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Abstract
The response of sweetgum (*Liquidambar styraciflua* L.) seedlings grown either without or inoculated with the vesicular-arbuscular mycorrhizal (VAM) fungus *Gigaspora margarita*'Becker' and 'Hall' to 25, 50, and 100 ppm soil phosphorus (P) and adjusted soil pHs of 4.5, 5.5, 6.5, and 7.8 was observed during the first growing season. The best seedling growth for both VAM and noninoculated seedlings occurred at soil pH 4.5 and 100 ppm of soil P where mean heights and top dry weights averaged > 28 cm and 8 g, respectively. As soil pH increased, seedling growth decreased significantly and at pH 7.8 the seedlings averaged < 4 cm in height regardless of the soil P level or mycorrhizal condition. Seedling growth at all pH levels, except pH 7.8, decreased with decreasing soil P. Inoculated seedlings were significantly larger than noninoculated seedlings at 25 ppm soil P and pHs 4.5 and 5.5. Soil P, soil pH, and mycorrhizal condition significantly influenced nutrient levels in plant parts. Soil nutrient levels varied significantly with soil pH.

Keywords
nursery practices, seedling production, soil acidity

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Soil Phosphorus and pH Influence the Growth of Mycorrhizal Sweetgum[1]

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ABSTRACT

The response of sweetgum (*Liquidambar styraciflua* L.) seedlings grown either without or inoculated with the vesicular–arbuscular mycorrhizal (VAM) fungus *Gigaspora margarita* 'Becker' and 'Hall' to 25, 50, and 100 ppm soil phosphorus (P) and adjusted soil pHs of 4.5, 5.5, 6.5, and 7.8 was observed during the first growing season. The best seedling growth for both VAM and noninoculated seedlings occurred at soil pH 4.5 and 100 ppm of soil P where mean heights and top dry weights averaged > 28 cm and 8 g, respectively. As soil pH increased, seedling growth decreased significantly and at pH 7.8 the seedlings averaged < 4 cm in height regardless of the soil P level or mycorrhizal condition. Seedling growth at all pH levels, except pH 7.8, decreased with decreasing soil P. Inoculated seedlings were significantly larger than noninoculated seedlings at 25 ppm soil P and pHs 4.5 and 5.5. Soil P, soil pH, and mycorrhizal condition significantly influenced nutrient levels in plant parts. Soil nutrient levels varied significantly with soil pH.

Additional Index Words: **nursery practices, seedling production, soil acidity.**

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THE increased establishment of hardwood plantations by the forest industry in the southern United States has created a need for improved production of plantable hardwood nursery stock. Sweetgum (*Liquidambar styraciflua* L.) is one of the most promising hardwood species used because of its ability to grow rapidly on a wide variety of sites.

Studies have shown that mycorrhizal sweetgum seedlings are able to achieve plantable size (Belanger and McAlpine, 1975) in acidic soils with extractable phosphorus levels as low as 5 to 8 ppm while uninfected seedlings do not exceed 7 cm in height until extractable soil phosphorus levels reach 70 to 80 ppm (Kormanik et al., 1977a; 1977b; 1977c; Schultz et al., 1979, 1981; Brown et al., 1981). Soil pH values in these studies have been controlled at about 5.6 by adjusting the level of soil calcium to 1,120 kg/ha. This study was designed to determine the effect of adjusted soil pH and extractable phosphorus on noninoculated and VAM sweetgum seedlings infected with the VA fungus *Gigaspora margarita* 'Becker' and 'Hall'.

Soil phosphorus levels of 25, 50, and 100 ppm used in the study provided levels above and below the approximate threshold for uninfected sweetgum seedling response (Kormanik, Schultz, and Bryan, unpublished data). Soil pH values of 4.5, 5.5, 6.5, and 7.8 were selected to provide a wide range of conditions from an unlimed acid soil to a highly limed soil.

MATERIALS AND METHODS

The soil for the study was a Bladen series (clayey, mixed, thermic Typic Ochraqualt) sandy loam topsoil, obtained from a slash pine (*Pinus elloitti* Engelm.) plantation near Hinesville, Ga. The Bladen soil was chosen for this study because it is well drained, very acidic, extremely low in extractable P, and is a typical coastal plain soil that supports the growth of natural sweetgum. The soil was collected and tested to determine pH, nutrient content, particle-size distribution, and percent organic matter (Table 1).

Soil pH was determined using the 1:1 soil-to-water method of Peech (1965). The dilute double-acid technique (0.025*N* H_2SO_4 – 0.05*N* HCl) was used for extractable soil nutrients (Issac and Jones, 1971). Extractable soil P was detected with a Technicon Auto Analyzer II (Industrial Method no. 94-70W, Technicon Instruments Corp., Tarrytown, N.Y.) and the other extractable nutrients were analyzed on a Perkin Elmer Model no. 560 (P-E 560) Atomic Absorption Spectrophotometer (Agricultural Method AY-2, Perkin–Elmer Corp., Norwalk, Conn.). Total Kjeldahl nitrogen (TKN) and total phosphorus were determined using Industrial Methods no. 325-74W and 327-74W, respectively, for the Technicon Auto Analyzer II. Particle-size distribution was determined by the hydrometer method (Bouyoucus, 1936; Day, 1965). Organic matter percent was determined by digestion with $K_2Cr_2O_2$ and H_2SO_4. Water, H_3PO_4, NaF, and diphenylthaline were added before titration with $Fe[(NH_4)_2\,SO_4]_2 \cdot 6H_2O$ (Jackson, 1958).

The soil was sieved through a 1.3-cm (1/2 in) mesh screen to remove debris. A 1:4 perlite-to-soil mixture by volume was used to provide adequate infiltration and percolation of water. The soil was fumigated with methyl bromide (Dowfume MC-2, Dow Chemical Co.) at the rate of 1 can per 10 m^2 of soil 15 cm deep. This rate has been found to effectively eliminate pathogens or natural mycorrhizal inoculum in soils collected from the field (Menge, 1978; Riffle, 1980).

As an initial fertilizer treatment, N, P, and K in the form of a commercial 10 · 10 · 10 fertilizer was mixed with the soil at a rate of 280 kg/ha. A supplemental supply of N was applied in solution every 2 weeks throughout the growing season in the form of ammonium nitrate for a total of 1,681 kg/ha. Previous studies indicated that these fertilizer levels are optimal for the growth of mycorrhizal sweetgum seedlings in soil of similar nutrient status and texture (Kormanik et al., 1977a; Brown et al., 1981).

Dicalcium phosphate was used to adjust the soil P levels to 25, 50, and 100 ppm. The soil–perlite mixture was analyzed for extractable phosphorus and it was calculated that after addition of the NPK fertilizer the soil would contain 5.9 kg/ha of extractable P and, therefore, 38.62, 94.65, and 206.71 kg/ha of P, respectively, were required to raise the levels to the desired treatment rates.

Soil pH values were achieved by adding 0, 85, 180, or 450 g of $Ca(OH)_2$ to the soil mixes. These levels were determined from a pH vs. the level of $Ca(OH)_2$ plot of data obtained by incubating samples of the soil–perlite mixture with different amounts of $Ca(OH)_2$ for 4 weeks. It was calculated that $CaHPO_4$, at the levels used, would have a minor effect on pH and this factor was ignored. At 4 weeks, after the $Ca(OH)_2$ had been given time to react with the soil, the actual pHs were determined to be 4.9, 5.7, 6.7, and 7.8 ± 0.1. This was desirable since it was anticipated that periodic ammonium nitrate additions and watering would cause some decrease in pH.

Soil amendments were blended with the prepared soil in a cement mixer for 30 min, one treatment at a time. Each treatment consisted of 12 pots 20 cm in diameter each.

The species of VAM fungus selected for use in the study was *Gigaspora margarita* 'Becker' and 'Hall' obtained from Dr. R. W. Roncadori of the Plant Pathology Dep., University of Georgia. Soil was inoculated with the fungus by mixing 500 spores per pot. The inoculum was produced in pots on *Coleus* spp. (Lour.) and the spores were collected by subjecting the soil to a nematode illutriation technique (Sasser and Jenkins, 1960).

Sweetgum seeds were collected in 1978 from an upland (half-sib) selection on the Scull Shoals Experimental Forest in Green Co., Georgia. Seeds were soaked in H_2O at 34°C for 30 d, surface-sterilized in 25% Chlorox for 10 min, rinsed with water, soaked in 0.01*N* HCl for 10 min to remove any trace of Chlorox, and planted 10 May 1979 at a rate of 6 to 8 per pot. After establishment, the seedlings were thinned to 1 per pot.

Soil samples were analyzed for extractable P and pH 4 weeks after the study began, at the halfway point, and at the end of the study (Table 2). Seedling heights and root collar diameters were recorded every 2 weeks.

Final height and diameter measurements were taken and the seedlings were harvested on 8 Oct. 1979. Soil samples were taken from each pot and analyzed for pH, total P, TKN, and extractable P, K, Ca, Fe, Mg, Mn, Al, and Zn. The seedlings were removed from the pots by gently washing the soil from the roots. Samples of the fine feeder roots were taken from four places on the root systems of each seedling and were stored in fomalin acetic alcohol (FAA) for mycorrhizal analysis. Tops and roots of each seedling were separated, placed in labeled bags, and dried to constant weight in a forced draft oven at 70°C. Leaf, stem, and root weights were recorded, and these plant parts were analyzed for P, Ca, N, K, Fe, Mg, Mn, Al, Zn, and Cu.

Levels of these nutrients, except for total Kjeldahl nitrogen, were determined by digesting plant parts in a mixture of nitric, perchloric, and sulfuric acids. Phosphorus was detected using Industrial Method no. 144-71A, Technicon Instruments Corp., Tarrytown, N.Y., for the Technicon Auto Analyzer II. The other elements were detected on a P-E 560 Atomic Absorption Spectrophotometer (Agricultural Analytical Method AY-5). Total Kjeldahl nitrogen was determined with a sulfuric–selenous acid digest and analysis using Industrial Method no. 334-74A for the Technicon Auto Analyzer II.

Table 1—Characteristics of the study soil (Bladen sandy loam).

Organic matter	pH	Particle-size distribution		Nutrient content: Extractable				Nutrient content: Total	
%		%		ppm					
3	4.4	Sand	76	Al	122	Mn	8	TKN	1,389
		Silt	17.5	Mg	59	Zn	2	P	130
		Clay	6.5	Fe	133	K	28		
				Ca	186	P	33		

Table 2—Soil analysis comparing desired treatment rates for the Bladen sandy loam soil-perlite mixture to measured values on three sampling dates.

Desired soil treatments		Sampling date—1980					
		15 June	22 Aug.	8 Oct.	15 June	22 Aug.	8 Oct.
P, ppm	pH	pH	pH	pH	P, ppm	P, ppm	P, ppm
25	4.5	4.9†	4.9	4.8	25.0	26.0	27.0
25	5.5	5.7	5.6	5.3	29.3	27.1	26.0
25	6.5	6.7	6.3	6.4	30.7	29.0	27.9
25	7.8	7.8	7.7	7.8	26.0	22.0	17.7
50	4.5	4.8	4.7	4.5	50.6	51.2	52.7
50	5.5	5.5	5.5	5.5	55.7	59.3	58.5
50	6.5	6.8	6.7	6.6	62.5	71.1	68.7
50	7.8	7.8	7.5	7.6	46.7	50.7	51.8
100	4.5	5.0	4.8	4.6	108.1	103.2	96.2
100	5.5	5.9	5.5	5.6	123.2	119.0	114.3
100	6.5	6.6	6.6	6.5	99.8	112.2	121.5
100	7.8	7.8	7.8	7.8	104.6	92.3	97.4

† All values represent an average of two samples.

Vesicular–arbuscular mycorrhizal assay was made using a new root clearing and staining schedule reported by Kormanik et al. (1980). The samples were evaluated for the percentage of roots infected and for the intensity of infection. This examination was performed at 6X power under a dissecting microscope equipped with a transmitted light. Each sample was placed into one of five infection classes: (i) 0 to 5% of the fine feeder roots showed some infection; (ii) 6 to 25%; (iii) 26 to 50%; (iv) 51 to 75%; and (v) 76 to 100%. Intensity of infection was rated as: (i) small widely scattered infection sites; (ii) larger, more uniformly distributed infection sites which are rarely continuous; and (iii) a heavy continuous infection along the length of the feeder root. Particular care, which included the use of a compound microscope, was taken with samples from noninoculated seedlings to insure that they were indeed free from mycorrhizal infection.

The experiment was a factorial (mycorrhizal condition × soil phosphorus level × soil pH) pot study arranged in a split plot design in an outdoor area at the Whitehall Experimental Forest near Athens, Ga. The two mycorrhizal treatments were arranged in blocks to minimize contamination from splashing resulting from rain or watering. The three phosphorus levels and four pH treatments were completely randomized within each block. There were 24 treatment combinations with 12 replications per treatment for a total of 288 pots.

Data were subjected to analysis of variance and Duncan's multiple range test using the Statistical Analysis System (SAS) (Barr et al., 1976).

RESULTS AND DISCUSSION

Soil pH, rate of phosphorus fertilization, mycorrhizal condition, and interactions of these variables had highly significant effects ($p = 0.0001$) on seedling growth. Differences in growth were seen in seedling height and top and root dry weights (Fig. 1).

The best overall seedling growth for either inoculated or noninoculated seedlings occurred in soil of lowest pH (4.5) and highest P level (100 ppm) ($p = 0.05$). Vesicular–arbuscular mycorrhizal seedlings grown at pH 4.5 and 100 ppm P were significantly larger than those grown at 25 or 50 ppm. There were no significant differences between the latter two treatments. At pH 4.5 all three soil P levels produced large VAM seedlings with mean heights of 20.01, 23.3, and 28.2 cm, respectively. Noninoculated seedlings grown at pH 4.5 and 25 ppm P averaged only 8.6 cm in height. However, at 50 and 100 ppm P the respective mean heights of 23.5 and 31.7 cm were markedly greater. The same general relationship existed for both VAM and noninoculated seedlings grown at pH 5.5, although heights were somewhat less in each case. Seedlings grown at pH 7.8 averaged < 4 cm in height regardless of the P level or mycorrhizal condition. Large seedlings were produced in both inoculated and noninoculated treatments at pH 4.5 and 5.5 with 100 ppm P with mean stem diameters of 7.41, 6.10, 6.84, and 6.93 mm, respectively. Inoculated seedlings at pH 4.5 and 5.5 over all P levels and noninoculated seedlings at the same pHs and 50 and 100 ppm P exhibited a growth spurt from the end of August to the middle of September (Table 3). Inoculated seedlings at pH 6.5 and all P levels grew slowly throughout the season and lacked a growth spurt at the end of the season. No further growth was observed after the first month with noninoculated seedlings at pH 6.5 and seedlings at pH 7.8 regardless of the mycorrhizal condition.

The largest seedlings were produced in unlimed soil, and seedling growth decreased with increasing soil pH at all three soil P levels tested. Although sweetgum can grow in a wide variety of soils (USDA, 1965) over its natural range, the seed source selected was from a tree growing on acidic soil in northern Georgia. In addition, the isolate of *G. margarita* used was obtained from a cotton field with a pH of 5.2. One could speculate that the VA symbiont and host may have been ecologically adpated to low pH soils. Whether this soil P and pH interaction would be comparable if the VAM isolate used had been adapted to higher soil pH conditions is an important question because high soil pH does not limit the distribution of VAM fungi (Graw, 1979; Green et al., 1976). The interaction of soil P and pH with the isolate of the VAM fungi and tree species genotype requires further study to minimize the possible establishment of symbioses unsuited for particular soil conditions.

The greatest differences in seedling height and dry weight between inoculated and noninoculated seed-

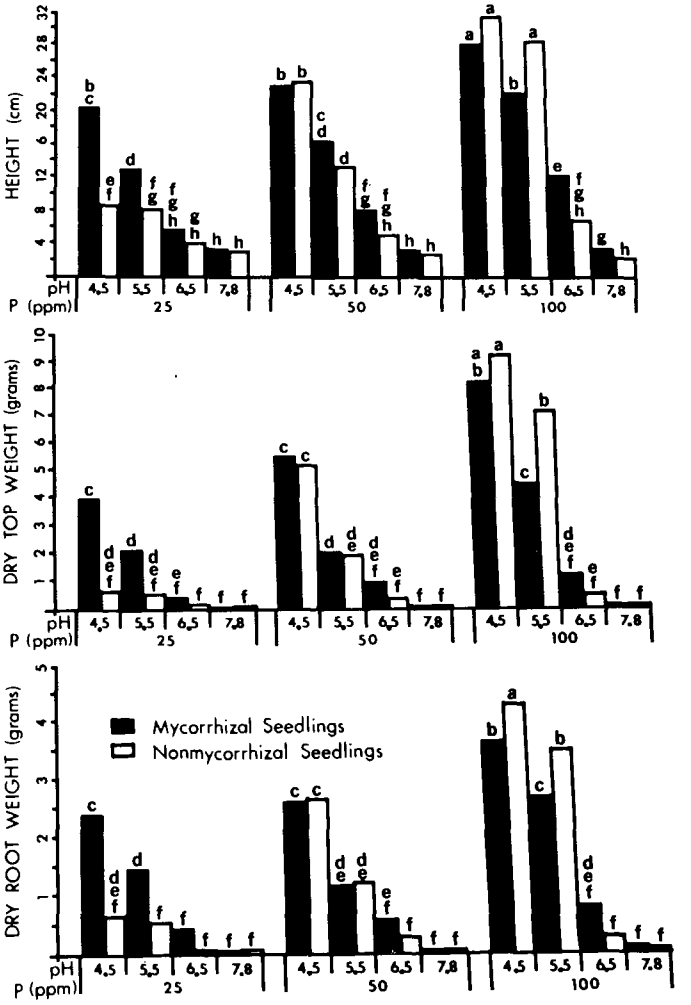

Fig. 1—Height, top weight, and root weight for sweetgum seedlings inoculated with the VA endomycorrhizal fungus *G. margarita* and nonmycorrhizal sweetgum seedlings grown under three soil P levels and four soil pHs. Bars within a graph with the same letter are not significantly different at the 5% level of probability by Duncan's Multiple Range Test.

Table 3—Mean height over time for VA mycorrhizal inoculated and noninoculated sweetgum seedlings produced at three soil P levels and four soil pHs.

	Treatments																							
	25 ppm†								50 ppm								100 ppm							
	4.5‡		5.5		6.5		7.8		4.5		5.5		6.5		7.8		4.5		5.5		6.5		7.8	
Date measured	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
27 July	7.8	6.3	6.0	5.2	4.3	2.8	2.5	2.6	7.7	12.1	6.1	6.1	4.6	3.7	2.8	2.4	9.6	12.6	8.3	9.8	5.2	3.2	3.0	2.7
14 Aug.	10.8	7.7	7.5	6.0	4.8	3.0	2.9	3.0	11.2	13.0	8.0	7.6	5.4	3.9	2.8	2.7	13.6	14.5	11.2	13.8	6.2	5.0	3.1	2.9
27 Aug.	13.3	8.3	8.1	6.3	5.0	3.2	3.3	3.2	12.0	14.0	8.9	8.8	5.7	4.2	3.2	2.8	16.3	17.7	12.8	16.5	7.1	5.2	3.5	3.1
10 Sept.	15.7	8.4	9.5	7.1	5.6	3.5	3.3	3.2	19.6	18.2	11.5	11.7	6.8	4.7	3.2	2.8	24.7	25.9	18.2	23.0	9.8	6.2	3.6	3.0
24 Sept.	19.0	8.4	12.2	7.6	5.6	3.6	3.3	3.2	22.8	21.6	14.2	13.2	7.7	4.8	3.2	2.8	27.8	30.8	21.9	27.1	11.8	6.7	3.7	3.0
8 Oct.	20.1	8.6	13.0	7.9	5.7	3.7	3.3	3.2	23.2	23.5	16.5	13.6	8.2	4.9	3.2	2.8	28.2	31.7	22.7	28.3	12.5	6.8	3.7	3.0

† Extractable soil P (ppm).
‡ Soil pH.
§ Mycorrhizal condition: 1 = inoculated with the VA mycorrhizal fungus *Gigaspora margarita*, 2 = noninoculated.

lings occurred at 25 ppm extractable P and pHs 4.5 and 5.5. At pH 6.5 and 100 ppm P inoculated seedlings, while small relative to mycorrhizal seedlings at lower pHs, were significantly taller than noninoculated seedlings ($p = 0.05$). Seedlings grown at this pH were stunted at all phosphorus levels indicating that pH was the limiting factor. The significant difference which occurred at 100 ppm P suggests that mycorrhizal infection may have been beneficial in helping the seedlings overcome this adverse soil pH. It seems that the adverse effect of this pH was manifested, at least in part, by a decrease in the availability of phosphorus since a significant growth increase due to mycorrhizal inoculation occurred only at high P. This is believed to be only part of the pH effect since other soil nutrient levels are dependent on pH as well.

Large noninoculated sweetgum seedlings were produced at only 50 ppm soil P at low pH. Past studies with sweetgum indicate that nonmycorrhizal sweetgum seedlings exhibit height growth of 7 cm or less until soil P levels reach 70 to 80 ppm (Kormanik et al., 1977a; Schultz et al., 1979). The large size of the noninoculated seedlings at 50 ppm P in this study is believed to be related to the particular half-sib sweetgum family used. This particular seed source responded similarly in a multifamily study conducted concurrently with this one (Paul P. Kormanik, U.S. Forest Service Mycorrhizal Institute, unpublished data). Different families are used each year and this was the first season such responses have been observed at 50 ppm P.

Significant interactions between soil P, pH, and mycorrhizal condition can be seen by comparing height and dry weight between treatments (Fig. 1). Inoculated seedlings were larger than the noninoculated ones at 25 ppm and pHs 4.5 and 5.5 and at pHs 6.5 and 7.8 at 100 ppm P. In other treatments where P was sufficient for growth without mycorrhizal symbiosis, noninoculated seedlings were as large or larger than VAM seedlings. At pHs 4.5 and 5.5 at 100 ppm noninoculated seedlings were 12 and 39% greater in total dry weight.

Acidic soil (pH 4.5) with high available P (100 ppm was the best treatment for producing noninoculated seedlings from the particular seed source used. At pH 5.5 less growth was observed and it is possible the higher level of calcium was binding P making it unavailable to the plant. If this was the case, there was still enough P to produce large, noninoculated seedlings. As the Ca ties up the soil P at pH 6.5, more of the soil must be explored by the plant to obtain P for growth. The data (Table 2) does not indicate any binding of P by Ca. This may have been due to the fact that the dilute double-acid extraction was used. The dilute double-acid extraction procedure is not suited to high pH soils and will actually extract Ca-bound P that would be unavailable to plant roots. It is likely that a less stringent procedure such as Olsen's sodium bicarbonate extraction (Olsen et al., 1954) would have given a better approximation of available P at high pH and would have illustrated the widely accepted phenomenon of Ca binding P at high pH. Vesicular–arbuscular mycorrhizae significantly improves P uptake due to the ability of the fungi to exploit a significantly larger volume of soil than roots alone (Powell, 1975; Rhodes and Gerdemann, 1975) and perhaps more important, due to a greater site affinity for phosphate associated with the fungus (Cress et al., 1979). Under low P soil conditions, growth is substantially enhanced even with the carbohydrate drain needed to maintain this beneficial symbiotic relationship (Losel and Cooper, 1979; Smith, 1980). The implication is that although nonmycorrhizal seedlings of large size may be produced in the nursery at high P, such seedlings may respond poorly and exhibit poor survival if they are outplanted on a forest site that is low in P and which has a low indigenous VA fungi population present.

Table 4—Mycorrhizal infection in sweetgum seedlings grown at three soil P levels and four soil pHs.

Treatments		Infection	Intensity
P, ppm	pH	percent	rating†
25	4.5	12.1 abc*	1.36 abc
25	5.5	55.7 a	1.58 a
25	6.5	50.0 ab	1.58 a
25	7.8	33.4 bc	1.08 bc
50	4.5	31.3 bc	1.33 abc
50	5.5	46.1 abc	1.81 abc
50	6.5	34.8 bc	1.42 abc
50	7.8	27.4 c	1.17 abc
100	4.5	9.5 d	0.92 c
100	5.5	48.8 ab	1.08 bc
100	6.5	38.1 abc	1.33 abc
100	7.8	27.5 c	1.50 ab

* Figures within a column with the same letter are not significantly different at the 5% level of probability by Duncan's Multiple Range Test.
† 1.0 = low intensity; 2.0 = medium intensity; 3.0 = high intensity.

Table 5—Mean extractable P, K, Ca, Al, Fe, Mg, Zn, and Mn levels for the Bladen sandy loam soil-perlite mixture at the study harvest.

Treatments										
P	pH	Mycorr. cond.	P	K	Ca	Al	Fe	Mg	Zn	Mn
ppm			ppm							
25	4.5	1†	28.4 h*	11.6 efgh	183.3 j	160.2 j	160.2 a	21.3 a	1.25 fgh	5.20 fghi
25	4.5	2	27.2 h	17.7 ab	190.7 j	146.7 b	145.0 a	25.5 defgh	2.78 a	5.50 efgh
25	5.5	1	26.5 h	11.5 efgh	369.5 hij	131.3 c	121.3 cd	19.7 h	0.98 cde	5.60 defg
25	5.5	2	25.5 h	13.8 cdef	395.7 hij	118.1 de	128.4 c	20.0 h	1.13 bcde	7.38 a
25	6.5	1	25.6 h	20.1 a	910.0 defg	104.8 fg	190.8 e	31.5 cdefgh	0.88 cde	5.80 bcdefg
25	6.5	2	30.1 h	15.9 bc	837.0 defg	85.7 fi	88.9 f	26.7 defgh	0.74 e	5.40 efgh
25	7.8	1	19.2 h	15.2 bc	2548.0 bc	84.1 ijk	51.4 h	79.4 ab	0.81 dce	5.90 bcdefg
25	7.8	2	16.2 h	14.4 cd	2864.0 abc	78.6 jkl	37.8 i	44.3 c	0.67 e	5.60 efg
50	4.5	1	53.0 gh	11.2 fgh	219.0 ij	125.4 cd	137.8 ab	20.6 h	1.46 bcde	4.20 j
50	4.5	2	52.3 gh	9.6 hi	720.5 efghi	134.9 c	130.1 bc	22.6 efgh	1.35 bcde	4.70 hij
50	5.5	1	64.6 f	14.3 cde	540.9 ghij	106.8 efg	114.2 de	25.6 defgh	1.30 bcde	5.70 cdefg
50	5.5	2	52.4 fg	9.9 hi	412.9 hij	115.0 def	113.2 de	21.1 gh	0.90 cde	5.90 bcdefg
50	6.5	1	80.0 e	15.4 bc	1177.0 de	81.2 ijkl	93.7 f	37.8 cdefg	0.83 cde	6.00 bcdef
50	6.5	2	57.3 gh	13.3 cdefg	1054.0 def	92.0 hi	85.5 fg	22.5 efgh	0.71 e	5.70 cdefg
50	7.8	1	56.8 gh	17.6 ab	2943.0 ab	81.4 ijkl	48.0 h	70.1 b	1.25 bcde	6.20 bcde
50	7.8	2	46.7 g	13.6 cdef	2432.0 c	70.6 l	38.2 i	38.5 cde	0.70 e	6.70 ab
100	4.5	1	92.4 de	10.5 hi	243.4 ij	108.0 efg	124.8 c	18.2 h	1.78 b	4.40 ij
100	4.5	2	99.9 cd	8.0 h	250.3 ij	111.8 efg	115.4 de	20.0 h	1.18 bcde	5.00 ghij
100	5.5	1	118.5 ab	14.5 cd	622.0 ghij	92.3 hi	114.5 de	27.6 defgh	1.22 bcde	6.30 bcde
100	5.5	2	110.0 bc	10.6 ghi	445.0 ghij	100.9 gh	106.4 e	22.7 efgh	1.56 bcd	6.50 bcd
100	6.5	1	130.7 a	16.1 bc	1250.3 d	72.9 jkl	93.9 f	38.2 cdef	1.12 bcde	6.60 abc
100	6.5	2	112.2 bc	11.5 efgh	1061.0 def	79.6 ijkl	79.8 g	40.0 cd	0.79 cde	6.10 bcdef
100	7.8	1	113.7 bc	17.9 ab	3157.0 a	68.8 l	51.7 h	89.4 a	1.12 bcde	6.60 abc
100	7.8	2	81.0 e	12.0 defgh	2658.0 bc	72.5 kl	39.5 i	90.2 a	1.61 bc	6.30 bcde

* Figures within a column with the same letter are not significantly different at the 5% level of probability by Duncan's Multiple Range Test.
† MC = mycorrhizal condition; 1 = inoculated with the VA mycorrhizal fungus *Gigaspora margarita*, 2 = noninoculated.

The VAM infection percentages were moderate to low relative to similar studies with sweetgum (Brown et al., 1981). No significant correlations were observed between soil treatments and VAM infection (Table 4). Root analysis determined that noninoculated seedlings were completely free from mycorrhizal infection.

Nutrient data is not available at pH 7.8 due to the production of insufficient biomass for analysis. In addition, samples had to be combined in certain of the other treatments resulting in reduced sample sizes. However, nutrient analysis did indicate several interesting relationships.

Nutrient analysis of soil (Table 5) shows P levels similar to those calculated from $CaPO_4$ additions. Extractable soil calcium levels ranged from an average of 301 ppm at low pH to an average of 2,767 ppm at high pH. There was a significant decrease in the extractable levels of soil aluminum, iron, and apparently zinc with increases in soil pH. As expected, pH had the opposite effect on magnesium levels.

Nutrient data from plant parts was analyzed at the 0.1 confidence level for reasons described above (Table 6). Soil treatments, for this confidence level, significantly influenced the levels of N, P, K, and Ca in leaf tissue. Leaf P was increased with soil P as one might expect. Total P uptake was much greater at high soil P due to the large size of seedlings produced at this P level. Leaf K decreased with soil P. Leaf ni-

Table 6—Nutrient content of seedling tissues for VA mycorrhizal inoculated and noninoculated sweetgum seedlings produced at three soil P levels and three soil pHs.

Treatments			Leaves				Roots				
P	pH	MC†	N	P	K	Ca	P	Ca	Mg	Al	Fe
ppm			mg/g								
25	4.5	1	2.1 ab‡	1.0 b	5.9 abc	3.6 f	0.7 d	2.7 d	0.8 de	0.17 de	0.11 ef
25	4.5	2	2.0 abc	0.6 c	7.0 a	3.8 ef	0.6 d	3.1 cd	0.8 de	0.28 bc	0.21 b
25	5.5	1	1.6 d	0.9 bc	6.1 abc	4.3 dc	0.8 cd	4.4 b	1.2 ab	0.23 bcd	0.18 bcd
25	5.5	2	1.7 cd	0.8 bc	7.6 a	4.3 cde	0.6 d	4.6 ab	1.0 cde	0.35 b	0.31 a
25	6.5	1	1.7 cd	1.0 bc	5.6 abcd	4.8 abc	0.8 bcd	4.8 ab	1.0 abcde	0.19 bcde	0.21 bc
25	6.5	2	–§	–	–	–	–	–	–	–	–
50	4.5	1	2.0 bc	1.0 b	5.2 cd	3.8 ef	0.8 cd	3.1 c	0.9 cde	0.15 de	0.10 efg
50	4.5	2	2.3 a	1.1 b	5.4 bcd	3.8 ef	0.8 cd	3.0 cd	0.7 e	0.16 de	1.08 fgh
50	5.5	1	1.8 cd	1.1 b	6.4 ab	4.3 bc	0.9 bc	4.7 ab	1.2 a	0.27 bc	0.20 bc
50	5.5	2	2.0 bc	0.9 bc	6.9 a	4.6 bc	0.8 cd	4.8 ab	1.0 bcde	0.30 b	0.14 de
50	6.5	1	1.6 cd	0.9 bc	5.7 abcd	4.7 abc	0.8 bcd	5.0 ab	1.1 abcd	0.18 cde	0.14 de
50	6.5	2	–	0.8 bc	5.8 abcd	5.3 a	0.6 d	5.5 a	1.0 cde	0.36 b	0.15 de
100	4.5	1	2.3 a	1.3 a	4.5 d	4.0 de	1.0 ab	3.2 c	0.9 de	0.13 de	0.08 gh
100	4.5	2	2.0 bc	1.1 b	4.9 d	3.7 ef	0.9 bc	2.7 d	0.9 cde	0.11 e	0.07 gh
100	5.5	1	2.1 ab	1.3 a	5.3 cd	4.9 a	1.1 a	5.0 ab	1.0 cde	0.08 e	0.07 h
100	5.5	2	2.0 bc	1.3 a	5.3 cd	4.3 c	0.9 bc	4.6 b	0.8 e	0.10 e	0.04 i
100	6.5	1	1.8 bc	1.3 a	4.1 d	4.8 ab	1.1 ab	5.3 a	1.2 bc	0.58 a	0.15 cd
100	6.5	2	1.9 bcd	1.1 ab	4.8 d	5.3 a	1.0 abc	5.2 ab	1.4 a	0.26 bcd	0.17 bcd

† MC = mycorhizal condition; 1 = inoculated with the VA mycorrhizal fungus *Gigaspora margarita*, 2 = noninoculated.
‡ Insufficient plant material for analysis.
§ Figures within a column with the same letter are not significantly different at the 10% level of probability by Duncan's Multiple Range Test.

trogen decreased with soil pH at all three soil P levels. One can speculate that this resulted from greater ammonia loss at high pH and a potentially greater amount of nitrifying bacteria leading to a larger quantity of nitrate which would be easily leached out of the sandy study soil. This may have been a contributing factor to the smaller seedling size observed at high pH. Leaf calcium reflected the level of the soil calcium in a particular treatment ranging from an average of 3,786 ppm at low pH to an average of 4,977 ppm at high pH. It is possible that small seedling size at high pH was due directly to excessive calcium levels; however, it is also possible that the detrimental effect of high lime was expressed indirectly through its effect on available soil P by the formation of calcium phosphate precipitates as discussed earlier.

As in leaf tissue, root P and Ca were influenced by soil P and pH, respectively. Root magnesium levels increased as pH increased reflecting this occurrence in soil samples. Soil aluminum and iron decreased with increases in soil pH; however, this was not observed in root samples where wide ranges occurred for both but no observable trends could be detected.

CONCLUSIONS

Many nurseries in the southeast produce sweetgum seedlings in acid, sandy soils similar to the one used in this study. The results of this experiment suggest that over-liming such soils may prove detrimental to the growth of sweetgum which is adapted to acidic soils. Soil pH values of $\geq$ 6.5 should be avoided. Perhaps different species of mycorrhizal fungi would produce optimal growth of sweetgum seedlings at different pH values. However, the failure of noninoculated seedlings to respond at pH 6.5, even with adequate phosphorus fertilization, indicates that more acidic conditions are desirable for this seed source. The soil's phosphorus fixation capacity was not a factor in this study but should be considered in soils with high clay and metal ion levels. In soils of that type, a pH of 5.5 may be more desirable than pH 4.5.

It is recommended that soil pH be monitored periodically to insure that a favorable range is maintained. Discriminate liming of sandy southeastern nursery soils should allow the production of maximum sized 1-0 sweetgum planting stock.

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