The Nutrition of Loblolly Pine Seedlings Exhibits Both Positive (Soil) and Negative (Foliage) Correlations with Seedling Mass

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Abstract

Sulfur and lime experiments at a sandy nursery in Texas detected no significant rate effect on height, root-collar diameter, or seedling mass of 1-0 loblolly pine (*Pinus taeda* L.) seedlings. Location of replications, however, had a large effect ($P < 0.001$) on seedling growth, which was related to nutrient levels in the soil. Positive correlations occurred between seedling height and the level of four macronutrients and three micronutrients in the soil. In contrast, due to carbohydrate dilution, negative correlations occurred between seedling mass and concentrations of nutrients (e.g., nitrogen and phosphorus) in needles. Height of seedlings at time of lifting was negatively related to foliar levels of aluminum and five other nutrients. In this study, low levels of organic matter (0.5 to 0.8 percent) and low levels of cation exchange capacity (0.9 to 1.9 meq 100 g^{-1}) were not correlated with seedling morphology. It appears that applied fertilizers and inherent levels of soil nutrients affect seedling growth more than soil pH (3.6 to 6.3) or small changes in organic matter.

Introduction

Bareroot loblolly pine (*Pinus taeda* L.) seedlings are produced in nurseries with soils that vary in texture (South and Davey 1983). Coarse-textured soils with high sand content have advantages when it comes to sowing seed and lifting seedlings (South et al. 2016). As a result, most loblolly pine nurseries established after 1990 were established on soils with more than 85 percent sand. These soils typically retain fewer nutrients than fine-textured soils typical of nurseries established before 1960. Because coarse-textured soils typically have low cation exchange capacity (CEC), they require more fertilizer to achieve target seedling growth. Even so, Wakeley (1935: p. 37) said, "Fairly sandy soils frequently meet all forest nursery requirements if they are underlain by less pervious soils. The cost of enriching such soils with various fertilizers is offset by greater ease of working, and most pine species develop better root systems in light than heavy soils." Although we have gained knowledge about seedling fertilization during the past century, much remains to be learned about nutrition of pine seedlings on sandy soils.

Trials at a nursery in Texas revealed that applying sulfur or dolomitic lime had no significant effect on shoot or root growth of fertilized loblolly pine seedlings (South et al. 2017). Soil properties, however, varied greatly due to location of plots in the seedbed resulting in large seedling growth differences. We asked the question, if adding calcium, magnesium, or sulfur does not increase seedling mass, might differences in other nutrients account for observed differences in seedling size? The objectives of this investigation were to document the degree of soil nutrient variability in bareroot seedbeds and to compare seedling morphology with soil and foliar nutrition at time of lifting.

Materials and Methods

Two studies were established at the Richard O. Barham SuperTree Nursery (Bullard, TX). In March 2016, the soil was fumigated with a combination of chloropicrin and 1,3-dichloropropene. The trials were established on separate beds in the same field on a loamy sand soil (83:1:16 sand:silt:clay) with a CEC < 2.0 meq 100g^{-1}. Stratified loblolly pine seed (half-sib family) were machine sown on April 16. The sulfur (S) trial was established on bed 7 and the lime trial was established on bed 3 (figure 1). On April 9, elemental S treatments (0, 813, 1,626 and 2,439 kg/ha) and pelletized dolomitic lime (90 percent passing 100 mesh sieve) treatments

Figure 1. The dolomitic lime study was established on bed 3 (far left), and the sulfur study was established on bed 7 (foreground). The distance between flags within a bed is 6.1 m. (Photo by Gene Bickerstaff, July 2017)

(0, 813, 1,626 and 3,252 kg/ha) were applied. Material was mechanically incorporated into the soil to a depth of 15 cm. For each study, the size of each treatment plot was 183 cm by 610 cm and each replication (four plots) covered 44.6 m^2. Rainfall in April was above average and totaled 254 mm (South et al. 2017).

Herbicide applications began on June 7 when oxyfluorfen (122 g a.i./ha) was applied as a broadcast application. Similar amounts of oxyfluorfen were applied on June 15, 23, 30, July 8, 18, and August 8. Insecticide applications (esfenvalerate) began on June 14 and were applied periodically through October 2 to control *Lygus linenarious* (Palisot de Beauvois). Fungicide (tridimefon at 140 g a.i./ha) was applied three times to control *Cronartium quorum f. sp. fusiforme* (Hedg. & Hunt ex Cumm.). Other fungicides were also applied to lower the incidence of foliar diseases. Seedlings were wrenched in mid-July, top-pruned on August 2 and September 18 (to a height of 27 cm), and undercut on October 28. Prior to sowing, calcium (Ca), potassium (K), magnesium (Mg), and S (448 kg/ha of gypsum and 280 kg/ha of sulfate of potash-magnesium) fertilizers were applied and tilled into the soil. Small amounts of chelated micronutrients (< 90 g/ha/element: boron [B], copper [Cu], iron [Fe], manganese [Mn], molybdenum [Mo], and zinc [Zn]) were applied in April. Top dressings of fertilizer were applied from June through September (a total of 179 kg/ha of nitrogen [N] and 58 kg/ha of K). In July, seedlings received a foliar application containing 1.17 kg/ha Ca, 0.23 kg/ha B and 0.46 kg/ha Zn. The average seedling density was estimated at about 215 seedlings/m^2.

The experiment was terminated after 10 months (February 7, 2017), at which point soil samples were collected (top 15 cm; one pooled sample per treatment plot). In addition, a sample of 15 seedlings was lifted from the center of each plot using shovels and transported to Auburn University, where they were placed in a cooler at 3 ºC. Seedling root-collar diameter (RCD) and height were measured and recorded. The seedlings were then dried for 72 hours at 70 °C, and dry weights of roots and shoots were recorded. The root weight ratio (RWR) was determined by dividing the root mass by the total seedling mass. Waypoint Analytical (Memphis, TN) analyzed foliar nutrients, and the Mehlich 3 extraction procedure was used to analyze soil samples. Organic matter (OM) was determined by loss on ignition. Temperature and precipitation data were recorded at the nursery.

For each trial, the original study design was a randomized complete block design with 4 treatments and 4 replications (i.e., 16 experimental units). Results of those trials are presented in South et al. (2017) and showed no effect of S or lime treatments on seedling morphology. Because differences among replications in both the S and lime trials were notable, however, further data examination was warranted. For this secondary investigation, the 2 trials were combined for a total of 8 replications, 4 dummy treatments, and 32 sampling units. The zero, low, medium, and high lime (or elemental S) rates were assigned dummy variables of A, B, C, and D, respectively. Plot means were analyzed using PROC GLM and PROC CORR of the Statistical Analysis System software package (SAS 1988). Replicates were treated as random effects, and correlations between variables were declared significant at the alpha = 0.05 level. Statistics were not conducted for soil B, because all data were the same (i.e., 0.1 ppm).

Results and Discussion

Because the S and lime treatments had no effect on seedling morphology (South et al. 2017), the meaningless dummy variables also had no effect on seedling morphology. In contrast, plot location (i.e., replication) impacted seedling growth. For example, seedlings from the control plot in L3 were 13 percent taller, 25 percent larger in RCD, 123 percent heavier in root mass, and

95 percent heavier in total mass than seedlings from the control plot in S1 (data not shown). As it turned out, replication L3 produced the greatest seedling mass and the highest levels of phosphorus (P), Cu, and Zn, while the smallest seedlings (replication S1) were growing in soil with low levels of K, Cu, and Zn (table 1). Several factors like soil moisture, soil compaction, and soil oxygen content can affect seedling growth, but these factors were not measured. Soil pH, OM, and CEC were not correlated with shoot mass or root mass (table 2). Exploratory examinations indicate that inherent variations in soil fertility likely explain why seedling size varied among replications.

Table 1. Replication (Rep) means for seedling morphology, soil nutrients, soil pH, and soil organic matter (OM) (n = 4). The replication effect (P > F) was significant at $\alpha = 0.01$ for all listed variables except OM and sodium (Na). The least significant difference (LSD) values are provided at the 0.05 level of probability. Means in a column with the same small letter are not statistically different at $\alpha = 0.05$ according to Duncan's Multiple Range test.

Rep	RCD (mm)	HT (cm)	Root (g)	Shoot (g)	Total (g)	P (ppm)	K (ppm)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Mn (ppm)	pH (water)	Na (ppm)	OM (%)
S1	6.9d	30d	1.8c	7.5c	9.4c	48bc	22c	0.20c	133c	0.45b	8cd	4.6c	7	0.60
S2	7.5bc	30d	2.2bc	9.6bc	11.8bc	46cd	24c	0.20c	116c	0.60ab	12abc	4.9bc	7	0.60
S3	7.9b	31d	2.2bc	9.2bc	10.0bc	50bc	27bc	0.35a	235a	0.72a	9bcd	4.4c	11	0.67
S4	7.7b	31cd	2.0c	8.0bc	11.4bc	50bc	28bc	0.22c	186b	0.57ab	6d	4.2c	9	0.65
L1	7.5bc	33b	2.5bc	8.1bc	10.6bc	47bc	32ab	0.25bc	126c	0.92ab	19a	5.5ab	7	0.62
L2	7.1cd	33bc	2.0c	7.6c	9.6c	42c	27bc	0.20c	110c	0.80b	14ab	5.5ab	7	0.57
L3	8.7a	36a	3.8a	13.5a	17.3a	59a	35a	0.35a	215ab	1.17a	13abc	5.7a	11	0.62
L4	8.5a	35a	2.8b	10.4b	13.2b	52b	36a	0.3ab	196b	1.07ab	15ab	5.7a	9	0.70
P > F	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.004	0.119	0.330
LSD	0.6	1.5	0.65	2.4	3.0	4.9	5.3	0.06	30.4	0.025	5.8	0.7	3.3	0.11

Cu = copper. Fe = iron. HT = height. K = potassium. L = lime trial. Mn = manganese. P = phosphorus. RCD = root-collar diameter. Root = root mass. S = sulfur trial. Shoot = shoot mass. Total = total seedling mass. Zn = zinc.

Table 2. Pearson correlation coefficients (r) among soil properties and loblolly pine seedling attributes for all plots (n = 32). Significant r values are show in bold; absolute values above 0.54 are statistically significant at $\alpha = 0.001$, and absolute values above 0.34 are significant at $\alpha = 0.05$. Rows are ordered according to correlations with total seedling mass (Total).

Soil factor	Total	Root	Shoot	Height	RCD	H/D	RWR
Phosphorus	**0.63**	**0.61**	**0.65**	**0.53**	**0.66**	– 0.27	– 0.20
Zinc	**0.52**	**0.49**	**0.56**	**0.84**	**0.55**	0.21	– 0.27
Copper	**0.50**	**0.50**	**0.47**	**0.50**	**0.63**	– 0.27	– 0.04
Potassium	**0.49**	**0.46**	**0.56**	**0.77**	**0.63**	0.04	– 0.34
Iron	**0.44**	**0.44**	**0.41**	0.33	**0.66**	**– 0.48**	– 0.01
Sodium	0.34	**0.35**	0.28	0.21	**0.43**	0.33	0.08
Magnesium	0.26	0.23	0.33	**0.73**	0.27	**0.44**	– 0.30
Calcium	0.16	0.12	0.28	**0.69**	0.19	**0.50**	**– 0.41**
pH	0.23	0.21	0.30	**0.63**	0.15	**0.49**	– 0.25
Organic matter	0.20	0.19	0.22	0.24	0.45	– 0.30	– 0.12
Manganese	0.09	0.06	0.17	**0.42**	0.04	**0.39**	– 0.28
Cation exchange capacity	– 0.05	– 0.05	– 0.02	0.06	0.15	– 0.13	– 0.08
Sulfur	– 0.12	– 0.14	– 0.03	– 0.26	– 0.06	– 0.20	– 0.23

Root = root mass. Shoot = shoot mass. Height = shoot height. RCD = root-collar diameter. H/D = height/RCD. RWR = root mass/total seedling mass.

Replicate location affected various soil nutrients (P, K, Mn, Fe, Cu, Zn; table 1) and foliar nutrients (N, S, P, B, Mg, Cu; table 3). Not surprisingly, Ca ($P = 0.001$) and Mg ($P = 0.003$) were highest in lime-treated replications (152 ppm Ca; 26 ppm Mg; 12 ppm S), and sulfate (S) was highest in S-treated replications (77 ppm Ca; 14 ppm Mg; 19 ppm S).

All 32 soil samples contained 0.1 ppm B, and foliar B levels were all above 14 ppm. In contrast, much variability occurred in soil S levels (coefficient of variation [CV] = 93.5) and soil sodium (Na; CV = 25.8). As a result, replication location had no effect on B, S ($P = 0.49$), or Na ($P = 0.12$).

Table 3. Replication (Rep) means for foliar levels of selected elements (n = 4). The replication effect (P > F) was significant at $\alpha = 0.001$ for all listed variables except copper and potassium. The least significant difference (LSD) values are provided at $\alpha = 0.05$. Means in a column with the same small letter are not statistically different at $\alpha = 0.05$ according to Duncan's Multiple Range test.

Rep	Nitrogen (%)	Sulfur (%)	Phosphorus (%)	Boron (ppm)	Manganese (ppm)	Copper (ppm)	Aluminum (ppm)	Potassium (%)
S1	1.39a	0.13a	0.17a	18cd	950ab	12b	626a	0.75
S2	1.38a	0.11b	0.16ab	19cd	1058a	12b	599ab	0.76
S3	1.21bc	0.11b	0.14cd	22ab	784cd	11b	524bc	0.75
S4	1.38a	0.11b	0.15bc	23a	829bc	16a	573ab	0.82
L1	1.31ab	0.09c	0.14cd	18cd	772cd	11b	422de	0.71
L2	1.26bc	0.08c	0.13cd	17d	675d	10b	461cd	0.67
L3	1.08d	0.08c	0.14cd	18cd	705cd	9b	354e	0.73
L4	1.20c	0.09c	0.13d	18bc	706cd	10b	368de	0.74
P > F	0.001	0.001	0.001	0.001	0.001	0.031	0.001	0.275
LSD	0.09	1.8	1.6	2.3	126	3.4	91	0.11

L = lime trial. S = sulfur trial.

Because soil nutrients are often correlated with other nutrients (table 4), it was not possible to be certain which elements produced better growth at this nursery. For example, the correlation between Zn and K was high (figure 2), and several cations were positively correlated with Mg, Mn, and Na. Similar positive correlations were observed when comparing nutrients from several nurseries that ranged in soil texture from 95 percent sand to a silt loam with only 15 percent sand (table 5). As a result, inherent difficulties exist when assumptions are based on correlations between pine growth and foliar or soil nutrients (MacCarthy and Davey 1976). A significant correlation does not prove that an underlying relationship exists.

Table 4. Pearson correlation coefficients (r) among soil properties and loblolly pine seedling attributes for all plots (n = 32). Significant r values are show in bold; absolute values above 0.54 are statistically significant at $\alpha = 0.001$, and absolute values above 0.34 are significant at $\alpha = 0.05$. Rows are ordered according to correlations with total seedling mass (Total).

Soil factor	Soil phosphorus	Soil potassium	Soil copper	Soil iron	Soil zinc	Soil manganese	Foliar nitrogen
Potassium	**0.55**	**—**	**—**	**—**	**—**	**0.55**	**– 0.44**
Copper	**0.56**	**0.56**	**—**	—	—	0.19	**– 0.62**
Iron	**0.67**	**0.39**	**0.78**	—	—	– 0.30	**– 0.59**
Zinc	**0.43**	**0.87**	**0.64**	0.34	—	0.55	**– 0.59**
Sodium	0.43	**0.39**	**0.60**	**0.63**	**0.39**	– 0.11	– 0.23
Organic matter	0.30	**0.40**	**0.43**	**0.61**	0.26	– 0.16	– 0.22
pH	0.14	**0.65**	0.26	– 0.12	**0.76**	0.73	**– 0.37**
Cation exchange capacity	0.13	0.03	0.20	**0.39**	– 0.06	– 0.29	– 0.02

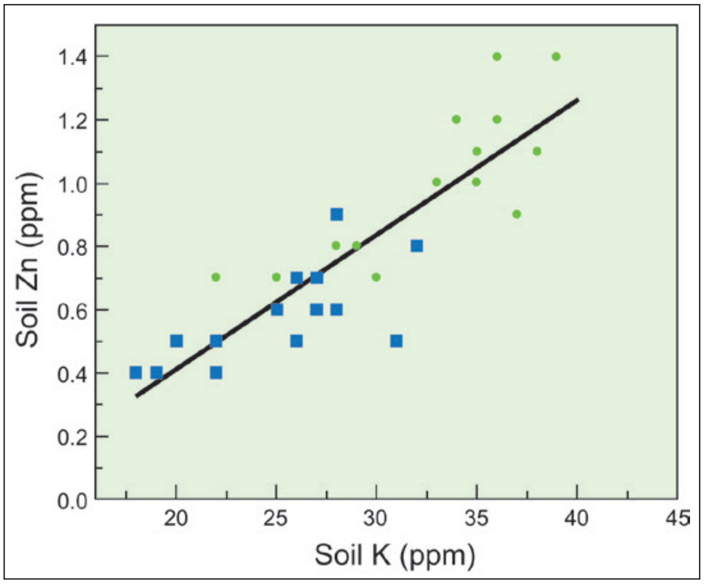

Figure 2. The Pearson correlation between soil potassium (K) and soil zinc (Zn) was significant (r = 0.87; P = 0.004; n = 32). Squares represent plots in the sulfur trial, and dots represent plots in the lime trial.

Table 5. A comparison of Pearson correlation coefficients (r) between various soil cations. A nursery survey (n = 43) was conducted between 1977 and 1980 (South and Davey 1983), and the nursery soil in this study was sampled in February 2017. As expected, Pearson correlation coefficients were higher when soil samples were taken from only one soil type (n = 32). All coefficients in the table are significant at $\alpha = 0.05$.

Correlation	1977-80 nursery soils (n = 43)	2017 nursery soil (n = 32)
Magnesium - calcium	0.80*	0.92**
Magnesium - potassium	0.49	0.74
Magnesium - manganese	0.44	0.71
Manganese - potassium	0.67	0.88
Manganese - calcium	0.44	0.69
Sodium - iron	0.43	0.62
Sodium - copper	0.39	0.60
Sodium - potassium	0.36	0.39

* Nursery soils are typically limed with dolomitic limestone.
** Dolomitic lime applied to 12 out of 32 plots.

Macronutrients

Macronutrients were within the normal range for loblolly pine seedlings lifted in winter (table 6). Soil P and K were positively correlated with seedling mass (table 2), and soil P, K, Ca, and Mg were correlated with seedling height (figure 3). Height growth after top pruning (to 27 cm) was greater on the limed bed (7.5 cm) compared with the S-treated bed (3.7 cm). Seedling height at lifting was significantly correlated with five macronutrients in the limed bed, but no measured soil macronutrient correlated with seedling height at lifting on the S bed. Typically, too much height growth after September is not considered a desirable seedling trait by nursery managers.

Table 6. Foliar nutrient concentrations considered deficient for conifers, two loblolly pine surveys (sampled in December to January), and the loblolly pine study discussed in this article. High values, marked with an asterisk (*), might be due to soil contamination.

Element		Deficient conifers[a]	Survey1[b]	Survey2[c]	This study
Nitrogen	%	< 1.1	0.92–2.24	0.61–1.38	1.04–1.44
Phosphorus	%	< 0.09	0.12–0.30	0.07–0.21	0.12–0.18
Potassium	%	< 0.4	0.82–1.47	0.31–1.19	0.60–0.85
Calcium	%	< 0.12	0.22–0.66	0.25–0.59	0.32–0.85
Magnesium	%	< 0.05	0.03–0.23	0.06–0.15	0.09–0.12
Sulfur	%	< 0.1	0.05–0.16	0.07–0.15	0.07–0.15
Iron	ppm	< 30	107–2150*	85–1161	107–355
Manganese	ppm	—	85–1350*	135–1677	532–1106
Zinc	ppm	< 5	30–87	21–115	33–54
Copper	ppm	< 3	2–10	6–52	7–23
Boron	ppm	< 3	10–65	6–25	15–26
Aluminum	ppm	—	340–6380*	185–2097	297–744

— = not estimated. [a] Powers (1974). [b] Boyer and South (1985).
[c] Starkey and Enebak (2012).

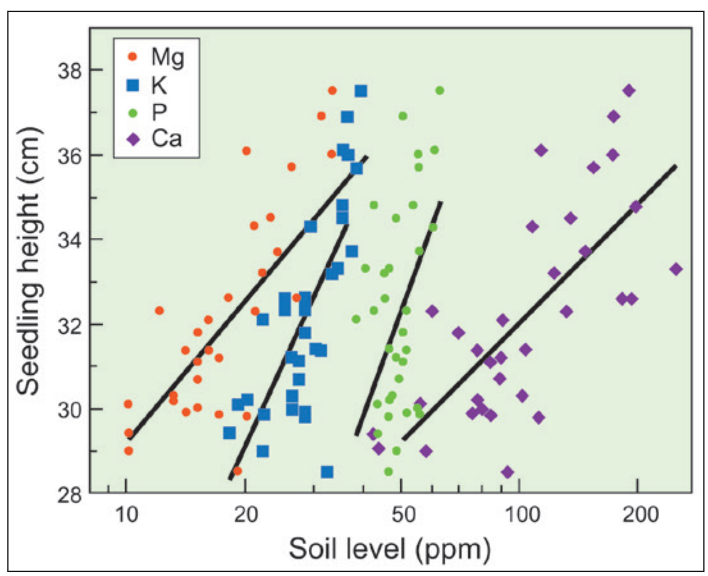

Figure 3. Relationships between seedling height and soil magnesium (Mg), potassium (K), phosphorus (P), and calcium (Ca) were evident in the study (n = 32). Overall, seedlings taller than 34 cm were growing in plots that had higher levels of macronutrients.

Phosphorus

Without ectomycorrhiza, pine seedlings have difficulty obtaining P from the soil, even when levels of P in the soil are high. For example, even when soil P was 155 ppm (Mehlich 3), needles from nonmycorrhizal seedlings contained 0.09 percent P (August), and mycorrhizal seedlings had 0.16 percent P (South et al. 2018). Similarly, foliage of nonmycorrhizal seedlings in Alabama had 0.07 percent P in July of 1986, and mycorrhizal seedlings had 0.15 percent P (South et al. 1988). Because seedlings in July (figure 1) were mycorrhizal, foliar P levels in February averaged 0.15 percent P (S study) and 0.14 percent P (lime study), and RCDs (table 1) were above average (South et al. 2016).

Because seedlings grow taller when fertilized with both N and P (Blackmon 1969), nursery managers might apply monoammonium or diammonium phosphate to stimulate growth during the summer (Teng and Timmer 1994). For example, one manager applied diammonium phosphate in August, and growth was noticeable only 1 week after treatment (figure 4).

In a comparison of loblolly pine seedlings from various nurseries, foliar P was related to height growth (r = 0.51) after outplanting (Larson et al. 1988). Applying P to seedbeds in the fall before lifting can increase seedling growth after outplanting (South and Donald 2002). The correlation between soil P and seedling mass was positive (table 2). Positive correlations with shoot mass and P in growing media have also been reported for Scots pine (*Pinus sylvestris* L.) (Memisoglu and Tilki 2014) and pitch pine (*Pinus rigida* Mill.) (Helm and Kuser 1991).

Potassium

Soil K was positively correlated with total seedling mass (r = 0.49; P = 0.005; n = 32). Tentative minimum K levels for nursery soils (at sowing) range from 41 ppm (Wilde 1957) to 80 ppm (Davey 1991). Harvested seedlings may remove as much as 150 kg K/ha, and the above-average rainfall in April likely leached additional soil K. Hence, fertilizers containing K were applied before and after sowing. At lifting, foliar K averaged 0.74 percent, which is typical for bareroot seedlings lifted in January. Foliar K levels of 0.26 percent or lower are considered deficient (Sucoff 1961).

In the past, K was applied to nursery beds in late summer in hopes of hardening off pine seedlings (Davey 2002) or inducing bud set (Walker et al. 1989), but this practice proved to be ineffective (Dierauf 1982, Rowan 1987, Sarjala et al. 1997, South and Donald 2002, Switzer 1962). Similarly, fertilization with K has not been found to increase drought tolerance of pine (Del Campo et al. 2011, South et al. 2016).

Calcium

Resin exudation, death of the terminals, and chlorosis (figure 5) are symptoms of Ca deficiency (Lyle 1969, Sucoff 1961). When soil tests indicate less than 200 ppm Ca, nursery managers often apply either gypsum or lime before sowing. Because the topsoil in the current study contained about 107 ppm of Ca (March 2016), the soil was fertilized with 101 kg/ha of Ca. The following February, the replication with the lowest amount of Ca (42 ppm) produced seedlings that were 29 cm tall with foliar Ca levels

Figure 4. Soil in this field averaged 96 ppm phosphorus (P; Mehlich 3) before sowing. The bed on the left received no top dressing of P, and the bed on the right was treated with diammonium phosphate (22 kg/ha of P and 20 kg/ha of N) on August 7th, 8 days prior to the photos. (Photos by Hamp Holmes, 2017)

Figure 5. Symptoms of calcium deficiency on loblolly pine include death of the terminal, chlorosis, and resin exudation. (Photo by David South, 2008)

of 0.32 percent. In contrast, replication with the greatest amount of Ca (248 ppm) produced 33 cm tall seedlings with 0.45 percent foliar Ca. By comparison, stunted, chlorotic, Ca deficient seedlings at two sandy nurseries in Wisconsin had 0.16- to 0.21-percent foliar Ca (Voigt et al. 1958). The significant correlation with seedling height (table 2) might be due to confounding with other nutrients (figure 3). Typically, adding gypsum or lime to soil before sowing does not increase shoot mass (Marx 1990, South et al. 2017) unless the amount of Ca in a sandy soil is near zero (Beyer et al. 2013, Pharis et al. 1964, Switzer 1962).

Magnesium

In plots with only 10 ppm soil Mg (February), seedlings were taller than 28 cm (figure 3). Seedlings with foliage levels of 0.02 percent Mg are considered to be deficient (Sucoff 1961), and at lifting, foliage had five times this concentration. Adding 370 kg/ha of Mg (to four of the high lime plots a week prior to sowing) did not increase seedling height, and seedling mass was not correlated with soil Mg levels (table 2). These findings are consistent with other Mg fertilization trials with loblolly pine (Edwards et al. 1991, Wall 1994). Foliar Mg at lifting averaged 10.4 ppm and was not correlated with seedling growth (table 7).

Table 7. Pearson correlation coefficients (r) between foliar nutrient concentrations and loblolly pine seedling attributes for all plots (n = 32). Absolute values above 0.54 are statistically significant at α = 0.001, and absolute values above 0.35 are significant at α = 0.05. Rows are ordered according to correlations with seedling height.

Foliage	Height	RCD	Root	Shoot	Total	H/D	RWR
Aluminum	**– 0.82**	**– 0.52**	**– 0.56**	**– 0.46**	**– 0.49**	– 0.23	– 0.32
Nitrogen	**– 0.66**	**– 0.65**	**– 0.64**	**– 0.62**	**– 0.64**	0.11	– 0.14
Sulfur	**– 0.61**	– 0.28	**– 0.37**	– 0.25	– 0.28	– 0.31	– 0.30
Manganese	**– 0.59**	– 0.30	– 0.26	– 0.12	– 0.16	– 0.26	– 0.33
Phosphorus	**– 0.56**	**– 0.52**	**– 0.43**	– 0.32	**– 0.35**	0.04	– 0.28
Copper	**– 0.40**	– 0.24	– 0.33	– 0.28	– 0.30	– 0.13	– 0.15
Iron	– 0.24	– 0.10	– 0.13	– 0.19	– 0.18	– 0.13	0.12
Boron	– 0.23	0.14	– 0.20	– 0.15	– 0.16	**– 0.41**	– 0.17
Potassium	– 0.22	– 0.13	– 0.27	– 0.23	– 0.24	– 0.09	– 0.14
Sodium	– 0.04	0.10	0.22	0.17	0.18	– 0.17	0.12
Magnesium	0.22	– 0.07	0.07	0.01	0.03	0.33	0.18
Calcium	0.25	0.19	0.05	– 0.01	0.00	0.05	0.12
Zinc	0.31	– 0.11	0.08	– 0.09	– 0.06	**0.46**	**0.42**

H/D = height/RCD. RCD = root-collar diameter. RWR = root mass/total seedling mass.

Nitrogen

Fertilization with N during the growing season increases growth of loblolly pine seedlings (Barker 2010, Marx 1990, Pharis et al. 1964). Nursery managers in the past typically applied N as granules, but many in the South now use liquid formulations of urea or urea and ammonium nitrate (UAN). The 179 kg/ha of N (applied as UAN) produced seedlings with a dry mass of 11.7 g, which is about 7 g above the average reported for 2012–2014 (South et al. 2016).

Foliar N at lifting averaged 1.3 percent, and a negative correlation existed between soil pH and foliar N concentration (table 4; figure 6). Others have also observed an increase in foliar N as soil pH decreases (Coultas et al. 1991, Helm and Kuser 1991, Marx 1990, Schier 1986). The negative correlations between foliar N and various soil nutrients (table 4) is likely due to a carbohydrate dilution effect where larger seedlings have lower N concentrations in foliage. When growing in a fine sandy loam, carbohydrate dilution can reduce foliar N concentration to as low as 0.5 percent in only one growing season (Barker 2010).

Micronutrients

Soil nutrients correlated with seedling mass included Fe, Cu and Zn (table 2). Because each of these elements is correlated with K and P (table 4), a fundamental relationship might not exist, per se, with micronutrient levels at this nursery and seedling growth. A significant correlation is no proof of a cause-and-effect relationship. The correlations in this study might simply reflect plots with higher levels of micronutrients being associated with plots with higher levels of various macronutrients.

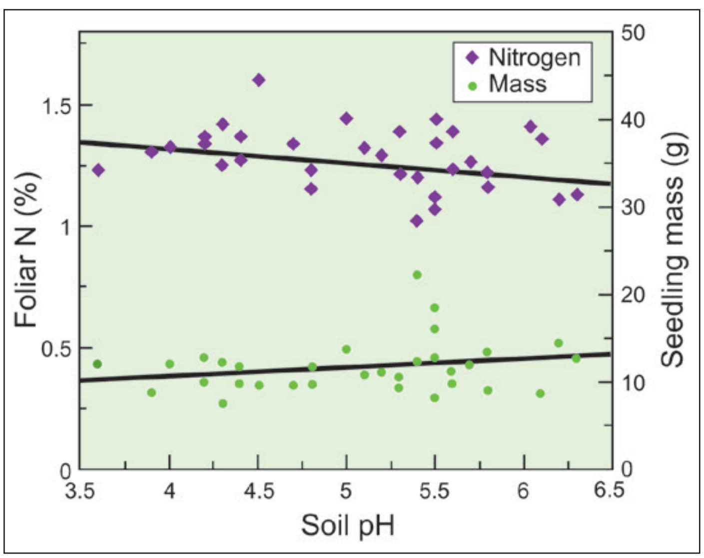

Figure 6. The Pearson correlation coefficient between soil pH and foliar nitrogen (N) was significant ($r = -0.37$; $P = 0.039$), but the correlation between soil pH and seedling mass was not significant ($r = 0.23$; $P = 0.20$; $n = 32$). Diamonds represent foliar N and dots represent seedling mass.

Iron

Chlorosis can occur soon after the first application of N in June (Carter 1964) or when soil pH is too high (Blackmon 1969, Mizell 1980, Nelson and Switzer 1969). In this study, symptoms of Fe chlorosis did not occur on any plots, including three plots with acidity values of pH 6.1 to 6.3. Foliar Fe levels (average 175 ppm) did not differ with replication location ($P = 0.38$) and were far above the 30 ppm deficiency value (table 6). Other studies also found loblolly pine seedlings with 27 to 35 ppm Fe in the foliage were not chlorotic (Ruehle and Wells 1984, Vogel and Jokela 2011).

Soil Fe was positively correlated with RCD and seedling mass (table 2). Ayan and Tufekcioglu (2006) also reported a positive correlation ($r = 0.51$) between Fe levels in container media and seedling mass of Scots pine seedlings. When growing in sand, lodgepole pine (*Pinus contorta* [Dougl.]) increased in height when extra Fe and S were applied in irrigation water (Majid 1984). Foliar Fe has been correlated ($r = 0.44$ and 0.68, respectively) with outplanting survival of loblolly pine and Aleppo pine (*Pinus halepensis* Mill.) (Del Campo et al. 2011, Larsen et al. 1988).

Copper

A tentative minimum value level for soil Cu in nursery seedbeds is 0.8 ppm (double-acid extraction) (Davey 1991), and the average for the two seedbeds in this study was 0.26 ppm. Although low Cu levels are common in southern pine seedbeds, no Cu deficiencies have been reported for 1-0 loblolly pine seedlings. Cu deficiency occurred after pine seedlings were outplanted on low pH soils in the Coastal plain (South et al. 2004) or when pine seedlings are grown in sand in a greenhouse (Majid 1984). Others have reported no significant correlation ($r = 0.22$ and $r = -0.23$) between Cu concentrations in container media and pine seedling mass (Ayan and Tufekcioglu 2006, Memisoglu and Tilki 2014). All foliage samples in this study had more than 6 ppm Cu (table 6). Pine needles with less than 3 ppm of Cu may exhibit deficiency symptoms (South et al. 2004), and those with 4.4 ppm Cu might not show deficiency symptoms (Helm and Kuser 1991).

Zinc

A tentative minimum level for Zn in nursery soils may be 1 ppm (Davey 1991), and an average value for the nursery in this study is 1.8 ppm. The area selected for the S study, however, had low Zn (0.7 ppm) but still produced seedlings with more than 11 g of mass (table 1). In another study, omitting zinc chloride from nutrients resulted in larger Scots pine seedlings (Goslin 1959). Although sandy, easily leached soils with very high P levels are likely candidates for Zn deficiency, no Zn deficiencies have been reported for loblolly pine seedbeds. All seedlings in this study received a foliar application of Zn in July, and all foliar Zn levels were within surveyed ranges (table 6) and averaged 42 ppm.

Boron

Boron deficiencies are rare in loblolly pine seedbeds, perhaps because B is usually applied before sowing, and soil acidity is typically maintained below pH 6. A tentative minimum level for B in nursery soils is 0.3 ppm (Davey 1991). Prior to sowing, the soil in this study had 0.2 ppm B, and a year later (February 2017), the soil was at 0.1 ppm with no deficiency symptoms present on seedlings. The application of 0.16 kg/ha of elemental B (applied in July) helped to maintain foliar B levels above 14 ppm (table 3).

Figure 7. Boron (B) deficiencies occurred at a sandy nursery in Florida in 1979 and 1980 (Stone et al. 1982). Injury was observed on shoot tips, and some necrotic buds were covered with resin. A spring application of B at 0.26 kg/ha was insufficient to prevent damage observed in October 1980. (Photo by Ed Barnard, 1980)

A deficiency in B (foliar level = 1.9 ppm) occurred at a sandy nursery in Florida (figure 7), when the soil pH was greater than 6.0, and extractable Ca levels exceeded 600 ppm (Stone et al. 1982). In this study, an examination of soil fertility at time of lifting on the limed bed indicated OM averaging 1 percent, 152 ppm Ca, and an average soil acidity of pH 5.6 (table 1). The lack of a B deficiency observed in seedlings may be attributed to the low soil Ca levels, adequate pH values and sufficient B residing in lower soil profiles.

When seedling production is 2 kg/m2 (dry mass) with 20 ppm B in seedlings, then total B removal at harvest is 0.4 kg/ha. When a hectare of topsoil equals 2 million kg, then 0.1 ppm is equivalent to 0.2 kg/ha (i.e., one-half the amount removed). A meter of rainfall might add 0.04 kg/ha of B to the soil (Martens and Harriss 1976), and 30 cm of irrigation might add 0.06 kg/ha. Therefore, nursery managers rely primarily on fertilizers, OM, and adequate B in the 25 to 40 cm depth (Pinyerd et al. 1984) to supply the remaining 0.1 kg/ha. When applying B to the soil, nursery managers need to be careful, because toxicity can occur if too much is applied (Khan et al. 2010).

Manganese

Loblolly pine foliage contained more Mn than any other micronutrient (table 6). A positive correlation occurred between soil Mn and seedling height (table 2), which is consistent with a similar correlation ($r = 0.71$) for container-grown Scots pine (Ayan and Tufekcioglu 2006). Lowering soil pH tends to increase the uptake of Mn (figure 8), and this effect may explain positive correlations between Mn and growth in some experiments. Additional height growth due to lowering soil pH may have little to do with the associated increase in Mn nutrition. Because most bareroot nurseries have adequate Mn in the soil (Davey 1991, South and Davey 1983), a need to fertilize with Mn is rare. In fact, high levels of Mn in some nursery soils can induce a Ca deficiency (South 2017), and might contribute to a Cu

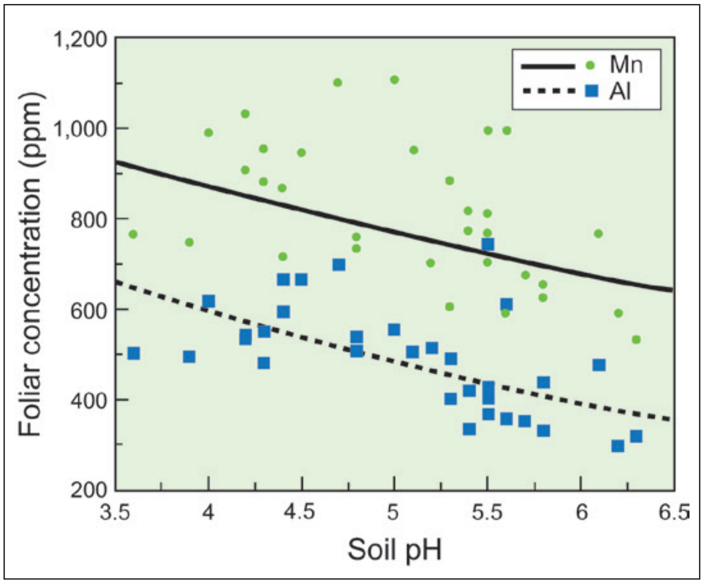

Figure 8. The relationship between soil pH and aluminum (Al; R^2 = 0.46) and manganese (Mn; R^2 = 0.37) in the foliage of loblolly pine (n = 32). Squares represent foliar Al, and dots represent foliar Mn.

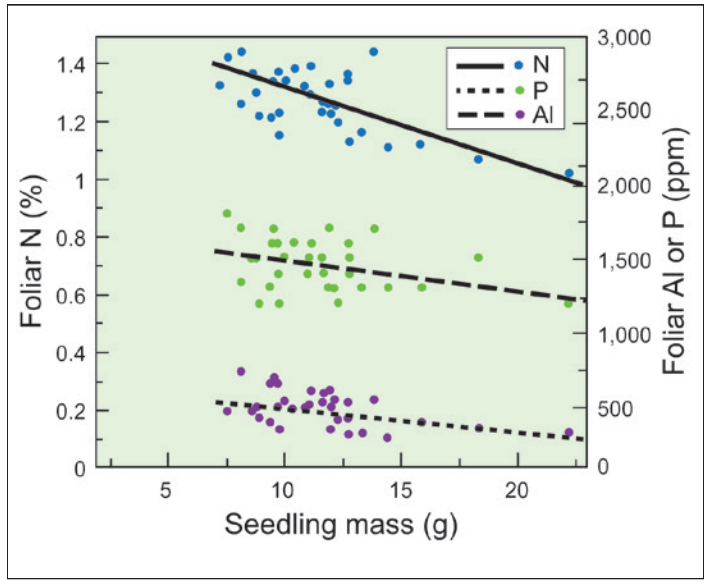

Figure 9. The effect of carbohydrate dilution on nitrogen (N), phosphorus (P), and aluminum (Al) appears to be linear (n = 32).

deficiency (Turvey et al. 1992). Visual symptoms of Mn toxicity were not observed when pine foliage had more than 1,000 ppm Mn (figure 8; Adams and Walker 1975, Beyer et al. 2013).

Aluminum

Soil aluminum (Al) was not measured, but foliage samples suggest that increasing soil pH with lime decreased the amount of Al in the foliage (figure 8). The high rate of lime reduced Al in the foliage (P = 0.08) from 454 ppm (untreated) to 350 ppm (high rate of lime). These values are relatively low, because the median value in bareroot nurseries is about 650 ppm (Boyer and South 1985). The observed decline is consistent with other research where lime reduced the concentration of foliar Al in pines (Helm and Kuser 1991, MacCarthy and Davey 1976, Marx 1990). Although pines seem to be very tolerant of Al (Cronan et al. 1989; Moyer-Henry et al. 2004, South 2017), some warn against high levels of available Al in the soil (Davey 1991, Paganelli et al. 1987). In this trial, toxicity symptoms were not noticed when soil pH was 5.0 and foliage contained 1,106 ppm Al. Seedlings with this level of Al in needles had a total seedling mass of 13.8 g. These observations support the view that naturally high levels of Al are not known to have undesirable effects on conifers (Stone 1965).

Foliar Al was negatively correlated with seedling height, but this correlation might be due to a carbohydrate dilution effect, because several nutrients also had negative correlations (table 7). Other researchers have shown positive correlations between foliar Al and pine seedling height growth. In studies with loblolly pine (Marx 1990) and pitch pine (Helm and Kuser 1991), liming reduced shoot growth and decreased foliar Al by 100 to 118 ppm.

Carbohydrate Dilution

It is well known that as crop yield increases, carbohydrate dilution tends to lower mineral percentages (Haase and Rose 1995). Data from this study show that as seedling mass increases, carbohydrate dilution lowered nutrient concentrations. Except for Ca and Mg (which increased in foliage in limed plots), all nutrients had negative correlations with total seedling mass (table 7). Therefore, less fertile replications that produced smaller seedlings (table 1) tended to produce foliage with a higher percentage of N, P, Cu, and Mn (table 3). The effect of carbohydrate dilution on N, P, and Al appears to be linear (figure 9). Other data also show a carbohydrate dilution effect for foliar N as loblolly pine seedlings increase in mass during the fall (Marx 1990, Sung et al. 1997, Switzer and Nelson 1956, Williams et al. 2004).

Conclusions

Soil nutrient levels in fertilized sandy nurseries can affect loblolly pine seedling growth more so than differences in soil pH (3.5 to 6.3) or small differences in OM (0.5 to 0.8 percent). Macronutrients (P, K) and micronutrients (Cu, Fe, Zn) in the soil were positively correlated with seedling mass. Due to carbohydrate dilutions, we should not be surprised when larger seedlings have lower concentrations of nutrients in foliage.

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