosphorus fertilizer continue to be important research and operational questions, due to the dramatic recent increases in fertilizer prices. Phosphorus applied in the first rotation may not be sufficient to support rapid growth of the subsequent rotations. Harvest removals of phosphorus, immobilization of P in soil organic matter and adsorption of P to soil iron and aluminum compounds are all factors which may influence the availability of residual P fertilizer to second and third rotation stands.

Historically, procedures used to identify phosphorus deficient sites were based on foliar analyses, soil chemical analyses and/or land classification. Presently, land classification plus knowledge of previous fertilizer additions (amounts and dates) are used to identify stands to be fertilized at establishment (Fox et al., 2007b). Geologic regions where P is applied at establishment include the Citronelle terrace on the uplands of the Gulf Coast, as well as poorly drained sites on the Lower Coastal Plain of the Atlantic and Gulf Coasts (Albaugh et al., 2007; Fox et al., 2007a,b).

Foliar analyses are a direct measure of trees' phosphorus status, and are usually the best predictor of response to P fertilization. Widely recognized critical levels for foliar P concentrations are 0.09% P for slash pine and 0.10% P for loblolly pine (Ballard, 1980; Ballard and Pritchett, 1975b; Pritchett, 1968; Wells et al., 1973, 1986). One expects a response to P fertilization when the foliar P concentration is initially less than the critical level. The principal limitation to using foliage samples for deciding what sites to fertilize is that the technique can not be used unless pine trees are present which are suitable for sampling. In the 1970s and 1980s some companies delayed P fertilization for 1 or 2 years and collected foliage samples from planted seedlings. Normally in the 1970s and 1980s, a decision to fertilize at time of planting was based either on soil chemical analyses or on land classification rather than sampling mature trees, from the previous stand, prior to harvest.

The most commonly used soil chemical analysis is HCl–H_2SO_4 extractable P (0.05N HCl + 0.025N H_2SO_4) also known as the dilute double acid or Mehlich 1 soil test. Critical levels reported for HCl–H_2SO_4 extractable P are 3 μg/g P (Wells et al., 1973) and 5 μg/g P

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(Ballard and Pritchett, 1975b) for 0–20 cm depth soil samples. Wells et al. (1973) found 75% of their Lower Coastal Plain study sites were correctly classified when HCl–H_2SO_4 extractable P was used to predict whether or not loblolly pine would respond to P fertilization. Similarly, Ballard and Pritchett (1975b) found that slash pine response to P fertilization, or the lack thereof, was correctly predicted by the Mehlich 1 soil test for 65% of their study sites. HCl–H_2SO_4 extractable soil P has been evaluated more often than other soil chemical analyses because several of the soil testing laboratories in the southeastern United States have used it as a routine procedure for many years. The HCl–H_2SO_4 extractable P method has compared favorably to other soil tests in several studies investigating southern pine response to P fertilization (Ballard and Pritchett, 1975a,b; Comerford and Fisher, 1982; Wells et al., 1973, 1986).

Information gained from land classification can be as useful as soil test results for making decisions on what sites to fertilize with phosphorus (Ballard and Pritchett, 1975b; Comerford and Fisher, 1982; McKee and Wilhite, 1986; Kushla and Fisher, 1980). The effects of soil parent material (e.g. geologic formation or terrace) on subsoil P status, soil drainage class, and depth to a spodic horizon, argillic horizon or mottles are all factors related to pine response to P fertilization on the Lower Coastal Plain. Conventional field data collected as part of a land classification program can be combined with laboratory soil chemical analyses to improve P-fertilizer recommendations on specific sites. Comerford and Fisher (1982) found soil drainage class could be used to correctly classify study sites as responsive to P fertilization 60% of the time. Use of HCl–H_2SO_4 extractable P in conjunction with soil drainage class increased the percentage of sites correctly classified to 80%.

Southern pines grown on poorly drained soils need phosphorus to compensate for anaerobic soil conditions and promote root growth (DeBell et al., 1984; McKee et al., 1984). Good responses to P fertilization are observed on poorly drained soils because P is frequently limiting, but ample nitrogen and water are available for tree growth once phosphorus is supplied. Some of the most responsive sites in the southeast are poorly drained clayey soils which are classified as aquults (Kushla and Fisher, 1980). Substantial responses to relatively low P-fertilizer rates (22–67 kg/ha P) have been observed on these soils (Gent et al., 1986; McKee and Wilhite, 1986; Pritchett and Comerford, 1982; Wells et al., 1986), but in some cases application rates as high as 157 kg/ha P have produced an additional pine growth response (Pritchett and Comerford, 1982).

The effectiveness of residual phosphate fertilizer as a source of phosphorus for crop growth has been studied extensively in agriculture (Barrow, 1980) and to a limited extent in forestry of New Zealand (Ballard, 1978; Comerford and Skinner, 1989; Comerford et al., 2002), Australia (Flinn et al., 1982; Gentle et al., 1986; Turner, 1982; Turner and Lambert, 1985, 1986; Turner et al., 2002), and southern Africa (Crous et al., 2007). Little information is available as to the effectiveness of residual P fertilizer on the growth of second or third rotation plantations in the southeastern United States (Comerford et al., 2002; Harding and Jokela, 1994; Torbert and Burger, 1984). Working on the Coastal Plain, Comerford et al. (2002) conducted a greenhouse pot study and found no significant difference in P content of seedlings grown in soil from field plots which received 0–70 kg/ha P 29 years before the soil samples were collected. Comerford et al. (2002) did find that P content of the F layer of the forest floor was greater in the 35 and 70 kg/ha P treatments than in the 0 and 17.5 kg/ha P treatments, and concluded that the bioavailable P from the forest floor would be sufficient to meet the needs of 1-year-old seedlings of the second rotation.

2. Methods

MeadWestvaco's second rotation phosphorus fertilization trial was located near Andrews, South Carolina. The study involved reestablishing a P fertilization trial following harvest of the first rotation loblolly pine stand. The soil at the Andrews study site is classified as a Typic Albaquult, clayey, mixed, thermic (Bladen Series), having poor internal soil drainage and clayey subsoil with mixed mineralogy. Clayey aquults are common on the Lower Coastal Plain, and the Andrews study site is representative of hundreds of thousands of hectares in the southeastern United States. Drainage ditches were installed in 1963, and the area was disked and bedded prior to planting of loblolly pine in 1967. The first rotation study was harvested in 1989, and the second rotation study planted in 1991.

The study was designed as a split-block experiment with phosphorus rates applied in 1967 as the main plots and subsequent first and second rotation retreatments applied to subplots (see Table 1). The retreatments crossed perpendicular to the main plots; hence the study was randomized in two directions (rows and columns). The main plots were six beds wide (18.3 m) $\times$ 152.5 m (500 ft) long, and subplots were six beds by 30.5 m (100 ft) with 20 measurement trees. Each subplot had 20 measurement trees on the center two beds, and two treated buffer rows (two beds) to either side. On the center two rows there was 6.1 m of treated buffer at either end. Three rates of P were used at time of planting in 1967 (0, 28 and 56 kg/ha P). Superphosphate was broadcast uniformly over the ground, covering both bed and interbed areas on P-fertilized plots. Ordinary superphosphate (OSP) was used as the P fertilizer for the 28 kg/ha P treatment in all blocks and for the 56 kg/ha P treatment in Blocks 2 and 3. In Blocks 1 and 4, triple superphosphate (TSP) was used as the P source for the high P rate. Due to a calibration error the 56 kg/ha P treatment in Block 1 received 65 kg/ha P and the 56 kg/ha P treatment in Block 4 received 71 kg/ha P. Nitrogen treatments were applied at ages 2 and 4 in the first rotation, and two thinning regimes plus additional fertilizer treatments were applied in 1978 at age 11 years in the first rotation. Nitrogen applied at ages 2 and 4 had no effect on tree growth. Eighty percent of the subplots were row thinned in 1978, with every third row removed and leaving all of the measurement trees on the center two rows untouched. Row thinning had an effect on diameter growth between ages 11 and 15, but no effect on height growth. The fertilizer treatments used in 1978 were nitrogen applied at the rate of 103 kg/ha, phosphorus applied at the rate of 45 kg/ha and the combination of nitrogen plus phosphorus. The nitrogen source used was urea and the phosphorus source was triple superphosphate. Growth response in the first rotation to nitrogen plus phosphorus applied in 1978

Table 1
First and second rotation treatments at the Andrews study site.

First rotation P at planting
(1) Control, 1967
(2) 28 kg/ha P applied 1967
(3) 56 kg/ha P applied 1967
First and second rotation retreatments
(1) 112 kg/ha N applied 1969
Thinned, 103 kg/ha N, and 45 kg/ha P applied 1978
45 kg/ha P applied 1991
(2) 112 kg/ha N applied 1971
Thinned, and 103 kg/ha N applied 1978
(3) Thinned, and 45 kg/ha P applied 1978
(4) Thinned, 1978
45 kg/ha P applied 1991
(5) Unthinned, 1978

was no better than response to phosphorus applied alone in 1978. The entire field trial was 3.4 ha (8.5 ac) in size and included four replications of 15 treatments.

The field trial described above was one of eleven used by Wells et al. (1973) to calibrate loblolly pine response to P fertilizer with dilute HCl–H_2SO_4 extractable soil P. No aboveground response to nitrogen was observed in the first rotation. A strong response was obtained to P applied at planting and to P applied at age 11. The study was harvested in 1989 with tree foliage and limbs (i.e. logging slash) removed from the study plots. The site was rebedded in 1990 and replanted with half-sib Family 7–56 in 1991. Competition control consisted of 220 cm^3/ha (3 oz/ac) of Oust plus 2.34 l/ha (2 pints/ac) Velpar sprayed over the entire study area the spring following planting. As a follow-up treatment, Roundup (2% solution) was sprayed directly on surviving weeds twice afterward during 1991. Six of the 15 first rotation treatments were fertilized with TSP at the rate of 45 kg/ha P in June 1991, enabling one to evaluate all possible combinations of P applied in 1967, 1978 and/or 1991.

Soil samples were collected, prior to harvest in 1989, from 24 study plots. Twenty sample points were randomly located on each plot, and an 8-cm diameter root auger (manufactured by Eijkelkamp, The Netherlands) was used to collect 0–10 cm soil cores at each spot. The six treatments represented all combinations of the 1967 P treatments and the 1978 P treatments. Duplicate subsamples from each plot were analyzed for dilute HCl–H_2SO_4 extractable soil P (Olsen and Sommers, 1982).

Five extra trees were planted on each plot and harvested after 1 year of the second rotation to determine pine biomass response and phosphorus uptake. Needles and stems were separated, dried, weighed and analyzed for N, P, K, Ca and Mg. Conventional foliage samples were collected from ten individual trees per plot at ages 2 and 3. Trees to be sampled were selected at random from the tallest three-quarters of the trees on each plot at age 2. Composite foliage samples were also collected at age 5 from five trees per plot. These trees were a random selection from the ten previously sampled which remained amongst the tallest three-quarters of trees at age 4. In each case needle samples were dried, weighed and analyzed for N, P, K, Ca and Mg. Nitrogen was determined using a micro-Kjeldahl procedure, and the other elements measured by microwave digestion and inductively coupled plasma (ICP) spectrophotometry. Tree heights were measured annually through age 5 and again at age 9, and tree diameter at breast height (dbh) measured at ages 3, 4, 5 and 9. Tree volume was calculated using an allometric equation. Volume growth index was calculated as the difference between actual age 5 average tree volumes and that predicted by a regression equation. The regression equation related age 5 volumes to volume at age 3 on plots which were fertilized with P at the beginning of the second rotation. The volume growth index assumes tree growth through the third growing season was not limited by P availability. Use of the volume growth index was important because it made the block effect in the analysis of variance (ANOVA) nonsignificant.

The purpose of our experiment was to characterize the efficacy of residual phosphorus to support the growth of second rotation loblolly pine. We also sought to evaluate the effects of residual P on soil and foliar P on one site. Tree volume at age 5 and volume growth index were evaluated using analyses of variance (ANOVA). The relationship of residual phosphorus with HCl–H_2SO_4 extractable soil P and foliar P were characterized using regression analyses. Foliar P was also characterized using histograms (40–80 foliar analyses each) for specific P treatments. We further evaluated the relationship of foliar P at age 3 and volume at age 5 in the second rotation using a regression analysis. Finally, we presented data from age 9 for selected treatments to show the response to residual P continued for that length of time. Where needed for clarity, treatments were identified by amount of P applied at three times (1967, 1978 and 1991), for example 0–0–0 for the true control and 28–0–0 for 28 kg/ha P applied in 1967 with no P applied in 1978 or 1991.

3. Results

At the end of the first rotation (age 22), the control plots (0–0–0) averaged 19.4 m in dominant and codominant tree height, and the 56 kg/ha P in 1967 plots (56–0–0) averaged 22.2 m, a difference of 2.8 m (Everett and Patterson, 1991). This difference showed the effects of P fertilization lasted throughout the first rotation. Statistical analyses, for age 5 in the second rotation, showed highly significant interactions between tree response to phosphorus applied in 1967 and response to retreatments applied in 1978 and 1991 (ANOVA not shown). The split-block experimental design placed restrictions on randomization of treatments which made it difficult to evaluate 1967 P treatment $\times$ retreatment interactions. To fully evaluate the results it was necessary to subdivide the data. Two data sets were created based on whether or not plots were P-fertilized at the beginning of the second rotation in 1991. On plots where P was applied at the beginning of the second rotation (1991), 5-year growth was the same regardless of whether plots got fertilized or not during the first rotation (Table 2). Trees on the 24 plots which were fertilized with phosphorus in 1991 (included 0–0–45, 0–45–45, 28–0–45, 28–45–45, 56–0–45, and 56–45–45), averaged 7.72 m in height, 10.7 cm in diameter and 0.0283 m^3 in volume at age 5. The four plots P-fertilized for the first time in 1991 (0–0–45) averaged 7.59 m in height, 10.4 cm in diameter, and volume of 0.0274 m^3/tree.

Table 2
Average tree size at age 5 by treatment for Andrews study site.

Phosphorus (kg/ha)			Height (m)	Diameter (cm)	Basal area (cm^2/tree)	Volume (m^3/tree)	VGI[a] (m^3/tree)
1967	1978	1991					
0	0	0	6.74	9.1	68	0.0196	−0.0042
0	45	0	7.26	9.9	77	0.0238	−0.0014
0	0	45	7.59	10.4	86	0.0274	0
0	45	45	7.81	10.7	90	0.0291	0.0003
28	0	0	7.50	10.2	82	0.0258	−0.0022
28	45	0	7.59	10.4	86	0.0274	−0.0011
28	0	45	7.72	10.4	86	0.0280	0.0003
28	45	45	7.53	10.4	87	0.0274	0
56	0	0	7.75	10.7	89	0.0286	0
56	45	0	7.81	10.7	90	0.0291	0.0008
56	0	45	7.84	10.4	87	0.0283	0
56	45	45	7.81	10.7	90	0.0291	−0.0003

[a] Volume growth index.

Table 3
ANOVA excluding plots which received phosphorus in 1991.

Source	P			
	Height	Basal area	Volume	VGI[a]
Block	0.01	0.01	0.01	0.68
1967 P treatment	0.01	0.01	0.01	0.01
1978 P treatment	0.07	0.16	0.13	0.01
1967 P × 1978 P	0.34	0.33	0.36	0.12

[a] Volume growth index.

Excluding plots which were fertilized with 45 kg/ha P in 1991 (included 0–0–0, 0–45–0, 28–0–0, 28–45–0, 56–0–0 and 56–45–0), analyses of variance (ANOVA) results indicated a significant height, basal area and volume response to P applied in 1967. A response to P applied in 1978 was not evident in height, basal area or volume ANOVAs (Tables 2 and 3). On the control plots, which had never been fertilized with phosphorus (0–0–0), trees averaged 6.74 m in height, 9.1 cm in diameter, and 0.0196 m^3 in volume. The difference in volume between the controls (0–0–0) and all of the plots fertilized with 45 kg/ha P in 1991 (0–0–45, 0–45–45, 28–0–45, 28–45–45, 56–0–45, and 56–45–45) was 0.0087 m^3/tree or a 44% response to phosphorus. Second rotation volume on plots only fertilized with 28 kg/ha P in 1967 (28–0–0) was 0.0258 m^3/tree. This tree volume was 0.0062 m^3/tree or 31% more than the controls (0–0–0) but 0.0025 m^3/tree or 9% less than plots which were refertilized in 1991. Plots only fertilized with 56 kg/ha P in 1967 (56–0–0) had 0.0286 m^3/tree or 101% of the volume of plots refertilized in 1991.

The differences in 5-year growth between the first rotation and second rotation were dramatic (Fig. 1). Controls (0–0–0) in the first rotation were 2.5 m tall at age 5, while controls (0–0–0) in the second rotation were 6.7 m tall. Plots fertilized with P in the first rotation (28–0–0 and 56–0–0) had a height of 4.5 m at age 5, while plots fertilized with P in the second rotation (including 0–0–45, 0–45–45, 28–0–45, 28–45–45, 56–0–45, and 56–45–45) had a average height of 7.7. We attribute these differences between rotations to differences in competition control and improved genetics between 1967 and 1991. These results indicate that pine plantations on clayey aquults in the southeastern United States are sustainable, and that management differences have resulted in large increases in pine growth from one rotation to the next.

Analyses of the volume growth between ages 3 and 5 indicated plots which received 45 kg/ha or less in the first rotation, and not refertilized in the second rotation (0–0–0, 0–45–0, 28–0–0), were not keeping pace (VGI of −0.0042, −0.0014, and −0.0022 m^3/tree, respectively) with the plots fertilized in 1991. Regression analysis of the 24 plots fertilized in the second rotation (including 0–0–45, 0–45–45, 28–0–45, 28–45–45, 56–0–45, and 56–45–45) produced the following correlation between age 3 volume and age 5 volume (both in m^3):

$$\text{volume (age 5)} = 0.01415 + 4.526 \times \text{volume (age 3)}, \quad R^2 = 0.94$$

The difference between actual age 5 volume and that predicted by the above equation was then calculated for each plot and termed the volume growth index (VGI). Analyses of variance, excluding plots fertilized in 1991 (including 0–0–0, 0–45–0, 28–0–0, 28–45–0, 56–0–0 and 56–45–0), showed significant effects of both the 1967 P treatment and the 1978 P treatment on the VGI (Tables 2 and 3). The controls (0–0–0) produced −0.0042 m^3/tree or 15% less VGI than would have been expected if the plots had been fertilized in 1991. The 28 kg/ha P in 1967 treatment (28–0–0) produced −0.0022 m^3/tree or 8% less and the 45 kg/ha P in 1978 (0–45–0) treatment produced −0.0014 m^3/tree or 5% less VGI than would have been expected if those plots had been P-fertilized in the second rotation. The 56 kg/ha P in 1967 treatment (56–0–0) produced no less VGI than would have been expected with refertilization. Analyses of forest floor litter in three studies conducted in the southeastern United States indicate substantial quantities of phosphorus are present in the litter at the end of the first rotation (Comerford et al., 2002; Harding and Jokela, 1994; Richter et al., 2006). Mineralization of P in old litter incorporated into the beds in 1990 may be responsible for much of the efficacy of the 56 kg/ha P in 1967 treatment (56–0–0).

In most ANOVAs, experimental blocks had a significant effect on tree growth. Differences in ground elevation resulted in the watertable level being typically 24–36 cm closer to the surface in Block 4 than in Block 1 (based on monthly monitoring of 12 wells on the study site). For a particular fertilization treatment, tree growth was usually better in Blocks 1 and 2 than in Blocks 3 and 4. However, the watertable depth gradient could only be partially described using the four experimental blocks. The blocks encompassed discrete areas, each 0.85 ha in size, whereas watertable level varied continuously across the 3.4-ha study site.

Soil samples collected immediately prior to first rotation stand harvest in 1989 showed the effects of fertilization in 1967 and/or 1978 (including 0–0–0, 0–45–0, 28–0–0, 28–45–0, 56–0–0 and 56–45–0 treatments). Dilute HCl-H_2SO_4 soil test P values for the 0–10 cm depth were increased from 4.6 μg/g to 7.3 μg/g by application of 45 kg/ha either 11 or 22 years prior to sampling (Fig. 2). Taking into consideration the shallow sampling depth and

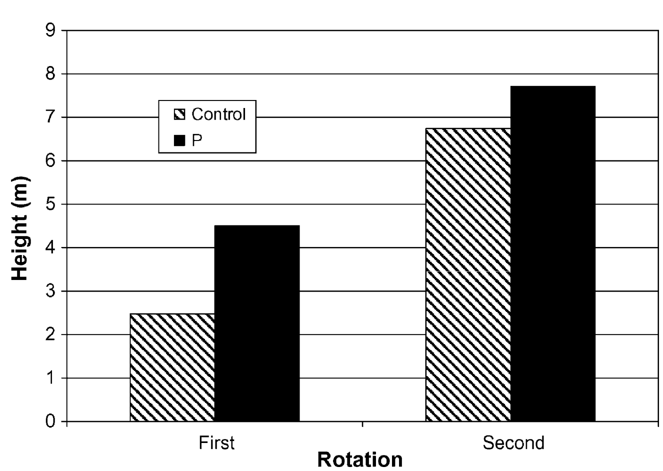

Fig. 1. Height at age 5 in the first and second rotation. Second rotation P includes all plots fertilized in 1991 whether or not previously fertilized in the first rotation.

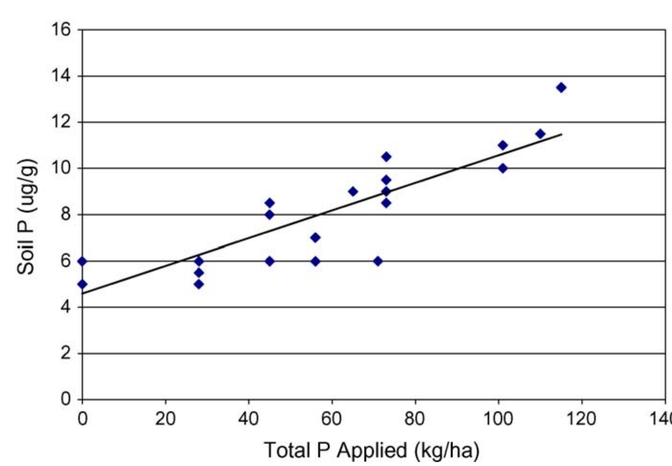

Fig. 2. Dilute HCl–H_2SO_4 extractable soil P as a function of phosphorus fertilizer applied in the first rotation (1967 and 1978).

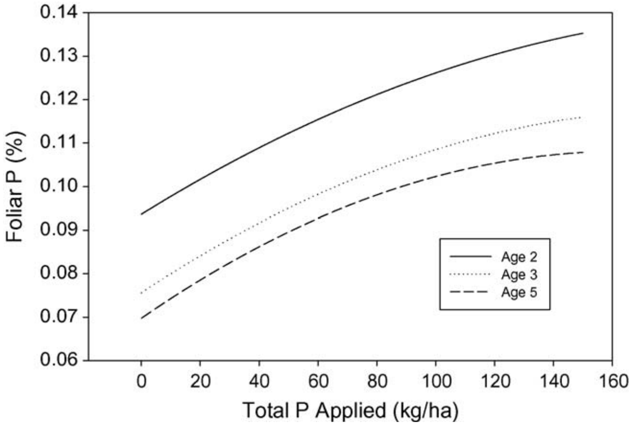

Fig. 3. Relationships between foliar P concentration in second rotation trees at ages 2, 3 and 5, and total P fertilizer applied in 1967, 1978 and/or 1991.

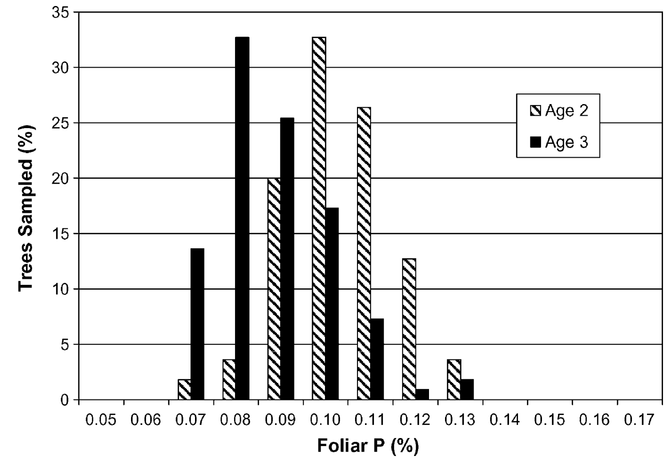

Fig. 5. Distribution of foliar P concentrations on plots fertilized with 28 kg/ha P in 1967 (28–0–0) at ages 2 and 3 in the second rotation ($N = 80$).

actual soil bulk density, the quantity of phosphorus accounted for was 4.9 kg/ha for control and 7.7 kg/ha for 45 kg/ha P applied. The following equation describes the relationship between P applied and residual P fertilizer in the soil accounted for (both in kg/ha):

$$\text{residual P fertilizer} = 0.06396 \times (\text{1967 P and 1978 P rates}), \quad R^2 = 0.75$$

Foliar phosphorus analyses proved to be a very useful indicator of phosphorus availability and a good way to evaluate the benefits of residual phosphorus fertilizer. For example, phosphorus uptake (in mg P/tree) of 1-year-old trees was significantly correlated with volume at age 5 (in m^3):

$$\text{volume (age 5)} = 0.01854 + 0.00003784 \times \text{P uptake (age 1)}, \quad R^2 = 0.36$$

Both P fertilizer effects and microsite variation in watertable level were accounted for by the P uptake variable. Phosphorus uptake of 266 mg P/tree was sufficient to produce a volume of 0.0283 m^3/tree at age 5, the average tree volume for all plots which were fertilized in 1991 (including 0–0–45, 0–45–45, 28–0–45, 28–45–45, 56–0–45, and 56–45–45).

Due to competition control, and perhaps improved genetics, the 1-year-old trees in the second rotation had higher foliar P concentrations than 1-year-old trees in the first rotation. Foliar P at age one on control plots was 0.090% in the first rotation and 0.130% in the second rotation. Similar differences between rotations were found at age 2. Two-year-old unfertilized controls in the first rotation had 0.072% P and 0.095% P in the second rotation. These results suggest competition control had a strong influence on phosphorus availability through the second growing season. Phosphorus in decomposing litter and soil organic matter was apparently much more available to pines in the first 2 years of the second rotation than at the beginning of the first rotation. Such differences among treatments in foliar P are striking given that tree growth was substantially better on all treatments in the second rotation than in the first rotation (Fig. 1).

Foliar P concentrations in the second rotation decreased dramatically from ages 2 to 3, but only slightly from ages 3 to 5 (Fig. 3). R^2 values for these equations were 0.65 for age 2, 0.69 for age 3, and 0.53 for age 5. Detailed analyses of foliar P at age 3 indicated there was considerable tree-to-tree variation within each treatment (Figs. 4–7). On control plots (0–0–0) none of the trees sampled had foliar P concentrations of 0.10% or above at age 3. Twenty-nine percent, 40% and 75% of the trees fertilized with 28 kg/ha P in 1967 (28–0–0), 56 kg/ha P in 1967 (56–0–0), and 45 kg/ha P in 1991 (0–0–45), respectively, had foliar P concentrations of 0.10% or above at age 3. Average tree volume at age 5 was correlated with foliar P at age 3 (Fig. 8, $R^2 = 0.49$). Foliar P concentrations of 0.10% P or above, at age 3, showed no additional volume response. Based on regression analysis (Fig. 3) one would need to have applied 66 kg/ha P in the first rotation to maintain foliar P levels at 0.10% P at age 3 in the second rotation without

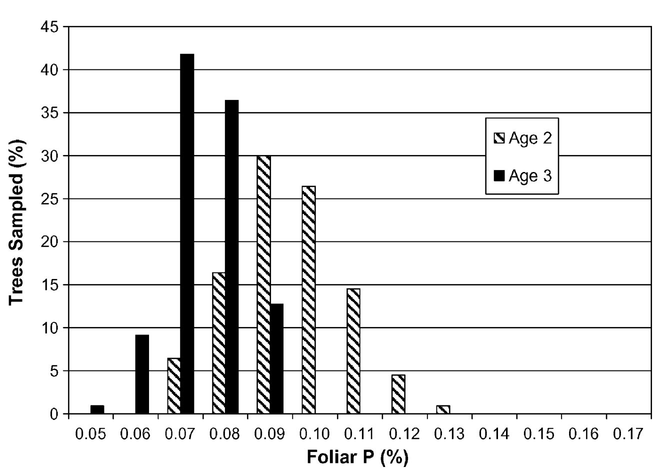

Fig. 4. Distribution of foliar P concentrations on control plots (0–0–0) at ages 2 and 3 in the second rotation ($N = 80$).

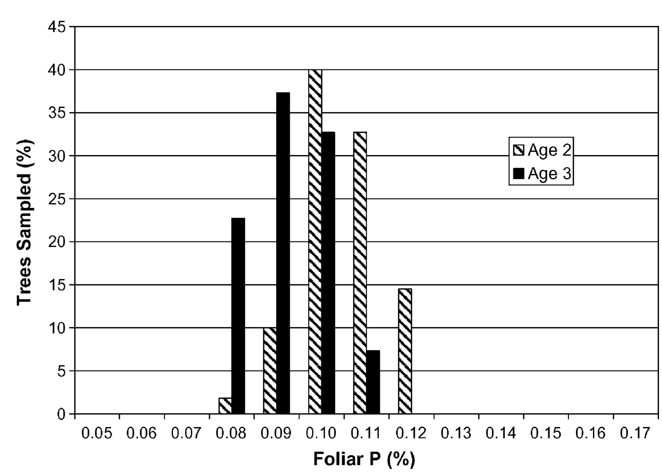

Fig. 6. Distribution of foliar P concentrations on plots fertilized with 56 kg/ha P in 1967 (56–0–0) at ages 2 and 3 in the second rotation ($N = 40$).

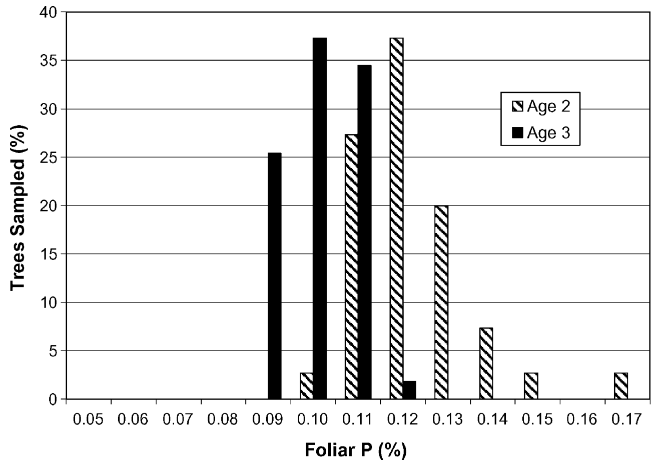

Fig. 7. Distribution of foliar P concentrations on plots fertilized with 45 kg/ha P in 1991 (0–0–45) at ages 2 and 3 in the second rotation (N = 40). Only data for plots fertilized for the first time in 1991 are shown.

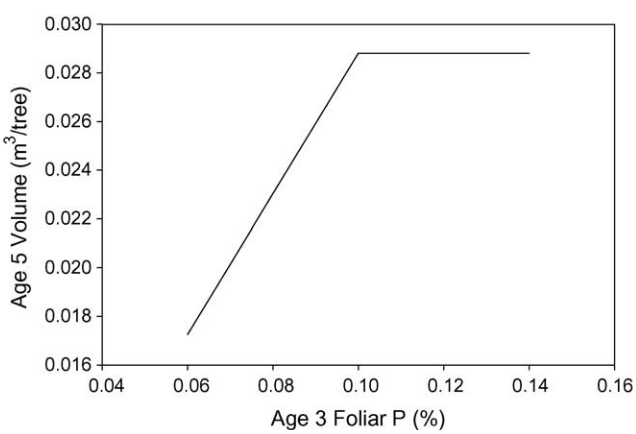

Fig. 8. Relationship between second rotation foliar P concentration at age 3 and second rotation tree volume (in m^3/tree) at age 5 (R^2 = 0.49).

additional P fertilizer being applied at the beginning of the second rotation.

Response to residual phosphorus continued through age 9 in 2000 (the last time this study was measured). Trees on control plots (0–0–0) averaged 11.2 m in height and had 150 m^3/ha volume at age 9. Plots fertilized with 45 kg/ha P in 1991 (including 0–0–45, 28–0–45, and 56–0–45) averaged 13.0 m in height and had 214 m^3/ha or 43% more volume than the controls at age 9. The 28 kg/ha P in 1967 treatment (28–0–0) had tree height of 12.3 m and volume of 185 m^3/ha, 14% less than the plots P-fertilized in 1991, but 23% more than the controls (0–0–0). Similarly, a regression estimate of the effect of 45 kg/ha P applied in 1967 (based on analysis of 0–0–0, 28–0–0, and 56–0–0) had tree height of 12.5 m and tree volume of 194 m^3/ha, 9% less than the plots P-fertilized in 1991, but 29% more than the controls at age 9.

4. Conclusion

Loblolly pine growth was substantially better in the second rotation than in the first rotation. We attribute these differences between rotations to differences in competition control and improved genetics between 1967 and 1991. These results indicate that pine plantations on clayey aquults in the southeastern United States are sustainable, and that management differences have resulted in large increases in pine growth from one rotation to the next.

Mineralization of P in old litter incorporated into the beds in 1990 may be responsible for much of the efficacy of the 28 kg/ha P in 1967 treatment (28–0–0), and 56 kg/ha P in 1967 treatment (56–0–0). In addition, dilute HCl–H_2SO_4 soil test P values for the 0–10 cm depth indicated 2.8 kg/ha of residual fertilizer P would be available in the mineral soil due to application of 45 kg/ha P in the first rotation (1967 or 1978). As described in Richter et al., 2006, slowly cycling P fractions such as soil organic P, aluminum-bound P, or iron-bound P may become available over time spans of decades. The results indicate there was ample P available on all treatments through age 2 in the second rotation. Beginning at age 3, growth limitations due to inadequate P availability were evident on the 28 kg/ha P in 1967 treatment (28–0–0) and the 45 kg/ha P in 1978 treatment (0–45–0). At age 3, the 28 kg/ha P treatment (28–0–0) had foliar P of 0.09%, but never the less at age 9 this treatment had tree height of 12.3 m and volume of 185 m^3/ha, 14% less than the plots P-fertilized in 1991, but 23% more than the controls (0–0–0). Such a growth response to a low P rate applied 24 years before the second rotation was planted indicates residual phosphorus fertilizer is cycling through the forest ecosystem at a rapid rate. While volume growth of the 56 kg/ha P in 1967 treatment (56–0–0) was comparable to that of the plots refertilized in 1991, foliar P concentrations at age 3 indicated that phosphorus availability was sub-optimal. Based on foliar analyses, we recommend refertilizing stands fertilized with 45 kg/ha P in the first rotation by age 3 in the second rotation.

References

Albaugh, T.J., Allen, H.L., Fox, T.R., 2007. Historical patterns of forest fertilization in the Southeast United States from 1969 to 2004. South. J. Appl. For. 31 (3), 129–137.

Ballard, R., 1978. Effect of first rotation phosphorus applications on fertilizer requirements of second rotation radiate pine. N. Z. J. For. Sci. 8, 135–145.

Ballard, R., 1980. Phosphorus nutrition and fertilization of forest trees. In: Khasawneh, F.E., Sample, E.C., Kamprath, E.J. (Eds.), The Role of Phosphorus in Agriculture. Am. Soc. Agron., Madison, WI, pp. 763–804.

Ballard, R., Pritchett, W.L., 1975a. Evaluation of soil testing methods for predicting growth and response of *Pinus elliottii* to phosphorus fertilization. Soil Sci. Soc. Am. Proc. 39, 132–136.

Ballard, R., Pritchett, W.L., 1975b. Soil testing as a guide to phosphorus fertilization of young pine plantations in the coastal plain. Agric. Exp. Stn. Tech. Bull. no. 778, Univ. of Florida.

Barrow, N.J., 1980. Evaluation and utilization of residual phosphorus in soils. In: Khasawneh, F.E., Sample, E.C., Kamprath, E.J. (Eds.), The Role of Phosphorus in Agriculture. Am. Soc. Agron., Madison, WI, pp. 333–359.

Comerford, N.B., Fisher, R.F., 1982. Use of discriminant analysis for classification of fertilizer-responsive sites. Soil Sci. Soc. Am. J. 46, 1093–1096.

Comerford, N.B., McLeod, M., Skinner, M., 2002. Phosphorus form and bioavailability in the pine rotation following fertilization: P fertilization influences P form and potential bioavailability to pine in the subsequent rotation. For. Ecol. Manage. 169, 203–211.

Comerford, N.B., Skinner, M.F., 1989. Residual phosphorus solubility for an acid, clayey, forested soil in the presence of oxalate and citrate. Can. J. Soil Sci. 69, 111–117.

Crous, J.W., Morris, A.R., Scholes, M.C., 2007. The significance of residual phosphorus and potassium fertilizer in countering yield decline in a fourth rotation of *Pinus patula* in Swaziland. South Hemisphere For. J. 69 (1), 1–8.

DeBell, D.S., Hook, D.D., McKee Jr., W.H., Askew, J.L., 1984. Morphology and physiology of loblolly pine roots under various water levels and phosphorus treatments. For. Sci. 30, 705–714.

Everett, C.J., Patterson, S.C., 1991. Effects of phosphorus fertilization at planting on loblolly pine fine root biomass at age 20 years. In: Dyck, W.J., Mees, C.A. (Eds.), Long-term Field Trials to Assess Environmental Impacts of Harvesting. Proceedings, IEA/BE T6/A6 Workshop, Florida, USA, February 1990. IEA/BE T6/A6 Report No. 5. Forest Research Institute, Rotorua, New Zealand, FRI Bulletin No. 161, pp. 177–185.

Flinn, D.W., James, J.M., Hopmans, P., 1982. Aspects of phosphorus cycling in radiata pine on a strongly phosphorus-adsorbing soil. Aust. For. Res. 12 (1), 19–35.

Fox, T.R., Jokela, E.J., Allen, H.L., 2007a. The development of pine plantation silviculture in the southern United States. J. For. 105 (7), 337–347.

Fox, T.R., Allen, H.L., Albaugh, T.J., Rubilar, R., Carlson, C.A., 2007b. Tree nutrition and forest fertilization of pine plantations in the southern United States. South. J. Appl. For. 31 (1), 5–11.

Gent Jr., J.A., Allen, H.L., Campbell, R.G., Wells, C.G., 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. South. J. Appl. For. 10, 124–128.

Gentle, S.W., Humphreys, F.R., Lambert, M.J., 1986. Continuing response of *Pinus radiata* to phosphate fertilizers over two rotations. For. Sci. 32, 822–829.
Harding, R.B., Jokela, E.J., 1994. Long-term effects of forest fertilization on site organic matter and nutrients. Soil Sci. Soc. Am. J. 58, 216–221.
Kushla, J.D., Fisher, R.F., 1980. Predicting slash pine response to nitrogen and phosphorus fertilization. Soil Sci. Soc. Am. J. 44, 1303–1306.
McKee Jr., W.H., Hook, D.D., DeBell, D.S., Askew, J.L., 1984. Growth and nutrient status of loblolly pine seedlings in relation to flooding and phosphorus. Soil Sci. Soc. Am. J. 48, 1438–1442.
McKee Jr., W.H., Wilhite, L.P., 1986. Loblolly pine response to bedding and fertilization varies by drainage class on Lower Atlantic Coastal Plain sites. South. J. Appl. For. 10, 16–21.
Olsen, S.R., Sommers, L.E., 1982. Phosphorus. 2nd ed. In: Page, A.L. (Ed.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. Agron. Monogr. no. 9, 2nd ed., Am. Soc. Agron., Madison, WI, pp. 403–430.
Pritchett, W.L., 1968. Progress in the development of techniques and standards for soil and foliar diagnosis of phosphorus deficiency in slash pine. In: Bengtson, G.W. (Ed.), Forest Fertilization, Theory and Practice. Gainesville, FL, 18–21 April 1967. Tennessee Valley Authority, Muscle Shoals, AL, pp. 81–87.
Pritchett, W.L., Comerford, N.B., 1982. Long-term response to phosphorus fertilization on selected southeastern Coastal Plain soils. Soil Sci. Soc. Am. J. 46, 640–644.
Richter, D.D., Allen, H.L., Li, J., Markewitz, D., Raikes, J., 2006. Bioavailability of slowly cycling soil phosphorus: major restructuring of soil P fractions over four decades in an aggrading forest. Oecologia 150 (2), 259–271.
Torbert Jr., J.L., Burger, J.A., 1984. Long-term availability of applied phosphorus to loblolly pine on a Piedmont soil. Soil Sci. Soc. Am. J. 48, 1174–1178.
Turner, J., 1982. Long-term superphosphate trial in regeneration of *Pinus radiate* at Belanglo State Forest. N. S. W. Aust. For. Res. 12, 1–9.
Turner, J., Lambert, M.J., 1985. Soil phosphorus forms and related tree growth in a long term Pinus radiate phosphate fertilizer trial. Commun. Soil Sci. Plant Anal. 16, 275–288.
Turner, J., Lambert, M.J., 1986. Fate of applied nutrients in a long-term superphosphate trial in *Pinus radiate*. Plant Soil 93, 373–382.
Turner, J., Lambert, M.J., Humphreys, F.R., 2002. Continuing growth response to phosphate fertilizers by a Pinus radiata plantation over fifty-years. For. Sci. 48, 556–568.
Wells, C.G., Crutchfield, D.M., Berenyi, N.M., Davey, C.B., 1973. Soil and foliar guidelines for phosphorus fertilization of loblolly pine. USDA For. Serv. Res. PapSE-110.
Wells, C.G., Craig, J.R., Kane, M.B., Allen, H.L., 1986. Foliar and soil tests for the prediction of phosphorus response in loblolly pine. Soil Sci. Soc. Am. J. 50, 1330–1335.