Sulfur and lime affect soil pH and nutrients in a sandy *Pinus taeda* nursery

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Abstract

Two pH experiments were conducted at a sandy, bareroot loblolly pine (*Pinus taeda* L.) nursery in Texas. A sulfur trial (0, 813, 1626, 2439 kg ha^{-1} of elemental sulfur) was installed to determine if lowering soil pH would result in nutrient toxicity symptoms and affect seedling morphology. Although soil acidity in the sulfur study ranged from pH 3.9 to pH 5.0, none of the treatments resulted in micronutrient toxicity and none affected height growth, root-collar diameter, root mass, shoot mass or the root-mass ratio (root dry mass/total dry mass). Acidifying soil with sulfur increased leaching of calcium, potassium, magnesium, manganese and zinc but there was no effect on seedling morphology. The objective of the liming trial (0, 813, 1626, 3252 kg ha^{-1} of dolomitic lime) was to determine if increasing alkalinity would result in an iron deficiency and reduce seedling growth. As expected, applying lime increased the calcium and magnesium levels but had no effect on soil levels of iron, phosphorus, potassium, sulfur, zinc and sodium. However, the root-mass ratio was reduced by applications of dolomitic lime (pH ranged from 5.3 to 6.0). Differences in soil properties (i.e. plot location) had a greater effect on seedling morphology than lime applications. Foliage levels of manganese and boron were reduced by the highest rate of lime and sulfur, respectively.

Keywords

Acidification; Bareroot; Mineral nutrition; Soil acidity; Toxicity

Contents

1 Introduction

Loblolly pine (*Pinus taeda*) seedlings are produced in bareroot nurseries with soils that range widely in soil acidity and soil texture (South and Davey 1983). Although pine seedlings have been operationally grown at pH 4.2 to 6.6 (Dickson et al. 1960, Marx et al. 1984, South and Davey 1983, South 2000) most managers use a more narrow range that is based on personal experience or suggestions from nursery experts. Some authorities recommend a range of pH 5.5 to 6.5 while others suggest a range of pH 4.5 to 5.5 (South 2017). In some cases, the desire to keep the pH range above pH 5.4 is based, in part, on fears about aluminum (Al) toxicity (Davey 1991) and reduced availability of nutrients like phosphorus (P) (Stone 1965; Bunting 1980).

Earl Stone (1965) said that although we have some “generalities” about the effect of pH on most soils, we have insufficient information about sandy soils. As a result, two trials were installed at a sandy nursery with a low cation exchange capacity (CEC). The objective of the sulfur (S) trial was to see if lowering soil pH would result in nutrient toxicity and negatively affect seedling growth. For loblolly pine, will symptoms of Al, zinc (Zn), copper (Cu) or manganese (Mn) toxicity materialize when soil acidity is increased? We also wanted to know if the availability of P would be reduced when soil was lowered to pH 4.0. A second study was installed to see if reducing soil acidity with dolomitic lime would reduce growth of loblolly pine seedlings.

2 Methods

Two studies were established at ROB SuperTree Nursery at Bullard, Texas. In March of 2016 the soil was fumigated with a combination of chloropicrin and 1,3-dichloropropene. For each trial, the study design was a randomized complete block design with four treatments and four replications (i.e. 16 experimental units). The size of each plot was 183 cm by 610 cm. On April 9th, 2016, the elemental sulfur (0, 813, 1626, 2439 kg ha^{-1}) and dolomitic lime (90% passing 100 mesh sieve) treatments (0, 813, 1626, 3252 kg ha^{-1}) were applied and the material was mechanically incorporated into the top 15 cm of soil. The trials were established on separate beds in field 5 on a loamy sand (sand 83%; silt 1%; clay 16%) with a CEC < 2.0. Stratified loblolly pine seed (half-sib family) were machine sown on April 16.

Herbicide applications began on June 7 when oxyfluorfen (122 g a.i. ha^{-1}) was applied as a broadcast application. Similar amounts of oxyfluorfen were also applied on June 15, 23, 30, July 8, July 18, and August 8. Insecticide applications began on June 14 and ended on October 2. Esfenvalerate were applied periodically to control *Lygus linenarious* (Palisot de Beauvois). Tridimefon (140 g a.i. ha^{-1}) was applied three times to control *Cronartium quorum* f. sp. *fusiforme* (Hedg. & Hunt ex Cumm.) and other fungicides were applied to lower the probability of detecting foliar diseases. Seedlings were wrenched in mid-July, undercut on October 28 and top-pruned on August 2 and September 18. Prior to sowing, calcium (Ca) (448 kg ha-1 of gypsum), potassium (K), Mg and S (280 kg $ha^{-1}$of sulfur, potassium-magnesium) fertilizers were applied and tilled into the soil. At that time, small amounts (< 90 g ha^{-1}) of each of the following chelated micronutrients [boron (B), copper (Cu), iron (Fe), Manganese (Mn), Molibnium (Mo) and zinc (Zn)] were applied to the soil. Top-dressings of fertilizer were conducted beginning in June and ending in September (a total of 179 kg ha^{-1} of nitrogen (N) and 58 kg ha^{-1} of K applied to the crop). In July, the seedlings received a foliar application containing 1.17

kg ha^{-1} Ca, 0.23 kg ha^{-1} B and 0.46 kg ha^{-1} Zn. The average seedbed density at harvest was estimated at about 215 seedlings per square meter.

Soil pH measurements were recorded in October and soil samples (top 15 cm) were taken in February, 2017. The experiment was terminated after 10 months (February 7, 2017). Seedling samples were lifted using shovels and were transported to Auburn University where they were placed in a cooler at 3° C. Root-collar diameters and heights of fifteen seedlings were measured and recorded. The seedlings were then dried in a forced-air oven for 72 hours at 70° C and dry weights of roots and shoots were recorded. The root mass ratio was determined by dividing the root mass by the total seedling mass. Foliage samples were analyzed by Waypoint Analytical (Memphis, TN) and soil samples were analyzed using the Mehlich III extraction procedure. Temperature and precipitation data were recorded at the nursery (Table 1).

Each trial utilized a randomized complete block plot design with four replicates and the trials were analyzed separately. Plot means were generated and these values were analyzed using PROC GLM of the Statistical Analysis System software package (SAS 1988). Orthogonal contrasts were employed to detect linear relationships. Treatments were treated as fixed, while replicates were treated as random effects. Differences among treatments were declared significant at the alpha = 0.1 level. Statistics were not conducted for soil B since all experimental units were low in B (i.e. 0.1 µg g^{-1}).

Table 1. Mean precipitation, maximum rainfall during one 24 h day, date of maximum rainfall, days of the month with more than 2.5 mm of precipitation, and mean monthly temperature for 2016.

Month	Total (mm)	Daily maximum (mm)	Date for maximum	Days > 2.5 mm	Mean Temperature (C°)
January	42	15	6	4	8.3
February	0	0	-	0	13.6
March	2	2	30	0	18.8
April	254	81	29	8	19.4
May	88	39	26	5	22.7
June	67	30	2	4	25.9
July	16	3	4	1	28.9
August	30	14	28	3	26.1
September	5	3	16	0	26.5
October	2	2	20	0	20.8
November	58	25	23	4	16.3
December	76	51	3	5	11.3

3 Results

3.1 Sulfur trial

As expected, applying S increased soil acidity (ten months after application) and the 1,626 kg ha^{-1} treatment reduced soil pH by 0.5 unit. As a result, there was a correlation between soil S (SO_4^-) and soil pH (pH = 8.2*sulfur µg $g^{-1 - 0.212}$); R^2 = 0.55; n =

16). The plot with the greatest S level had the lowest pH (Figure 1). The high rate of S reduced availability of Ca, Mg, K, Mn and Zn (Table 2). The level of S in the needles was increased by applying S (Table 3) but the greatest rate applied reduced the level of B in the foliage. In this study, S applications did not affect seedling morphology (Table 4). Location of replications in the seedbed had a much greater effect on soil Cu and iron (Fe) than did the S applications.

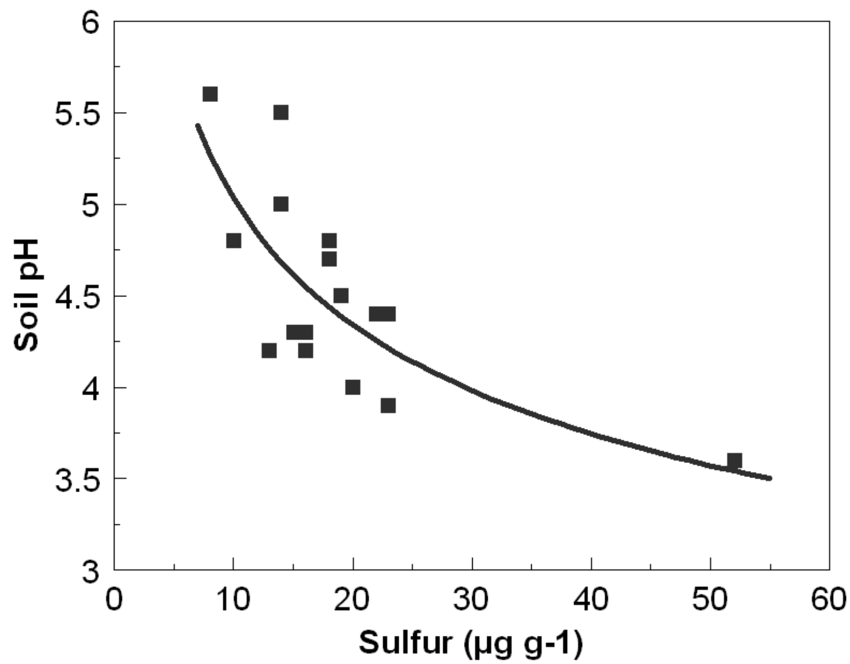

Figure 1. The relationship between soil sulfate sulfur and soil pH (February) in the sulfur trial.

Table 2. Effect of sulfur and dolomite on soil chemical properties ten months after treatment.

Trial	Rate (kg/ha)	pH	H (%)	CEC (meq)	OM (%)	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	S (ppm)	Cu (ppm)	Fe (ppm)
Sulfur	0	5.0	40	1.35	0.60	47	29	95	16	13	0.25	155
Sulfur	813	4.6	55	1.42	0.65	51	24	78	15	18	0.25	187
Sulfur	1626	4.5	57	1.55	0.60	49	25	79	14	16	0.25	155
Sulfur	2439	3.9	78	2.32	0.67	47	22	56	11	28	0.23	173
LSD-5%	-	0.55	20	0.95	0.13	4.5	4.2	18.4	4.1	14.9	0.66	38.6
Linear	P>F	0.002	0.002	0.046	0.365	0.444	0.011	0.001	0.030	0.079	0.442	0.693
Replication	P>F	0.123	0.169	0.176	0.508	0.139	0.039	0.373	0.272	0.552	0.002	0.001
Dolomite	0	5.3	31	1.42	0.65	49	31	135	21	23	0.25	161
Dolomite	813	5.4	28	1.17	0.60	50	31	114	19	9	0.25	161
Dolomite	1626	5.7	24	1.62	0.67	51	34	177	29	8	0.30	159
Dolomite	3252	6.0	15	1.57	0.60	51	33	181	33	6	0.30	165
LSD-5%	-	0.43	9.5	0.41	0.08	6.0	6.0	49.9	9.4	26.3	0.05	26.0
Linear	P>F	0.004	0.003	0.168	0.406	0.546	0.415	0.019	0.006	0.235	0.032	0.753
Replication	P>F	0.590	0.510	0.157	0.054	0.001	0.027	0.226	0.378	0.481	0.001	0.001

Table 3. Effect of sulfur and dolomite on foliar nutrients of loblolly pine.

Trial	Rate (kg/ha)	N (%)	S (%)	P (%)	K (%)	Mg (%)	Ca (%)	Na (ppm)	B (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)	Al (ppm)
Sulfur	0	1.35	0.10	0.16	0.80	0.10	0.39	0.03	22	42	907	191	13	609
Sulfur	813	1.28	0.11	0.15	0.72	0.10	0.39	0.04	21	38	860	196	11	615
Sulfur	1626	1.43	0.12	0.16	0.81	0.10	0.39	0.04	22	42	971	198	14	562
Sulfur	2439	1.31	0.13	0.15	0.77	0.10	0.38	0.03	19	38	882	168	11	537
LSD-5%	-	0.10	0.02	0.013	0.10	0.01	0.06	0.01	2.4	8.9	112	107	4.8	123
Linear	P>F	0.947	0.033	0.692	0.906	0.365	0.587	0.838	0.060	0.574	0.831	0.661	0.591	0.155
Replication	P>F	0.011	0.141	0.001	0.385	0.797	0.261	0.522	0.002	0.763	0.001	0.481	0.168	0.344
Dolomite	0	1.26	0.08	0.14	0.73	0.11	0.39	0.04	19	45	865	150	10	454
Dolomite	813	1.17	0.09	0.13	0.71	0.11	0.40	0.03	19	43	683	186	11	395
Dolomite	1626	1.25	0.08	0.14	0.70	0.10	0.39	0.03	19	43	705	153	11	406
Dolomite	3252	1.18	0.09	0.13	0.72	0.11	0.40	0.03	18	44	606	162	10	350
LSD-5%	-	0.10	0.02	0.02	0.13	0.01	0.06	0.02	2.6	7.7	106	53	2.4	78
Linear	P>F	0.295	0.645	0.765	0.879	0.747	0.748	0.267	0.438	0.952	0.001	0.979	0.699	0.021
Replication	P>F	0.005	0.335	0.668	0.696	0.932	0.786	0.436	0.148	0.253	0.278	0.536	0.194	0.043

Table 4. Morphology of *Pinus taeda* seedlings as affected by sulfur or dolomitic lime applied a week before sowing.

Test	Rate (kg/ha)	Height (cm)	RCD (mm)	Shoot mass (g)	Root mass (g)	Total mass (g)	Root mass ratio (g/g)
Sulfur	0	30.0	7.4	8.29	1.94	10.23	0.19
Sulfur	813	30.0	7.6	8.08	2.11	10.19	0.21
Sulfur	1626	30.5	7.5	8.78	1.99	10.77	0.19
Sulfur	2439	30.9	7.6	9.12	2.25	11.37	0.20
LSD-5%	-	1.54	0.58	2.425	0.522	2.772	0.034
Linear	P>F	0.168	0.453	0.372	0.306	0.918	0.331
Replication	P>F	0.216	0.017	0.232	0.362	0.217	0.753
Dolomite	0	33.7	7.9	9.55	2.82	12.38	0.228
Dolomite	813	33.9	8.2	10.93	3.08	14.01	0.219
Dolomite	1626	34.2	7.9	9.69	2.69	12.38	0.218
Dolomite	3252	35.1	7.9	9.51	2.52	12.03	0.209
LSD-5%	-	1.91	0.69	2.86	0.85	3.69	0.015
Linear	P>F	0.109	0.511	0.685	0.285	0.572	0.024
Replication	P>F	0.007	0.001	0.004	0.008	0.005	0.015

3.2 Lime trial

Dolomitic lime reduced soil acidity and the 1,626 kg ha-1 treatment increased soil pH by 0.4 unit. Although there was a correlation between soil pH and soil Ca (Figure 2), the correlation was stronger with Mg (pH=4.77 + 0.032*magnesium $\mu g\ g^{-1}$); $R^2 = 0.52$; n = 16). The lime treatments increased availability of Mn and Cu and had no effect on Fe (Table 2). The lime applications reduced the amount of Mg in the needles (Table 3). Dolomitic lime reduced the root-mass ratio and the increase in height growth was almost statistically significant (Table 4). Location of plots in the seedbed had a much greater effect on seedling morphology than did the liming treatments.

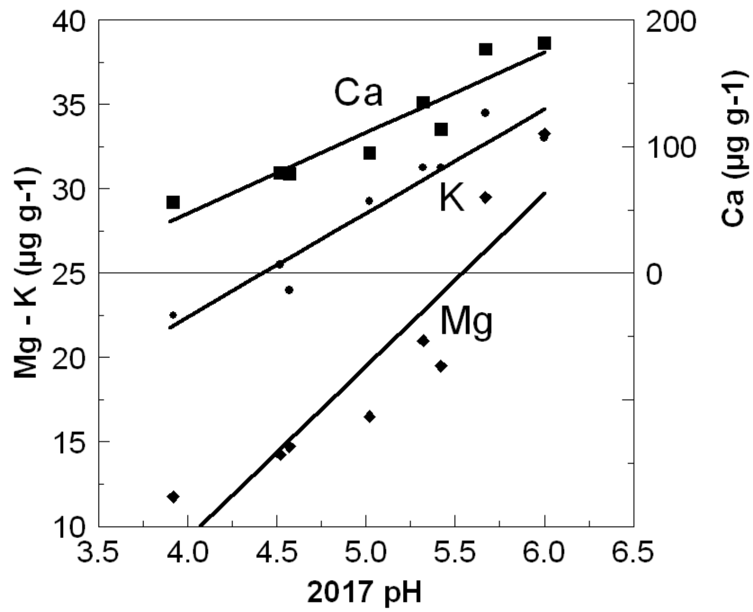

Figure 2. The relationship between soil pH (February) and three soil cations (calcium, potassium and magnesium) when treatment means for both studies are combined. Each point represents a treatment mean. Sulfur treatments are below pH 5.0 and lime treatments are above pH 5.3.

4 Discussion

4.1 Sulfur trial

Good growth of loblolly pine seedlings was observed in soil that was lowered to pH 3.6 to 3.9. This supports the view that hydrogen ions are not toxic at pH 4 (Howell 1932; Davey 1991) and that seedling quality is not harmed when soil pH is 4.3 (Dickson et al. 1960; South 2017). Much of the S was likely converted to sulfuric acid and sulfate ions were subsequently leached with rainfall (Swanson and Miller 1917). As a result, soil analyses in February (Table 2) indicated about 1% of the S applied in April remained in the topsoil as extractable sulfate S. An examination of pH values in October and February suggests that most of the acidification took place prior to October.

Millions of southern pine seedlings have been grown after applying 900 kg ha^{-1} of elemental S (a month or two prior to sowing) to sandy soils. However, occasionally this rate may stunt seedlings when rainfall after sowing is below average (Carey et al. 2002). Stunting may result when sulfuric acid comes in direct contact with roots. Gypsum crystals present on roots are a symptom that indicates sulfuric acid has been present in the rhizosphere. A lack of gypsum on roots in the high S plots may be explained by above average rainfall in April (Table 1). This suggests an interaction exists between rainfall and the amount of gypsum formation on pine roots. Since nursery managers cannot accurately predict the weather, it would be best to apply S several months before sowing to allow the sulfuric acid formation to occur prior to sowing seed.

For example, Armson and Sadreika (1979) suggest sowing seed at least two to three months after soil incorporation of S.

A rate of 900 kg ha^{-1} S is typically not applied to nursery soils unless the soil is greater than pH 6.0 (Mizel 1980). The reason we applied high rates of S to a pH 5.0 soil was to see if symptoms of Al, Zn, Cu or Mn toxicity would materialize or if a P deficiency would occur. Our results show no toxicity either from visual symptoms during the growing season or from foliar tests in February. In fact, increasing hydrogen ion concentrations reduced the amount of Zn and Mn in the topsoil.

Increasing acidity to pH 3.9 resulted in less Mn in the soil (Table 2) which was unexpected. Normally, lowering soil pH increases the availability of Mn (Marx 1990; Helm and Kuser 1991; Wright and Hinesly 1991). In both trials, soils initially contained less than 40 µg g^{-1} of Mn and therefore the risk of toxicity from this element was low. Although pine is relatively tolerant of Mn (St.Clair and Lynch 2005), the risk of toxicity to pines is higher when soils contain more than 200 µg g^{-1} Mn (Davey 1991). At one nursery, soil Mn exceeded 350 µg g^{-1} when the soil pH dropped below 5.0 and this resulted in a Ca deficiency (South 2017).

A plot with the highest soil acidity (pH 3.6) had 0.3 µg g^{-1} Cu, 0.6 µg g^{-1} Zn, and 5 µg g^{-1} Mn. In addition, lowering soil pH did not result in more uptake of Al, Zn, Cu or Mn in the foliage (Table 3). It seems likely that when the CEC of the soil is less than 2.0, there may be low probability of Al, Zn, Cu and Mn toxicity, even when the soil acidity is pH 4.0. The authors are not aware of any documented cases where low soil pH in bareroot nurseries resulted in toxic levels of Al, Zn, or Cu to loblolly pine seedlings.

In sandy nursery soils, the uptake of P depends on the presence of ectomycorrhiza (South et al. 1988) and some species of mycorrhiza grow better at low soil pH (Marx 1980; Shafer et al. 1985). Even so, some say that the availability of P is reduced when soil acidity is high (Bunting 1980; Davey 1991). However, at this location, increasing soil acidity had no effect on either soil or foliar P levels (Tables 2 and 3). Others also report no significant effect on P availability when either lowering or raising soil pH (Elzner 1978; Shafer et al. 1985; Marx 1990). In one greenhouse trial, the uptake of P in pine needles was reduced by increasing pH with lime (Helm and Kuser 1991).

4.2 Lime trial

Soil (with pH 5.2), treated with 2,905 kg ha^{-1} of dolomitic lime, increased in alkalinity to pH 5.6 by October and to pH 6.0 by February. In Georgia, Marx (1990) applied 2,850 kg ha^{-1} of calcium hydroxide to a loamy sand with pH 4.8 and the pH increased rapidly to pH 6.1 by June (and then it declined to pH 5.8 by October). Seedling mass was reduced by the calcium hydroxide treatment but we detected no effect of dolomitic lime on total mass (Table 4). It is not known what factors would explain this difference, but it might be due to the microbial makeup of the soil. The seedlings in the Georgia study were inoculated with *Pisolithus tinctorius* ectomycorrhiza and this species does well in acid soils (Marx 1990). The difference also might be due to the type of lime applied in Georgia. Calcium hydroxide may have about 25% more acid neutralizing power than dolomitic lime. Even so, others have reported stunting of *Pinus rigida* when dolomitic lime was added to a bark-sand media (Helm and Kuser 1991).

In theory, 2,905 kg ha^{-1} of dolomitic lime added 715 kg of Ca and 358 kg of Mn per hectare. This treatment increased extractable Ca and Mn in the topsoil (February) by perhaps 100 kg and 25 kg, respectively. Approximately 14% of the applied Ca and 7%

of the Mn remained active in the topsoil. The high amount of rainfall may have moved some of these cations to lower levels in the soil. As a result, the lime treatment had no effect on Ca levels in the foliage (Table 3).

The lime treatments increased the availability of Mn in the soil (Table 2) which was similar to results with container-grown media (Wright and Hinesley 1991). The increase in available Mn was 50% for the nursery soil (Table 2) and 100% for a pine bark and sand mixture (Wright and Hinsley 1991). However, this increase was not reflected by an increase in Mn concentration in pine needles. In fact, liming resulted in a reduction in foliar Mn (Table 3) which agrees with the findings reported by Helm and Kuser (1991) and Wright and Hinesly (1991). Liming also reduced the amount of Al in the foliage which is consistent with Helm and Kuser (1991) and Marx (1990).

The high rate of lime reduced the root mass ratio which was unexpected since others report an increase in this ratio as pH increases (Shafer et al. 1985; Marx 1990, Helm and Kuser 1991). Even so, a reduction in root mass ratio also occurred with *Pinus banksiana* when the alkalinity of a hydroponic solution was increased above pH 6.0 (Zhang et al. 2015).

5 Conclusions

Micronutrient toxicities were not detected when loblolly pine was growing in pH 3.9 soil with a CEC below 2.0 and phosphorus did not become unavailable. At this location, growth of loblolly seedlings was not affected by either dolomitic lime or S. Fears about growing loblolly pine seedlings at pH 4 on course textured soils are not based on empirical trials. Even so, conclusions from these experiments must be drawn with caution due to the above average rainfall that occurred soon after treatment.

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