Use of sulphur in bareroot pine and hardwood nurseries

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Abstract

During the 20th century, managers at sandy nurseries utilized sulphur (S) to lower soil pH and mitigate the risk of iron deficiency. During that time, however, applying S as a fertilizer was a rare event. At many nurseries, S in rain and irrigation water was sufficient to avoid visual deficiency symptoms. The S status of soil and foliage was typically unknown, and many researchers did not test for S due to the additional cost. Consequently, S became the most neglected macronutrient. While a few nursery trials demonstrated that elemental S reduced damping-off and increased height growth, a majority showed no benefit after applying S at rates lower than 100 kg ha^{-1}. Even so, by 1980, S-deficiencies occurred at bareroot nurseries in Alabama, Oklahoma, Virginia, Wisconsin, the United Kingdom, and likely in North Dakota and New York. The risk of a deficiency increases when N-only fertilizers are applied to seedbeds. Due to research, experience and the precautionary principle, several managers transitioned to using ammonium sulfate instead of, less expensive, N-only nitrogen fertilizers. After soil tests became affordable, managers began to ask questions about the need to apply S to seedbeds.

Only a few hydroponic trials with small pine seedlings have been used to estimate "threshold" or "critical values" for foliar S. Since an initial 1,500 µg g^{-1} S value is "unreliable" for pine seedlings, some authors lowered the value to 1,100 µg g^{-1} and even as low as 500 µg g^{-1} S. Others ignore all estimates based on total S concentrations and, instead, monitor only foliar SO_4 levels.

Keywords

Nutrition; Sulfur; Foliar analysis; Soil testing; Hidden hunger

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1 Introduction

In bareroot nurseries, Sulphur (S) comes from the air, rainwater, irrigation and the decay of organic matter in the soil. Where S-fertilizers are used, pine and hardwood seedlings will likely not be deficient in S. However, at some nurseries, seedlings may become S-deficient, especially when sandy soil is irrigated with water that is low in S. Typically, S is a neglected element when it comes to forest nursery research.

There are several reasons why managers of bareroot nurseries apply S to seedbeds and seedlings. #1- increase soil acidity: When soil pH is too high for optimum growth, S rates of 800 to 1,100 kg ha^{-1} can lower soil pH at sandy nurseries (South 2017). In some cases, increasing soil acidity will reduce the risk of an Fe deficiency. #2- soil fungi: At some nurseries, “flowers” of S (90% elemental S; 110 to 330 kg ha^{-1}) or sulphuric acid was used to control damping-off fungi in non-fumigated soil (Steer 1915; Wilde 1958). Occasionally S is applied to foliage in hopes of reducing the growth of powdery mildew (Landis et al. 2009). #3-nutrition: Even though the risk of a S-deficiency is low in bareroot nurseries, applying S fertilizers reduces the risk even further.

Although much is known about the effects of S on soil acidity, fungi, and growth of *Zea mays*, limited information is available on S-deficiencies in tree nurseries. A lack of research might be due to several factors. First, irrigation may contain sufficient S so S-deficient seedlings did not develop. Second, many state laboratories did not routinely test for S in either nursery soils, water, or seedling foliage. The Mehlich 1 soil test uses H_2SO_4 which means laboratories used a different test to analyze soil SO_4 (Wilde et al. 1972; Combs et al. 1998). Although the North Carolina Soil Testing Division had a space for reporting soil SO_4, customers rarely paid for this service. At that time, the standard recommendation was to apply 8 to 13 kg ha^{-1} of S to row-crops, so testing S levels in soil was deemed not necessary. Often a soil test for SO_4 might cost \$5 while 10 kg of S might cost <\$2.50. Even with topsoil tests, the SO_4 value often did not accurately predict the amount of S available to roots growing 25 cm below the surface. In general, subsoil samples provide a more reliable assessment of plant-available S. Routine testing of available S from bareroot nurseries began in the 1980’s when nursery managers and researchers sent samples to commercial laboratories. Currently, adding a test for SO_4 to a routine soil test may increase the cost by $2.50 per sample.

Currently, S-deficiencies in row-crops in the Northern Hemisphere are more common than during the 20th Century. Two reasons for this are increased harvest yields, and less atmospheric S deposition (Zhang et al. 2018). Although a risk of S-deficiency is low in most irrigated pine nurseries, nursery managers need to be aware of factors that might produce a growth response from S fertilization.

2 History

During the 19th century, sulphate-containing fertilizers such as AS, gypsum, superphosphate, kainit, and KS were available for purchase. However, due to cost, some nurseries did not purchase commercial fertilizers. Instead, managers relied on “green manuring” (Brock 1910) and raw humus (Retan 1914) to supply nutrients.

Schenck (1907) recognized the importance of nutrients in bareroot seedbeds. To replenish nutrient losses, Schenck applied several fertilizers including kainit (that contained 10 to 25% S). During his time, elemental S was mainly used in nurseries to control damping-off, mildew and even some insects (Brock 1910; Bourcart 1913). At some nurseries, better growth of seedlings occurred after fertilization with AS and KS (Retan 1914; Benzian 1965b). Tillotson (1917) discussed fertilizer usage in Federal nurseries and suggested that AS was a superior nitrogen source compared to sodium nitrate (chili saltpeter). He also mentioned the use of sulphuric acid to mitigate damping-off but did not specifically refer to S as a fertilizer. Steven (1928) tested AS and calculated LSD values to compare treatment means. Wahlenberg (1930) conducted fertilizer trials at the Savanic Nursery in Montana and tested S at 56 kg ha^{-1}. This rate of S did not affect the distribution of roots in topsoil. Benzian (1965b) conducted numerous tests with S at nurseries in the UK.

Wakeley (1935) noted that fertilization of southern pine nurseries had just begun and practically no fertilizer trials had been established. He mentioned that a liquid solution of AS could be applied over the top of pine seedlings if growth was below expectations. Others also reported good results from AS fertilization (McIntyre and White 1930; Rosendahl and Korstian 1945).

Although soil SO_4 could be measured (Ames and Boltz 1916; Wilde et al. 1972), most nursery soil tests during the 1970’s did not include S. Frequently, S-deficiency was not a problem in bareroot nurseries because of the use of sulphate-based fertilizers (Maxwell 1988). However, approximately one-third of managers were not using sulphate-based fertilizers to grow *Pinus taeda* seedlings (Table 1). After receiving soil test results indicating less than 10 µg g^{-1} S, nursery managers began to inquire about the need to apply S (Stone 1980).

Although S-fertilizers can be applied before or after sowing, some managers apply S after plants are 5 cm tall. Seedlings have roots at this stage and uptake efficiency may be greater than applying S to bare soil. In one survey, about 60% of managers did not apply S prior to sowing pines (Table 1). The first report of a S-deficiency at a bareroot nursery was either in 1945 in North Dakota (Stoeckeler and Ardeman 1960) or in Alabama in 1960 (Lyle and Pearce 1968).

In 1980, about 29% of managers applied AS to pines during the summer while 68% applied AN (Marx et al. 1984). Some managers applied AN since it was less expensive than AS while others relied on AS due to growth benefits (van den Driessche

1972; Morris 1979) plus the ability to lower soil pH and improve seedling quality (van den Driessche 1969; South and Davey 1983; South 2017).

Table 1. Sulphur (S) fertilizers used at bareroot pine nurseries (Marx et al. 1984). At some nurseries, harvesting 10 Mg of pine seedlings might remove 5 to 10 kg ha^{-1} of S.

Nursery-year	State	Soil N	Sand	Prior to sowing			After germination		Total S
		µg/g	%	Fertilizer	% S	S kg/ha	Fertilizer	S kg/ha	kg/ha
Buckeye-1977	FL	261	95	5-10-15	3	23	0	0	23
Andrews-77	FL	196	94	K_2SO_4	17.5	59	K_2SO_4	49	108
Buckeye-78	FL	237	94	0	0	0	0	0	0
Ft. Towson-78	OK	242	91	0	0	0	NH_4SO_4	182	182
Ft. Towson-77	OK	187	89	0	0	0	NH_4SO_4	182	182
Great Southern-77	GA	268	89	0	0	0	0	0	0
New Kent-77	VA	544	89	0	0	0	0	0	0
New Kent-78	VA	566	88	0	0	0	0	0	0
Buckeye-79	FL	335	88	0	0	0	0	0	0
Buckeye-80	FL	268	88	0	0	0	0	0	0
Champion-80	SC	260	88	0	0	0	NH_4SO_4	115	115
Magnolia-77	AR	283	87	0	0	0	NH_4SO_4	182	182
Westvaco-78	SC	282	86	0	0	0	0	0	0
Champion-79	SC	289	86	0	0	0	NH_4SO_4	132	132
Westvaco-80	SC	517	86	0	0	0	NH_4SO_4	26	26
Griffith-77	NC	654	84	8-8-8	3	17	0	0	17
Great Southern-78	GA	504	84	0	0	0	0	0	0
Westvaco-77	SC	920	83	0	0	0	0	0	0
Magnolia-78	AR	510	83	$MgSO_4$	14	16	NH_4SO_4	79	95
Ashe-77	MS	308	81	13-13-13	5	3	0	0	3
Beauregard-77	LA	256	79	$CaSO_4$	16.8	56	0	0	56
Beauregard-78	LA	550	69	0-0-22-22	22	98	0	0	98
Edwards-78	NC	464	67	0	0	0	K_2SO_4	70	70
Kentucky Dam-77	KY	523	66	15-15-15	9	20	0	0	20
Waynesboro-78	MS	731	65	0	0	0	0	0	0
Kimberly Clark-77	AL	780	53	0	0	0	K_2SO_4	105	105
Hiwassee-79	GA	787	51	20-20-20	0.06	0.3	0	0	0.3
Kimberly Clark-78	AL	731	48	0	0	0	NH_4SO_4	105	105
Oklahoma State-78	OK	777	47	Sulphur	100	560	NH_4SO_4	224	784
Pinson-77	TN	660	42	13-13-13	5	17	0	0	17
International-79	MS	916	15	6-12-12	3	13	13-13-13	6	19

3 Soil tests

Soil contains both inorganic and organic forms of S, which together are referred to as total S. However, soil tests commonly used by nursery managers extract the sulphate form (SO_4) and do not account for the unavailable organic forms. Different methods, such as Mehlich 3 and AA, are utilized to estimate the extractable S content in the soil (Mattila and Rajala 2022). Comparing the AA method with Mehlich 3, similar results of SO_4 may be obtained from extractions of identical soil samples. In a study involving 24 different soils, the Mehlich 3 test identified 4 soils as deficient in S, whereas the AA test indicated a deficiency in two soils (Mattila and Rajala 2022). Mehlich 1 extraction solution contains H_2SO_4 which is why it is not used for testing S.

The cost of soil analysis varies and several laboratories do not routinely test soil or water for S. For example, one laboratory processed 44,660 standard soil tests compared to 314 tests for S. Cost at this facility was \$6 per sample without S and \$11 when including S. Some agronomists argue that there is a weak correlation between growth of vegetables and Mehlich 3 results for S (Esmel et al. 2010) and, therefore, they see no value for increasing costs to landowners. In one trial, there was no positive correlation ($r = -0.26$) between height growth of pine seedlings and Mehlich 3 test results (South et al. 2018).

For most nutrients, Mehlich 3 tests vary little among laboratories (Tucker and Hight 1990). For example, after testing 21 soil samples, the average SO_4-S level was 5 6 µg g^{-1} for a laboratory in Tennessee and 6 µg g^{-1} for a Georgia laboratory. However, occasionally one laboratory may extract about three times more S than another (table 2). Also, researchers need to be careful when reporting test results. Does 9 µg g^{-1} SO_4 (Kelly and Johnson 1982) mean 9 µg g^{-1} of SO_4-S or 3 µg g^{-1} S?

Some managers test soil to determine if they should add S before sowing seedbeds (Figure 1) or if they need to apply AS over the top of 2-0 seedlings. Some set 10 µg g^{-1} S (Mehlich 3) as a satisfactory level for extractable S (Woodwell 1958; South and Davey 1983) while others might use a 20 µg g^{-1} value (Blake et al. 1988). In one test, seedlings growing in soil with 9 µg g^{-1} SO_4-S (AA extract) apparently did not need to be fertilized with S (Kelly and Johnson 1982).

Table 2. Examples of Mehlich 3 test results for soil sulphate. Laboratory A extracted about three times as much sulphate as laboratory B.

	Laboratory	
Sample	A	B
	µg g^{-1}	µg g^{-1}
9	6.5	2
12	7.5	3
16	10	3

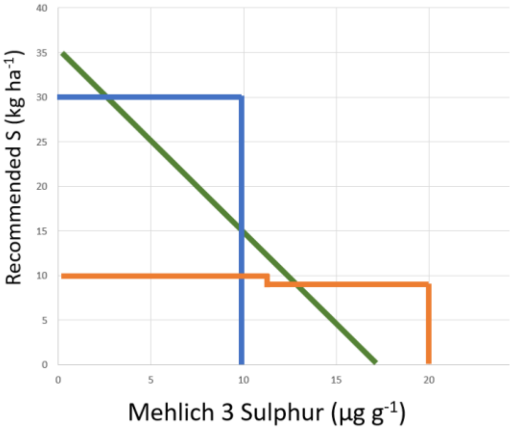

Figure 1. Various opinions exist regarding how much S fertilization to apply to pine seedbeds. When a Mehlich 3 test indicates soil contains 5 µg g^{-1} S, one agronomist (orange line) might recommend 10 kg ha^{-1} of S, another might apply 25 kg ha^{-1} (green line) and a third might suggest applying 30 kg ha^{-1} (blue line).

4 Tissue analysis

There are two types of tissue analyses: total S and SO_4. Total S encompasses both mobile (SO_4) and immobile (organic-S) sources. The mobile portion can range from 0-23% of the total S in leaves. Some researchers report only SO_4 levels in foliage (Table 3) as it might be a superior means of detecting a deficiency (Turner and Lambert 1977; Snowdon and Waring 1985; Schmalz and Coleman 2011). Confusion results when authors refer to foliar SO_4-S concentrations as S concentrations. For example, a 160 µg g^{-1} value for SO_4-S in pine needles might be mistakenly entered into a spreadsheet as 160 µg g^{-1} S. For this reason, total S values below 400 µg g^{-1} in foliage of *Pinus radiata, Pinus sylvestris* or *Pinus taeda* are suspect (Table 3). In bareroot *Pinus radiata* nurseries, SO_4-S in needles ranged from 143 to 570 µg g^{-1} (Flinn 1980).

In nursery environments, it is not known what level of foliar SO_4-S represents a S-deficient *Pinus taeda* seedling. In a greenhouse trial, *Pinus taeda* seedlings (foliage at 60 µg g^{-1} SO_4-S) did not respond to S fertilization (Kelly and Johnson 1982). In that trial, container-grown seedlings with the greatest shoot growth had about 30 µg g^{-1} SO_4-S in shoots nine months after fertilization with S and N. Low SO_4 levels in foliage might be an indicator of rapid shoot growth.

There are two contrasting schools of thought regarding S analysis of foliage. The “no S test” school believes foliar S tests are expensive and are not a worthwhile investment (Radwan and Brix 1986). They typically analyze foliage for all macronutrients except S (Madgwick 1964; McKee 1978; Mitchell et al. 1980; Donald and Young 1982; Weetman and Wells 1990; Ericsson 1994; Hans 2013; Potvin et al. 2014; Hachani et al. 2020). Since foliar values corresponding to a S-deficiency in non-fertilized forests likely did not exist (Ingestad 1962), some saw no need to analyze foliage for S. Often S fertilization was assumed to not affect growth and nutrient uptake of seedlings (McKee 1978). When S fertilization increased growth of bareroot seedlings by 60%, those from this school just assumed the positive response was due to soil acidification.

In contrast, members of the "test foliar S" school argued that valuable information could be gained by analyzing total S (Stefan et al. 1997; Talkner et al. 2019) or SO_4-S concentrations (Turner et al. 1977; Villarrubia 1980; Sanborn et al. 2005). Most members of this school analyze pine needles for total S while a few determine SO_4-S levels (Table 3).

Foliar concentrations of total S in the top 10 cm of seedlings vary depending on month, year, nursery location and fertilizer regime. For *Pinus taeda,* the median value for total S in bareroot seedlings was 25% greater in 2010 than three decades earlier (Figure 2). The shift in distribution is likely due to an increase in use of soil tests that include S (South and Davey 1983). Knowing soil is low in S promotes the applications of fertilizers that contain S.

A S-deficiency may be overlooked when levels in foliage are unknown. Due to the precautionary principle, some nursery managers sample needles in August to monitor the status of N, K, S and other nutrients. When N is below a target value, additional nitrogen can be applied (Sung et al. 1997) and when K levels are above target levels, extra K fertilization can be avoided (Rowan 1987; South 2019). Total S in *Pinus taeda* foliage in managed bareroot nurseries rarely drops below 1,000 µg g^{-1} in August (Figure 3).

Table 3. A list of references for foliar sulphur concentration in pines Values represent the lowest concentration mentioned in the reference.

Species	Location	Total sulphur µg g^{-1}	SO$_4$ sulphur µg g^{-1}	Reference
Pinus sylvestris	Russia	160	--	Stefan et al. 1997
Pinus nigra	Plantation	290	--	Cenni et al. 1998
Pinus ponderosa	Field	300	--	Shaw and Moore 1994
Pinus ponderosa	Plantation	340	--	Gleason 1989
Pinus taeda	Plantation	400	--	Sypert 2006
Pinus radiata	Plantation	412	--	Snowdon and Waring. 1985
Pinus pinaster	Plantation	500	--	Boardman et al. 1997
Pinus taeda	Nursery	500	--	Boyer and South 1985
Pinus radiata	Plantation	500	--	Lee et al. 1991
Pinus contorta	Field	500	--	Shaw and Moore 1994
Pinus ponderosa	Plantation	500	--	Will and Youngberg 1978
Pinus taeda	Outdoor pots	580	--	Tjoelker and Luxmoore 1991
Pinus ponderosa	Plantation	600	--	Baer 1984
Pinus contorta	Field	660	--	Sanborn et al. 2005
Pinus taeda	Plantation	690	--	Albaugh et al. 2010
Pinus taeda	Greenhouse	700	--	Walker and McLaughlin 1997
Pinus taeda	Nursery	700	--	Starkey and Enebak 2012
Pinus contorta	Field	740	59	Brockley 2004
Pinus elliottii	Plantation	776	--	Hooker 2019
Pinus contorta	Plantation	780	53	Brockley 2000
Pinus palustris	Plantation	781	--	Hooker 2019
Pinus strobus	Field	790	--	Roberts 1976
Pinus resinosa	Plantation	800	--	Bockheim 1989
Pinus palustris	Nursery	800	--	Starkey and Enebak 2012
Pinus contorta	Field	810	21	Brockley and Sheran 1994
Pinus taeda	Plantation	860	--	Carlson et al. 2013
Pinus contorta	Field	879	198	Legge et al. 1988
Pinus taeda	Plantation	889	--	Hooker 2019
Pinus contorta	Field	900	--	Beaton et al. 1965
Pinus elliottii	Plantation	900	--	Bengtson 1976
Pinus taeda	Nursery	900	--	South et al. 1988
Pinus taeda	Outdoor pots	957	--	Bays 2022
Pinus taeda	Nursery	970	--	South et al. 2018
Pinus elliottii	Sand	1,000	--	Malavolta et al. 1970
Pinus radiata	Nursery pots	1,000	--	Nakos 1979
Pinus echinata	Plantation	1,017	--	Hooker 2019
Pinus radiata	Plantation	1,030	130	Kelly and Lambert 1972
Pinus taeda	Greenhouse	1,065	30	Kelly and Johnson 1982
Pinus radiata	Plantation	1,194	--	Romanyá and Vallejo 1996
Pinus jefferri	Plantation	1,200	--	Walker 2002
Pinus caribaea	Plantation	1,700	--	Chaves et al. 2005
Pinus contorta	Nursery pots	2,500	--	Majid 1984
Pinus radiata	Plantation	--	0	Lambert 1986
Pinus radiata	Plantation	--	15	Green et al. 2023
Pinus radiata	Nursery	--	140	Flinn et al 1980
Pinus ponderosa	Nursery	--	197	Landis 1976
Pinus contorta	Nursery	--	518	Landis 1976

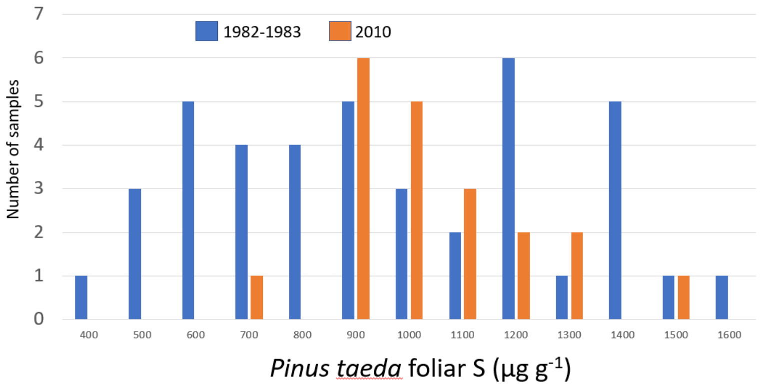

Figure 2. collected from nursery-grown *Pinus taeda* seedlings in December may range from 400 to 1,600 µg g^{-1} S. The median values for blue and orange bars are 800 and 1,000 µg g^{-1} S, respectively (Boyer and South 1985; Starkey and Enebak 2012). Foliage sampled from a silt-loam nursery at Natchez, Mississippi contained 400 µg g^{-1} S.

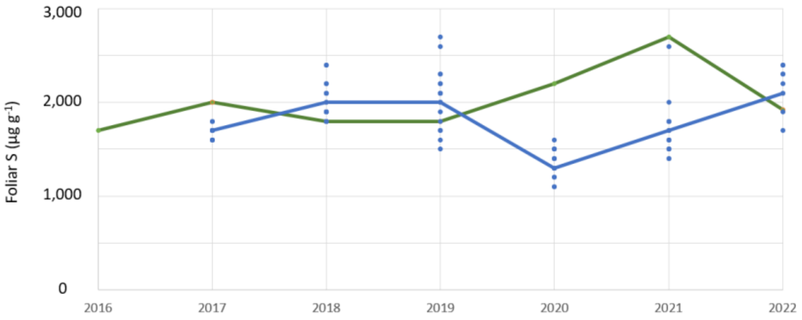

Figure 3. In August, managers check on the nutrient status of bareroot *Pinus taeda* seedlings growing in sandy nursery soils. Blue dots represent individual *Pinus taeda* samples from one nursery while the green line represents the mean trend for a second nursery. The least significant difference (α =0.05) for blue means is 176 µg g^{-1}. Unfortunately, the August total S concentration required to trigger a 10% growth reduction in bareroot *Pinus taeda* nurseries remains unknown. For *Pinus taeda,* the median value for total S in October 2009 was 1,300 µg g^{-1} (Starkey and Enebak 2012).

4.1 Deficiency symptoms

Several handbooks provide images of S-deficient row-crops (Bryson and Mills 2014; Grant and Hawkesford 2015) but photographs of S-deficient pine plantations are not available from Ireland, United Kingdom, Europe, New Zealand and the United States (Baule and Fricker 1970; van Goor 1970; Binns et al. 1980; Will 1985; Landis et al. 1989; Davis et al. 2015). This indicates rain typically contains sufficient S for adequate growth of most pine species. Even so, S-deficiencies have occurred in conifers in Canada (Sanborn et al. 2005), Australia (Lambert 1986), and the Pacific Northwest (Cochran 1978; Blake et al. 1990). It is possible a brief deficiency occurred on sand dunes in the United Kingdom (Binns and Keay 1963).

Photos of S-deficient seedlings in greenhouses have been published (Goslin 1959; Murison 1960; Hacskaylo et al. 1969; Erdmann 1979; Whittier 2018) but they have not been published when grown outside in bareroot nurseries (Benzian 1965a; Bengtson 1968; Truman 1972; Baer 1984; Will 1985). This is likely due to use of sulphate fertilizers plus irrigation water containing S plus atmospheric deposition. Although S-deficiencies on pine seedlings occurred at nurseries in Alabama, Oklahoma (Lyle and Pearce 1968; Morris 1979) and perhaps at Wisconsin (Tanaka et al. 1967), photographs were not archived. Applying S before sowing increased height growth of bareroot seedlings in nurseries in New York and North Dakota (Table 4). Fortunately, photographs comparing treated and untreated seedlings of *Pinus ponderosa* were published (Stoeckeler and Arneman 1960) but the growth increase was likely due to reducing soil pH.

Table 4. Effects of elemental sulphur (S) on heights of bareroot seedlings in nurseries. pH = before application. # = pH from $CaCl_2$ while others from H_2O. * = height significantly different from no sulphur treatment (α=0.05).

Species	Loc	pH	S Rate	+ S	No S	Difference	Reference
			Kg ha^{-1}	cm	cm	%	
Picea sitchensis	UK	3.2#	190	7*	9.2	-24	Bolton and Benzian 1970
Pinus ponderosa	MT	6.4	56	6.7	7	-4	Wahlenberg 1930
Pinus taeda	TX	5.0	813	30	30	0	South et al. 2017
Picea sitchensis	UK	?	753	2.2?	2.2?	0	Holmes and Faulkner 1953
Pinus resinosa	ON	7.4	840	24.6	24.4	+1	Mullin 1964
Liquidambar styraciflua	MS	5.9	672	73	69	+5	South and Cross 2020
Platanus occidentalis	MS	5.4	672	108	100	+8	South and Cross 2020
Pinus sylvestris- 1946	UK	4.8	2,750	3.2*	2.6	+21	Benzian 1965b
Pinus ponderosa	ND	7.9	1,525	6.5*	4	+61	Stoeckeler and Arneman 1960
Picea abies	NY	6.5	997	13.3*	8	+66	Bickelhaulpt 1987

Purnell (1958) published images of greenhouse-grown seedlings lacking N, P, K, Ca, or Mg, but photographs of S-deficient seedlings were not included since pines growing in low S water appeared normal. In order to produce a S-deficiency in a greenhouse, it is best to apply water that does not contain S and to protect the study from rainfall and S deposition. Because deficiency symptoms in pines are unspecific for S, diagnosis by visual symptoms is unlikely in bareroot nurseries. Without a visual symptom, one way to prove a S-deficiency in outside environments is to measure growth after fertilizing with sodium sulphate (Lyle and Pearce 1968; Kelly and Johnson 1982). A second way involves applying sulphate micronutrients that have a low chance of producing a growth response from adding micronutrients. For example, at the Boscobel Nursery in Wisconsin, applying Zn-sulphate over 2-0 *Pinus strobus* seedlings increased height growth slightly, but, unfortunately, foliage was not tested for S and Zn (Tanaka et al. 1967). Seedlings were likely S-deficient since (1) they did not exhibit typical Zn deficiency symptoms and (2) foliage from seedlings grown at this nursery can contain over 100 µg g^{-1} of Zn (Iyer et al. 2002).

In greenhouse trials, hardwood seedlings become stunted when S is absent the fertilizer solution (Table 5). In contrast, S-deficient hardwoods are rarely reported in bareroot nurseries (Leaf 1968; Stone 1980; Knight 1981; Aldhous and Mason 1994; Davey and McNabb 2019) likely because of frequent irrigation with water containing sulphur. At nurseries with no S in irrigation water, a lack of detection might be due to: (1) no obvious color symptoms in operational seedbeds; (2) operational use of fertilizers that contain S; (3) sufficient atmospheric deposition; and (4) assuming no growth response due to low statistical power (e.g. Table 4). For example, variability among plots is so high that a 25-percent increase in seedling height may not be declared statistically significant.

4.2 Color change

When grown in hydroponics, S-deficient *Pinus palustris* needles were thin and spindly and had a dark green color (Pessin 1937). In greenhouses, S-deficient *Pinus taeda* seedlings (Figure 4) and seedlings of *Pinus sylvestris* and *Liquidambar styraciflura* (Figure 5) were smaller than those grown in a complete nutrient solution.

Figure 4. *Pinus taeda* seedlings grown in water culture in a greenhouse (Lyle 1969). The smaller S-deficient seedlings on the left had needles with a color of 2.5 GY 6/6, 5/6 that started with the terminal needles.

S-deficient *Zea mays* plants typically display a light green-yellow appearance. However, their leaves darken to a deeper shade of green after being fertilized with AS at a rate of 12 kg ha^{-1} of S (Franzen et al. 2016). Some managers report seeing an improvement in color of pines when applying AS instead of AN and some report an increase in height growth (Lyle and Pearce 1968).

In hydroponic systems, S-deficient *Pinus taeda* seedlings exhibit stunted growth and their needles appear lighter green (Figure 4). Similarly, primary needles of *Pinus sylvestris* turn from blue-green to pale yellowish green when S is lacking in nutrient solutions (Figure 5). In a bareroot nursery in the UK, soil treated with 190 kg ha^{-1} of S grew seedlings with 1,960 µg g^{-1} S in foliage with green needles. Other seedlings grown without S had a lighter color with 820 to 920 µg g^{-1} S in foliage (Bolton and Benzian 1970). Fertilization with S also improved the color of *Pinus nigra* when growing on sand dunes (Binns and Keay 1963). At a nursery with soil pH 7.9, sulphur lowered soil pH and improved needle color of *Pinus ponderosa* seedlings (Stoeckeler and Arneman 1960). For these examples, the deficiencies were not “hidden”.

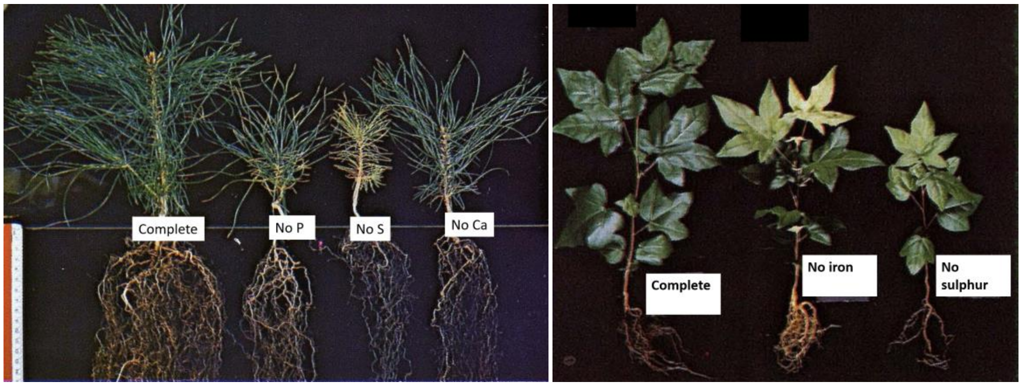

Figure 5. Seedlings of Pinus sylvestris and Liquidambar styraciflua were grown in HCl-washed silica quartz in a greenhouse using deionized water (Hacskaylo et al. 1969). Photo permission by The Ohio State University Extension Publishing.

Table 5. Effect of missing sulphur from nutrient solutions when growing seedlings in greenhouses. Mass represent seedling dry mass except for leaf mass in bold. Seedlings grown in sand, Perlite, HCl washed quartz or water. NL = needle length.

Species	Trial	Treatment	Height	Mass	Sulphur in leaves	Reference
			cm	g	μg g^{-1}	
Acer saccharum	Sand	Complete	27	4.32	1,900	Erdmann et al. 1979
--	Sand	No S	9	2.26	700	--
Acer rubrum	Sand	Complete	154	5.83	2,100	Erdmann et al. 1979
--	Sand	No S	79	3.02	600	--
Betula alnoides	HCl	Complete	49	4.90	3,090	Chen et al. 2010
--	HCL	No S	41	4.05	1,545	--
Betula papyrifera	HCl	Complete	179	4.59	2,200	Erdmann et al. 1979
--	HCl	No S	128	2.88	500	--
Fraxinus americana	HCl	Complete	62	3.51	1,500	Erdmann et al. 1979
--	HCl	No S	83	2.62	600	--
Juglans nigra	HCl	Complete	--	--	2,000	Hacskaylo, Finn and
--	HCl	No S	--	--	1,400	Vimmersted 1969
Pinus palustris	Water	Complete	27 NL	2.0	--	Pessin 1937
	Water	No S	21 NL	1.1	--	--
Pinus radiata	Perlite	Complete	8	0.55	2,500	Morrison 1962
--	Perlite	Low S	7	0.32	700	--
Populus deltoides	HCl	Complete	125	--	3,780	Hacskaylo and
--	HCl	No S	31	--	1,280	Vimmersted 1967
Robinia	HCl	Complete	--	--	1,600	Hacskaylo, Finn and
pseudoacacia	HCl	No S	--	--	1,200	Vimmersted 1969
Tectona grandis	Sand	Complete	53	25.66	580	Gopikumar and
--	Sand	No S	38	17.18	200	Varghesen 2004
Tectona grandis	Sand	Complete	21	4.77	2,300	Whittier 2018
--	Sand	No S	8	2.24	1,000	--

Since irrigation and rain at bareroot nurseries provide some S, the extent of color change is less severe than seen on foliage in hydroponics. Pine needles with low S have a light-green appearance and the color may return to normal when cool weather returns after the fall equinox. At the Stauffer Nursey in Alabama, chlorotic *Pinus taeda* seedlings developed in multiple areas during the summer of 1960. In areas with supposedly N-deficient seedlings, the only fertilizers effective in changing color back to a normal shade of green were AS and sodium sulphate (Lyle and Pearce 1968). Likewise, newly developed, S-deficient leaves on container-grown hardwoods often exhibit lighter green color than older, lower leaves (Hacskaylo et al. 1969; Erdmann et al. 1979).

Bareroot pine seedlings fertilized with only urea may have light-green needles when irrigation water contains less than 1 µg g^{-1} of S. If this occurs, managers might treat three beds with urea (21 kg ha^{-1} of N), three beds with urea plus $MgSO_4$ (17 kg ha^{-1} of S) and three beds with AS (24 kg ha^{-1} of S). If seedlings treated with S turn darker green, then seedlings treated only with urea would be S-deficient. In a greenhouse, height growth was equal or better when seedlings were treated with AS instead of AN (Figure 6). At a sandy nursery in Arkansas, darker green seedlings resulted when seedlings were fertilized with AS instead of urea (personal communication Chase Weatherly). Many nursery managers now apply liquid N fertilizers with 4% or 5% S.

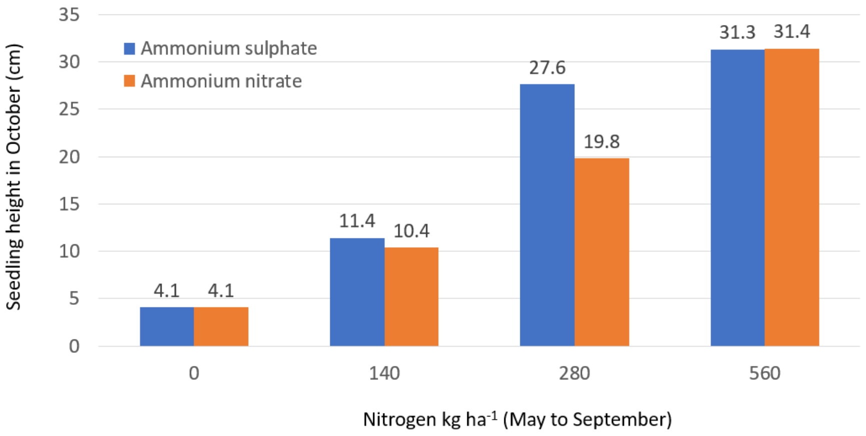

Figure 6. The effect of nitrogen (N) and nitrogen plus sulphur (S) on height growth of container-grown *Liquidambar styraciflua* seedlings (Brown et al. 1981). When fertilized with 280 kg ha^{-1} of N and 313 kg ha^{-1} of S (eight applications at 35 kg ha^{-1} of N and eight applications at 39 kg ha^{-1} of S), seedlings were 39% taller than seedlings treated with only 280 kg ha^{-1} of N ($\alpha = 0.05$). In this trial, if seedlings were only 25% taller (24.7 cm), the increase would not be declared significant ($LSD_{05} = 5.2$).

4.3 Critical level in foliage

A “critical level” for a nutrient is defined as the foliar concentration that occurs at 90% of maximum yield (Ingestad 1962; Ulrich and Hills 1967; Bates 1971). In Europe, the equivalent term is “threshold” (Stefan et al. 1997). Growth response curves are used to determine the point of 90% yield. Since typical, convex response curves have not been developed in soil, the critical values for S in southern pines are not known (Ingestad 1962; White et al. 1980; NCSFNC 1992; Allen 1987; Weetman and Wells 1990). Although speculative, the response curve in S-free soil might have a single-stairstep shape, with a flat, sudden sufficiency level for S (Browder et al. 2005; Santos 2013).

Data from a hydroponic trial with small *Pinus sylvestris* seedlings (Figure 7) were used to estimate a “moderate deficiency” range of 600 to 2,000 µg g^{-1} S

(Ingestad 1962). Another curve for *Pinus sylvestris* Ingestad (1960) indicates an estimated value of 1,500 µg g^{-1} (at 75 % of maximum growth in water) is "relatively undependable." It is likely that estimates that vary from 800 to 1,500 µg g^{-1} S are also undependable for *Pinus taeda* plantations (Sypert 2006). Critical values developed from seedlings that weigh less than 0.2 g are not useful for evaluating the nutrient needs of either 9-month-old or 9-year-old trees.

Over the past 6 decades, a range of critical values have been proposed without using hydroponic or fertilizer trials. Powers (1975) believed all conifers had a critical value of 1,000 µg g^{-1} S. Brockly (2001) proposed three critical ranges for SO_4-S for *Pinus contorta*; slightly, moderate and severely deficient. Others also believe values vary by species (Talkner et al. 2019) but most predict only a single threshold value for each element. For example, a 500 µg g^{-1} S value was proposed for *Pinus ponderosa* (Moore et al. 2004) and a 950 µg g^{-1} S threshold value was proposed for *Pinus sylvestris* (Göttlein 2015).

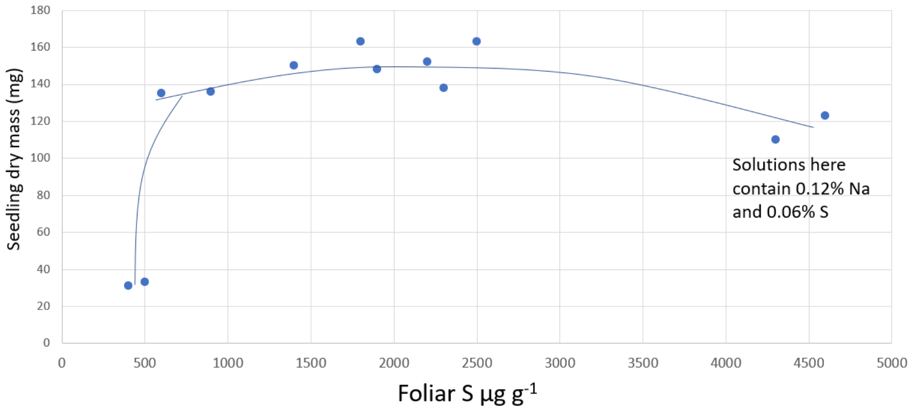

Figure 7. Non-mycorrhizal *Pinus sylvestris* seedlings were grown hydroponically using solutions of sodium sulfate. The small seedlings were grown in beakers for 99 days and were then measured for dry mass and foliar S concentration (Ingelstad 1962). The reduction in growth with a high concentration of Na_2SO_4 was likely due to Na toxicity (Franklin et al. 2002).

In a greenhouse trial with mycorrhizal *Pinus taeda*, adding sodium sulphate increased soil SO_4 but seedling growth did not increase (Kelly and Johnson 1982). Apparently, the untreated soil already contained adequate S. Similar results occurred at a nursery in Texas where soil contained 13 µg g^{-1} S (Mehlich 3). Adding 813 kg ha^{-1} of S had no effect on growth of bareroot *Pinus taeda* (Figure 8). Foliar concentrations were 1,000 and 1,300 µg g^{-1} at pH 5 and pH 3.9, respectively (South et al. 2017).

Without data from a response curve, "critical value" estimates are dubious, especially when one value is used for all conifers. Determining "critical values" by dividing N concentrations by an arbitrary N/S ratio is not valid when determining critical values. An overestimate of 1,100 µg g^{-1} S for *Pinus taeda* may be referred to as "tentative" but it is not a correct critical value (i.e. determined using a growth response curve). In fact, applying gypsum, Epsom salt and AS did not increase fascicle biomass of pine trees with 400 µg g^{-1} S in foliage (Sypert 2006). Pine seedlings are truly S-deficient when S fertilization causes a growth increase (Youngberg and Dyrness

1965; Lyle and Pearce 1968). Data from fertilizer trials do not support a "critical value" of 1,000 µg g^{-1} S for *Pinus taeda* (Sypert 2006; South et al. 2017).

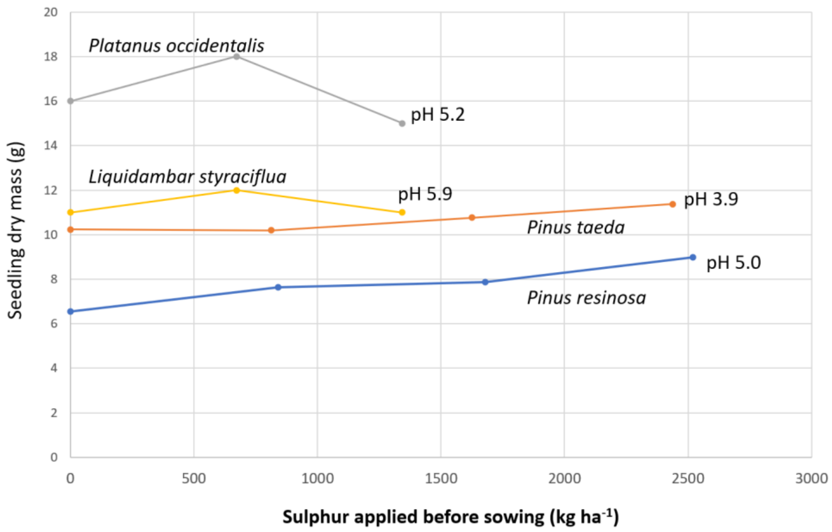

Figure 8. Hardwood seedlings were grown at the International Paper Nursery at Natchez, Mississippi (South and Cross 2022) and mycorrhizal pine seedlings were grown at the Orono Nursery in Canada (Mullin 1964) and at the SuperTree Nursery in Texas (South et al. 2017). Listed pH values are for the highest sulphur rate at the end of each study. The rate of elemental sulphur applied before sowing had no effect on biomass in Texas (P>0.90) or Mississippi (P>0.50) but the 2,520 kg ha^{-1} treatment increased biomass of *Pinus resinosa* seedlings in Canada (P=0.001). However, the 8.89 g mean was likely due to a 26% reduction in stand density (vs the 1,680 kg ha^{-1} S treatment).

There are various reasons why a response curve for S has not been developed for use in bareroot nurseries. First, irrigation plus atmospheric deposition have contributed to producing somewhat flat response curves (Figure 8). Second, the variability in S concentration in foliage is large (van den Driessche and Rieche 1974) which reduces the statistical power of the test. In some trials an increase of 190 µg g^{-1} S in foliage would not be statistically significant ($\alpha = 0.05$).

4.4 Hidden hunger

A hidden hunger occurs when there is no visible color change but seedlings are slightly stunted due to insufficient nutrition. While a hidden hunger for S is unlikely when seedling growth is limited by low N availability, it can occur when N fertilization promotes growth and creates a demand for S which exceeds supply (Figure 6).

5 Soils

Nurseries with more than 75% sand typically have low levels of exchangeable S in the topsoil (0-15 cm). The correlation (r = -0.38) between soil S (Mehlich 1) and sand content is negative (South and Davey 1983). Prior to sowing seed, many bareroot nurseries in the southern United States have soils that contain less than 20 µg g^{-1} of extractable S (Figure 9). In one greenhouse trial, applying AS to soil did not improve growth of *Pseudotsuga* seedlings when untreated soil contained more than 20 µg g^{-1} of of S when using Morgans reagent (Blake et al. 1988).

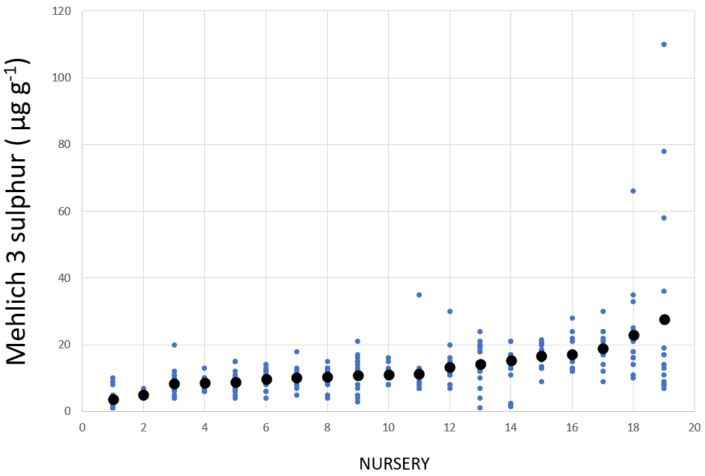

Figure 9. Soil sulphur (Mehlich 3) from 19 nurseries in the southern United States. Fields in nurseries vary from 1 to 110 µg g^{-1} S (blue dots). Each nursery is represented by a mean (black dot) of up to 15 soil samples. Sulphur fertilizer was applied to nursery fields in March if the soil test was <10 µg g^{-1} (Mehlich 3) or was applied with nitrogen over the top of seedlings during the summer.

Total soil S is the sum of organically-bound S and extractable S (Mehlich 3). Most soil laboratories report only the extractable portion (SO_4) and not the organic form of S. A soil with 1% organic matter might contain 25 µg g^{-1} as organic-S and 5 µg g^{-1} as SO_4-S (Kamprath and Jones 1986).

Since SO_4 can leach quickly in sandy topsoil, the top 15 cm of soil may not be the best location to sample. For some crops, the 15 to 30 cm zone is better correlated with total S in the top 30 cm of soil (Kamprath and Jones 1986). If managers sample this zone, they might save money on applying ATS to their crops.

5.1 Soil pH

In *Pinus taeda* plantations, S concentration in pine needles was negatively related to soil pH (r = -0.43; NCSFNC 1992). This might be due to an increase of available S in acid soils or perhaps due to a correlation between organic matter and soil pH (r =-0.50). In nurseries, negative correlations also occur between pH and available soil S. At 45 nurseries, the correlation was r = -0.23 (South and Davey 1983) and at one nursery the correlation was r = -0.76 (Figure 10). The correlations in nursery soils are likely due to applying elemental S to increase soil acidity (Mullin 1964). At some locations, liming might increase leaching of SO_4 (Scherer 2009; South et al. 2017).

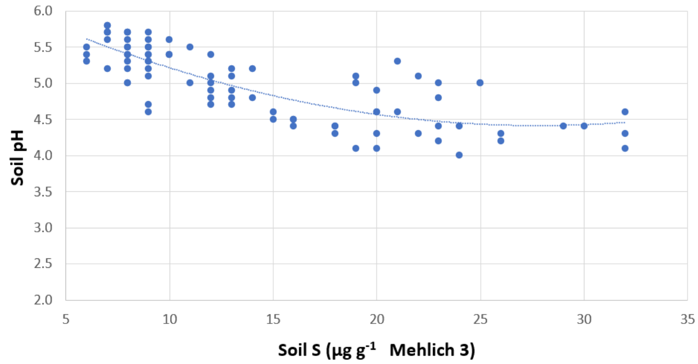

Figure 10. Soil sulphur (Mehlich 3) from 19 nurseries in the southern United States. Fields in nurseries vary from 1 to 110 µg g^{-1} S (blue dots). Each nursery is represented by a mean (black dot) of up to 15 soil samples. Sulphur fertilizer was applied to nursery fields in March if the soil test was <10 µg g^{-1} (Mehlich 3) or was applied with nitrogen over the top of seedlings during the summer.

Although AS lowers soil pH (Figure 11), only a few sulphate fertilizers increase soil acidity. For example, gypsum, Epsom salts, and KS do not strongly affect soil pH. When a lowering of pH is desired, elemental S can be incorporated prior to sowing a cover crop or several months before sowing a seedling crop. The rate of N applied and the form of N determine how rapid soil acidity is increased.

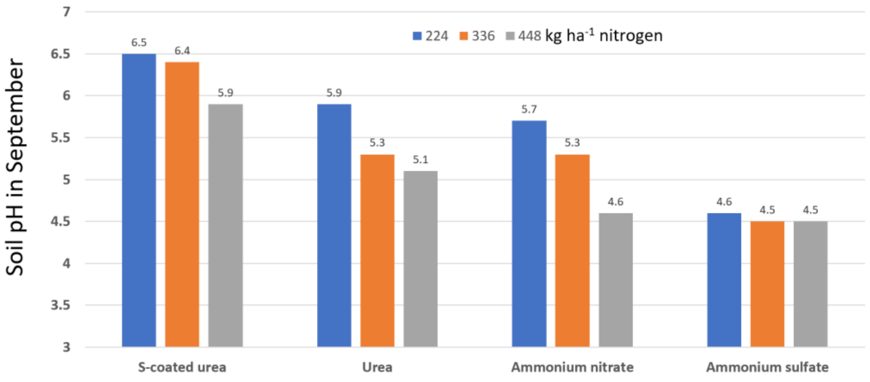

Figure 11. Soil pH in September is affected by both the rate of nitrogen (N) and the form of nitrogen. At a nursery in Virginia, sulphur coated urea releases N slowly and pH was slightly higher in September than three months earlier in June (Villarrubia 1980). When applied at 224 kg ha^{-1}, ammonium sulphate increased acidity more than ammonium nitrate.

5.2 Organic matter

Most soil S is tied up in organic matter. For example, if 100 tonnes of soil contain 1 tonne of organic matter, then about 1 kg of S is present in an organic form. If the same soil contains 0.5 kg of inorganic S (i.e. 5 µg g^{-1} Mehlich 3) then two-thirds of the total S is in organic form. Total soil S is therefore positively correlated with organic matter (Tabatabai and Bremner 1972) but Mehlich 3 S is typically not correlated with organic matter.

5.3 Nitrogen

There is a close relationship between N and S in plants. For example, for *Pinus taeda* foliage, the correlation between N and S is r = 0.88 in bareroot nurseries (Starkey and Enebak 2012) and 0.56 in plantations (NCSFNC 1992). Fast growth will increase the production of proteins and temporarily lower SO_4 concentrations in leaves. As a result, fertilizing with 200 kg ha^{-1} of N increases foliar N concentrations (VanderShaaf and McNabb 2004) while lowering foliar SO_4 (Brockley 2004). A similar relationship occurs in hardwood nurseries (Figure 12). Although bareroot seedlings may be fertilized with 200 kg ha^{-1} of N or more, visual S-deficiency symptoms have not been documented in either hardwoods or pines. However, growth reductions may occur when the application dose of AN or AS is too great (Figure 12).

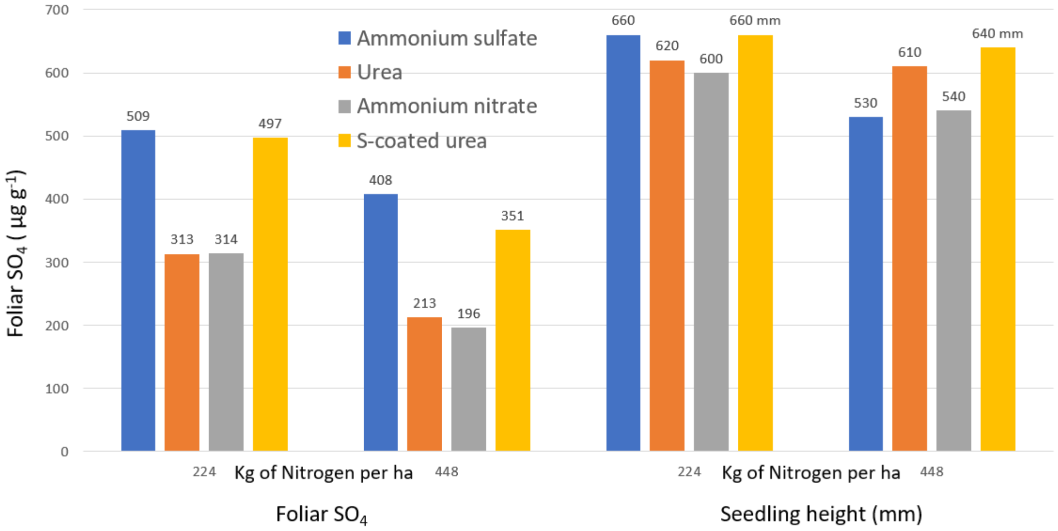

Figure 12. Fertilization of *Liquidambar styraciflua* with N at 448 kg ha^{-1} lowered foliar SO_4 levels by 20% (ammonium sulfate), by 32% (urea), and 29% (sulphur coated urea). Height and diameter growth were not increased by N rates above 224 kg ha^{-1} (Villarrubia 1980). If leaf biomass was increased by extra N, then carbohydrate dilution might explain the lower SO_4 concentrations. Seedlings fertilized with ammonium sulphate (N at 224 ha^{-1}) were taller than those fertilized with urea or ammonium nitrate (LSD_{05} = 32 mm). Treatments supplying S increased foliar SO_4 levels (LSD_{10} = 147).

For bareroot seedlings, a typical N/S ratio is determined by dividing foliar N concentration by the total foliar S concentration (i.e., organic S plus SO_4). Only a few laboratories in the southern United States compare a total N/S ratio for *Pinus taeda* needles with a "sufficient" ratio of 11.1 or 11.6 and the expected ratio is near 12.2 (Albaugh et al. 2010, Starkey and Enebak 2012). Forest stands of *Pinus contorta* with a N/S ratio >13 and a low level of foliar SO_4 will likely not respond to N fertilization (Brockley 2000).

At one nursery, two-week-old pine hypocotyls had a ratio of 14.7 (81,000 µg g^{-1} N and 5,500 µg g^{-1} of total S) and the seedlings were not deficient in S. The N/S ratio has no practical meaning for nursery managers. Managers might lower operational N rates based on fertilizer trials (Stone 1980; Brown et al. 1981; Irwin et al. 1998), but not based on a theoretical "optimum" N/S ratio. Various researchers do not even calculate N/S ratios for conifer seedlings (van den Driessche 1974; Mellert and Göttlein 2012).

Due to carbohydrate dilution, the concentrations of N and S in pine seedlings decline from July to February (Figure 13). Since N levels in bareroot *Pinus taeda* seedlings decline faster than S, the N/S ratio will typically be slightly higher in summer than in winter. In one year, the median N/S ratio for bareroot seedlings declined from 17.5 to 12.2 to 12.1 in July, October, and February, respectively (Starkey and Enebak 2012).

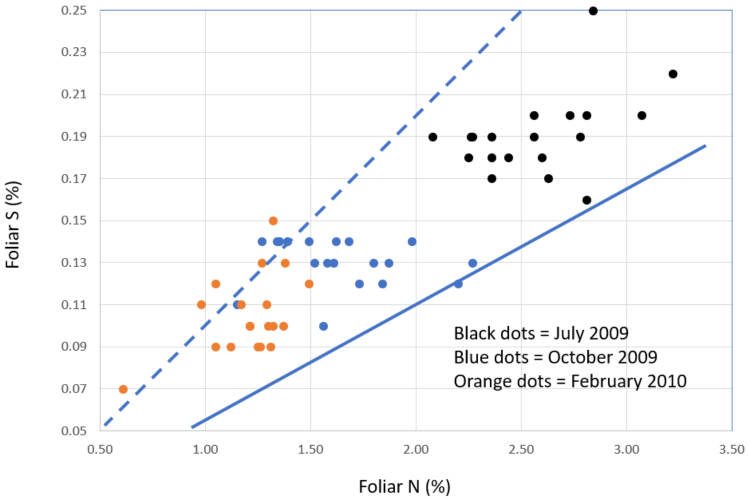

Figure 13. Due to carbohydrate dilution, sampling date affects the concentration of nitrogen (N) and sulphur (S) in bareroot *Pinus taeda* seedlings (Starkey and Enebak 2012). Each color dot represents a foliage sample taken from a different bareroot nursery (n=19). Chlorotic needles may occur when pine needles contain less than 10,000 µg g^{-1} N. The solid and dashed lines represent N/S ratios of 18 and 10, respectively. The Pearson correlation coefficient is 0.88.

6 Irrigation water

At many nurseries, SO_4 in irrigation water is enough to meet the S needs of pine seedlings (Argo et al. 1997; Olson and Rehm 1986; Ramussen and Kresge 1986; Tisdale et al. 1986; Landis et al. 2009). When irrigation water contains 7 mg L^{-1} of S, then 60 cm of irrigation would add approximately 42 kg ha^{-1} (Figure 14). About half of greenhouse water samples average more than 10 mg L^{-1} but some have less than 1 mg L^{-1} S (Argo et al. 1997). The recommended amount for greenhouse production is 20 to 30 mg L^{-1} of S (Bailey et al. 1999). Responses to crops from S fertilization may not occur when irrigation water contains >3 mg L^{-1} sulphate (Ramussen and Kresge 1986) but S fertilization is appropriate at nurseries with <1 mg L^{-1} SO_4-S in water.

Managers with low S in irrigation water can implement a straightforward test to identify a potential S-deficiency. The procedure involves preparing solutions of Zn-sulphate and Cu-sulphate (Lyle 1969). In the late afternoon, any off-color seedlings in a designated plot are treated with Zn-sulfate, while another area is treated with Cu-sulfate. If both the treated areas regain normal coloration within two weeks, it indicates seedlings were likely deficient in S. This approach was used at the Boscobel Nursery in Wisconsin (Tanaka et al. 1967).

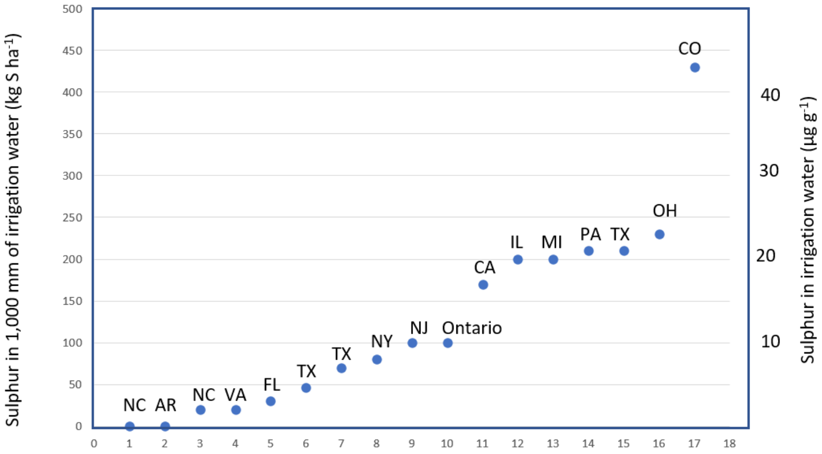

Figure 14. Soil sulphur in irrigation water in the United States and Ontario. Data are from horticultural nurseries (Argo et al. 1997) and from bareroot nurseries.

7 Mycorrhiza

Irrigated pine seedlings without mycorrhiza do not become S-deficient when S in soil or water is adequate (Ingestad 1962; Walker and McLaughlin 1997; Bücking et al. 2002). In a bareroot nursery, non-mycorrhizal *Pinus taeda* seedlings exhibited P deficiency symptoms while needles contained 900 µg g^{-1} S (South et al. 1988). Even so, mycorrhiza can enhance the uptake of S (Rennenberg 1999; Allen and Shachar-Hill 2009). At one nursery lowering soil pH by applying 336 kg ha^{-1} of elemental S enhanced ectomycorrhiza development on pine (Johnson and Zak 1977).

When foliage contains 400 µg g^{-1} S, non-mycorrhizal *Pinus sylvestris* seedlings were obviously S-deficient (Ingestad 1960) but mycorrhizal *Pinus taeda* trees did not exhibit visual deficiency symptoms (Sypert 2006). Deficiency symptoms were produced in a greenhouse with mycorrhizal pines (Figure 5) but, unfortunately, S concentrations in foliage were not measured. Although mycorrhizae are not needed for the uptake of S (Morrison 1962; Smith 2013), it is not known if they affect the critical S value of pine seedlings growing in soil. Several proposed critical values for S were based on non-mycorrhizal seedlings (Ingestad 1960, 1962) and these values appear to be too high for mycorrhizal *Pinus taeda* seedlings.

8 Sulphur removed at harvest

Continuous harvesting of crops without fertilization and irrigation can gradually deplete soil S levels. For *Zea mays* grain, harvesting 11 Mg ha^{-1} removes approximately 10 kg of S (Heckman et al. 2003), which could explain why some agronomists recommend a routine application of approximately 11 kg ha^{-1} of S. The amount of S added to soil by rainfall and dust in the southern United States might exceed 3 kg ha^{-1} each year.

Depending on species, cultural practices, and seedling age, a crop of 1-0 pine seedlings may remove approximately 5 to 10 kg of S (Flinn et al. 1980; Boyer and South 1985; South 2018). Considering four consecutive crops of pine seedlings, it is estimated that around 24 kg ha^{-1} of S could be harvested, resulting in a potential decrease of 12 µg g^{-1} in soil S levels. However, when atmospheric deposition contributes 24 kg ha^{-1} over an 8-year period, this would compensate for the S removal caused by the four pine harvests. Any reduction in soil levels would then be primarily attributed to leaching, which can be intensified by nitrogen fertilization.

At the Westvaco Nursery, there were no reports of a S-deficiency (Figure 15). In 1982, harvested pine seedlings had a dry mass of 3.4 g when grown at a seedbed density of 280 m^{-2} (Rose 1985). Harvesting a pine crop at this density could potentially remove 6.3 kg ha^{-1} of S (South 2018).

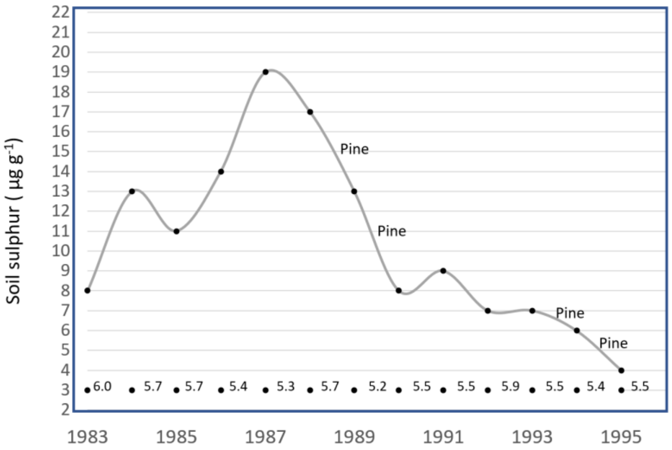

Figure 15. Soil sulphur levels (ammonium acetate extraction) at a bareroot nursery in South Carolina. Field B-1 (86% sand) was managed with cover-crops from 1983 to early 1989. *Pinus taeda* seed were sown in April of 1989, 1990, 1993, 1994. Soil pH values adjacent to dots represent soil acidity in October-November. In some years, sulphur (63 kg ha^{-1}) was applied as sulphate of potash magnesia a month before sowing pine seed.

9 Sulphur concentration after transplanting

Growth of seedlings after outplanting depends, in part, on N applied in the nursery but apparently not on nursery fertilization with S (Rowan 1987; Larsen et al. 1988; Gleason 1989; van den Driessche 1991). On some sites, the foliar S concentration after transplanting in the field can increase (Baer 1984) and in others it might decrease (Figure 16).

There have been only a few attempts to correlate foliar S of seedlings with subsequent growth in the field. For *Pinus taeda*, foliar S in December was not related to early growth after 3 years (Larsen et al. 1988). Likewise, early growth of *Pinus ponderosa* was not related to initial foliar S (Baer 1984). Although there is no doubt that growth of stunted seedlings (Figure 8) would be less than desired, seedlings of this type are not produced at most irrigated *Pinus taeda* nurseries. There is no evidence indicating foliar S levels at time of planting is an important seedling quality attribute. For example, in Virginia (Villarrubia 1980), heights of outplanted *Fraxinus* seedlings (fertilized with AS in the nursery), averaged 5 cm taller than stock fertilized with AN. However, this small difference was not statistically significant (P > F =0.35) and any growth effect might have been due to a larger root mass at planting.

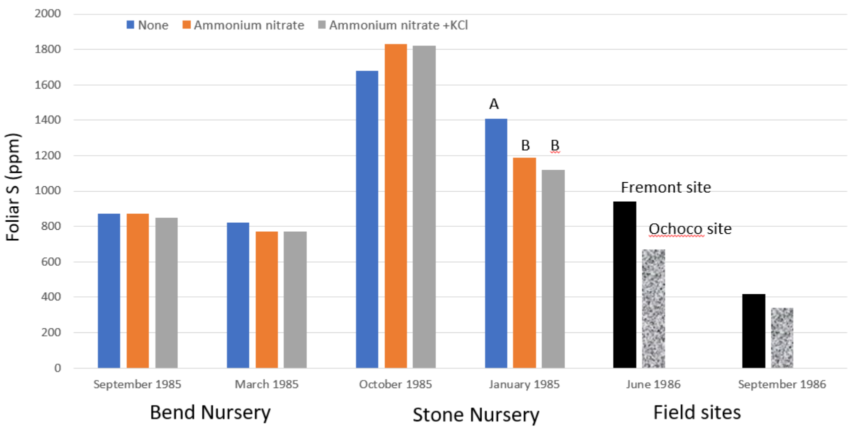

Figure 16. Fall fertilization (September 24, 1985 at Bend Nursery and October 4, 1985 at Stone Nursery; 46 and 37 kg ha^{-1} of N and K, respectively). Ammonium nitrate (AN) alone, and ammonium nitrate plus potassium chloride (KCl) reduced foliar sulphur (S) concentrations at the Stone Nursery in Oregon in January (α =0.05). There was no fertilizer effect on 2-0 *Pinus ponderosa* seedling morphology at either nursery (Gleason 1989). After outplanting at the Fremont site, seedlings treated with AN+KCl were 6 mm taller than non-fertilized controls (α =0.05). In September 1986, needles at the Ochoco site had 340 µg g^{-1} of S and 18,100 µg g^{-1} of N. There was no mention of chlorosis in the field for any treatment.

10 Toxicity

S can be toxic to some fungi and insects (Tweedy 1981; Williams and Cooper 2004), and high levels of SO_2 can injure trees (Kozlowski and Constantinidou 1986). For various reasons, the toxic level of SO_4 within pine needles is not known. Some readers might assume 4,500 µg g^{-1} S in foliage is toxic to pine (Figure 7) but this assumption is flawed since too much Na in solution will inhibit the growth of pine. In fact, two-week-old pine germinants with 5,500 µg g^{-1} S in stems grew normally. For *Acacia* leaves, the concentration of S can exceed 20,000 µg g^{-1} S (Reid et al. 2016).

In some plants, the accumulation of elemental sulphur can be linked to disease resistance (Cooper et al. 1996). In addition, some S-rich proteins may offer resistance against herbivory (Zenda 2021). Lowering soil pH with S can reduce damping-off of pine seedlings in nurseries (South 2017) but applying 336 kg ha^{-1} of S did not reduce the incidence of root-rot at a nursery in Oregon (Johnson and Zak 1977). In some trials, fertilization with gypsum reduced *Phytophthora* infection (Messenger et al. 2000) but it is not known if the effect was due to S or Ca. High rates of S can lower soil pH and improve growth of trees growing in *Phytophthora* infected soil (Cowles 2020).

The following discussion is limited to soil S. Sulphuric acid is formed after the application of S through microbial activity but production of acid is slowed in dry soil when microbial activity is low. The amount of injury to month-old seedlings depends on when sulphuric acid is formed, how much is formed and how much rain occurs after treatment (Hartley 1915). In the past, diluted sulphuric acid was applied to seedbeds before sowing to reduce damping-off. Sometimes adding sulphuric acid and nitric acid to irrigation water will increase growth of young *Pinus strobus* seedlings (Wood and Bormann 1977).

Armson and Sadreika (1979) suggest sowing seed at least 2 months after soil incorporation of S and van den Driessche (1969) said the interval should be as long as possible. This allows time for rainfall to activate the S and to dilute the toxicity. When rainfall is limited, however, applying S a few months prior to sowing can result in gypsum crystals forming on roots. Although chlorosis and stunted growth were observed after S application at two nurseries (Carey et al. 2002), stunting is attributed to the formation of sulphuric acid followed by gypsum formation on roots.

In years with sufficient rainfall, no stunting has been noted after applying S at 800 kg ha^{-1} prior to sowing seed in sandy soil. In a dry year, however, 900 kg/ha of S might cause problems (Carey et al. 2002; Bueno et al. 2012). When S increases soil acidity to below pH 5, growth of fertilized pine seedlings might be increased (South 2007). However, at one nursery, stand density decreased by 26% when 2,520 kg ha^{-1} of S was applied one month before sowing (Mullin 1964). This likely was due to remaining S converting to sulphuric acid soon after sowing and irrigation. In outplanting studies, 3,000 to 3,900 kg ha^{-1} of S lowered soil pH and increased growth of *Quercus rubra* (Hebberger 2000) and *Abies balsamea* (Cowles 2020).

11 Fertilizers

During the 20th century, bareroot nurseries were treated with granular fertilizers that often-contained S. Common fertilizers included calcium superphosphate and AS. Others occasionally applied were K-sulfate, Mg-sulphate and Fe-sulphate (Table 6).

Table 6. A partial list of sulphur fertilizers.

Name	Code (N-P_20_5-K_2O)	% Sulphur	Form
Elemental sulphur	0-0-0	90	Powder
Elemental sulphur	0-0-0	52	Liquid
Ammonium thiosulphate	12-0-0	26	Liquid
Ammonium sulphate	21-0-0	24	Granule
Sulphur coated urea	32-0-0	22	Granule
Gypsum – calcium sulphate	0-0-0	18	Granule
Potassium sulphate	0-0-50	17	Granule
Potassium thiosulphate	0-0-25	17	Liquid
Zinc sulphate	0-0-0	17	Powder
Manganese sulphate	0-0-0	17	Granule
Aluminum sulphate	0-0-0	16	Granule
Magnesium sulphate	0-0-0	12.8	Granule
Copper sulphate	0-0-0	12.5	Granule
Calcium superphosphate	0-20-0	11	Granule
Iron sulphate	0-0-0	11	Granule
Potassium magnesium sulphate	0-0-22	11	Granule
Ammonium sulphate	8-0-0	9	Liquid
N-P-K-S	15-15-15	5	Granule
Urea ammonium nitrate	25-0-0	2.6	Liquid
N-P-K+ micronutrients	20-20-20	0.06	Granule
Triple superphosphate	0-45-0	0	Granule

11.1 Elemental sulphur

Elemental sulphur can be applied either in powder form (Figure 17) or pelletized. When the primary goal it to lower soil pH, powders will lower pH quicker than pelletized forms. Bacteria is required to turn elemental sulphur to SO_4 and the biological conversion is slower when S particles are larger. Pellets are a slow-release form and may take months to completely convert to S that can be taken up by plants. As a result, the slower formation of sulphuric acid may reduce the risk of root injury to germinating seedlings. Typically, elemental sulphur is applied several months before sowing seed. At some locations, applying S will increase growth either by soil acidification or elimination of a S deficiency (Bickelhaulpt 1987).

Figure 17. Sulphur can be supplied by various types of fertilizers. Langbeinite is also known as potassium magnesium sulphate and kieserite is magnesium sulphate. Photo by Rob Mikkelsen.

11.2 Gypsum

At one nursery (Table 1), gypsum (336 kg ha^{-1}) was applied before sowing since it supplies Ca without increasing soil pH. In contrast, gypsum in some circles is known as a S-fertilizer because it contains about 18% S (Lambert 1986). Incorporating gypsum before sowing reduces the risk of S and Ca deficiencies. Although researchers have tested gypsum at rates >1,500 kg ha^{-1} (Maki and Henry 1951; Deines 1973; Flinn and Waugh 1983; Marx 1990), such high rates are not used by nursery managers. Too much gypsum can lower soil Mg (Figure 18) and can induce a Mg deficiency (South 2022). Some managers at sandy nurseries apply less than 850 kg ha^{-1} of gypsum. At two hardwood nurseries in North Carolina, there was no advantage of applying more than 965 kg ha^{-1} of gypsum (Table 5).

A 965 kg ha^{-1} of gypsum applied before sowing had no effect on growth of *Platanus occidentalis* but increased growth of *Liquidambar styraciflua* and *Fraxinus pennsylvanica* seedlings (Table 7). Deficiencies in S and/or Ca in might explain the increase in growth.

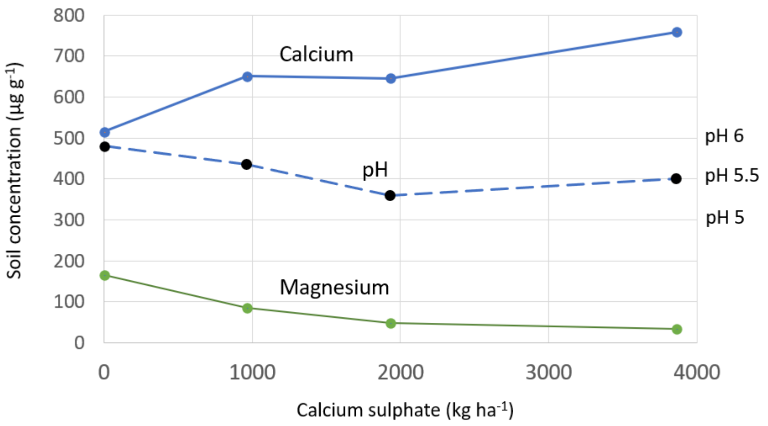

Figure 18. Fertilization with calcium sulphate (May 18) increased soil calcium (December) at the Morganton Nursery while increasing leaching of magnesium (Deines 1973).

Leaching of Mg due to higher soil Ca levels (Figure 18) might explain the reduction in growth of *Platanus* after fertilizing with 3,862 kg ha^{-1} of gypsum. In one sand-hydroponic study, *Fraxinus americana* seedlings were Mg-deficient when leaves contained 400 µg g^{-1} (Erdmann et al. 1979). All *Fraxinus pennsylvanica* seedlings at Murfreesboro were below this concentration.

Table 7. The effect of gypsum fertilization on foliar calcium (F-Ca), foliar magnesium (F-Mg) and seedling mass (Mass) of three hardwood species in North Carolina (Deines 1973). Foliage from *Liquidambar styraciflua* and *Platanus occidentalis* were sampled on October 13, 1972 while *Fraxinus pennsylvanica* was sampled on October 24, 1972. For seedling mass, LSD$_{10}$ values are 0.31 g, 1.23 g and 2.30 g for *Liquidambar, Platanus and Fraxinus*, respectively. * = mass significantly different from no gypsum treatment (α = 0.05). Fertilization with calcium sulphate (May 18) can increase soil calcium (December) while increasing leaching of magnesium (Deines 1973).

Location	Genus	Gypsum	Sulphur	F-Ca	F-Mg	Change	Mass	Change
		kg ha^{-1}	kg ha^{-1}	µg g^{-1}	µg g^{-1}		-g-	
Morganton	*Liquidambar*	0	0	545	364	--	2.7	--
Morganton	--	965	222	571	286	-26%	3.4*	+37%
Morganton	--	1,931	444	636	273	-29%	2.8	+9%
Morganton	--	3,862	888	700	300	-22%	2.6	-4%
Morganton	*Platanus*	0	0	1,344	448	--	10.1	--
Morganton	--	965	222	1,185	370	-17%	9.8	-3%
Morganton	--	1,931	444	1,400	320	-29%	9.1	-10%
Morganton	--	3,862	888	1,321	321	-28%	8.7*	-14%
Murfreesboro	*Fraxinus*	0	0	800	300	--	4.7	--
Murfreesboro	--	965	222	737	210	-30%	7.8*	+66%
Murfreesboro	--	1,931	444	800	266	-11%	6.4	+36%
Murfreesboro	--	3,862	888	750	250	-17%	5.4	+15%

11.3 Phosphorus

Single superphosphate (Figure 17) contained 11.9% S due to the presence of gypsum. However, when managers switched to applying triple-superphosphate, seedlings at some nurseries had reduced height and a light-green color. This effect was due to a deficiency in S at nurseries with low S in irrigation water.

Nursery managers should not worry about inducing a S-deficiency by applying P fertilizers. In a greenhouse in Texas, foliar S levels were not affected by fertilizing *Pinus taeda* seedlings with triple-superphosphate (Bays 2022). In a pine plantation in Australia, 2,000 kg ha^{-1} of dicalcium phosphate increased growth of *Pinus radiata* but the extra growth did not reduce S concentration in foliage (Snowdon and Waring 1985).

11.4 Potassium

Since uniformity of application is important, some managers spray potassium thiosulfate (Figure 17) over seedlings during summer. When using granular products, contractors may be hired to spread the material before sowing. Typically, granular K_2SO_4 does not acidify the soil, although pH may decline slightly for a short period (Martikainen 1985; von Wilpert and Luks 2003). At one nursery, an application of K_2SO_4 (224 kg ha^{-1} of K) lowered soil pH (α =0.10) by 0.5 unit (Deines 1973). The pH effect depends on application rate (Martikainen 1985; Wallace 1994) and soil texture. At a bareroot nursery in North Carolina, soil S was not limiting since fertilizing hardwood seedlings with K_2SO_4 did not improve height growth of hardwood seedlings (Figure 19).

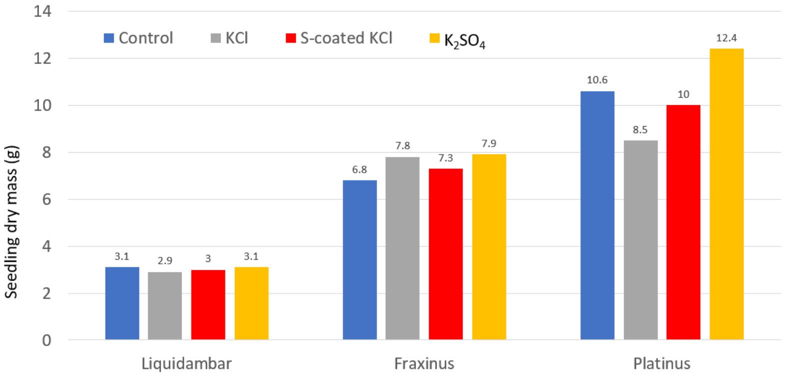

Figure 19. Fertilization with three forms of potassium (224 kg ha^{-1} of K) at two nurseries in North Carolina (Deines 1973). The yellow (99 kg ha^{-1} of S) and gray treatments were applied on May 18, July 10, and August 22, 1972. The red treatment (175 kg ha^{-1} of S) was soil-incorporated on May 18 with no subsequent applications. When compared to the blue bar, the sulphur treatments did not increase seedling dry mass. Based on standard errors, the LSD_{10} values are 0.46 g, 1.23 g and 2.30 g for *Liquidambar styraciflua, Platanus occidentalis and Fraxinus pennsylvanica*, respectively.

11.5 Ammonium thiosulfate

The use of liquid fertilizers has increased to the point where some nurseries no longer have equipment to apply granular products. After germination, a 9-bed sprayer is typically used to apply UAN solutions containing ATS. At nurseries that apply 200 kg ha^{-1} of N (with 25-0-0-2.6S), the amount of S applied is 20.8 kg ha^{-1}. Currently, ATS is the most used source of sulphur in fluid fertilizers.

12 Costs

Fertilizer costs vary by region, shipping distance, year, and distributor. Cost comparisons are time sensitive and vary by region. In the 19th century, the relative values of N, P, K, and S were \$0.44, \$0.187, \$0.121, and \$0.154 kg^{-1}, respectively (Scovell 1890). By 1950, values were \$0.203, \$0.183, \$0.176, and \$0.0 kg^{-1}, respectively (assuming gypsum in superphosphate was included at no additional cost; Maki and Henry 1951). At some nurseries in 2023, values were \$1.89, \$1.92, \$1.53, and \$0.22 kg^{-1}, respectively.

To keep fertilizer costs low, some managers applied KCl instead of K_2SO_4 (Figure 19). For these two products, the cost of K might be \$1.28 kg^{-1} more expensive when purchasing K_2SO_4 (South 2019). In addition, elemental S might cost \$0.20 kg^{-1} while ATS can cost \$0.70 kg^{-1} of S (South and Cross 2020). At nurseries that sell pine seedlings for 7 cents each, managers often purchase liquid sources of N, K and S due to convenience and uniformity of application.

13 Conclusions

(1) Due to less atmospheric deposition, S-deficiencies in row-crops in the Northern Hemisphere are more common now than during the middle of the 20th century.

(2) While various tests estimate soil SO_4 levels, a topsoil result of 4 $\mu g\ g^{-1}$ SO_4-S has little practical value in predicting a S-deficiency in sandy nurseries. When sampled near the fall equinox, foliar SO_4-S concentration has been proposed as a more effective prediction tool.

(3) Sulphur deficiencies in unfertilized pine forests are rare in North America, but they have occurred in Australia, Canada, and Oregon.

(4) In bareroot nurseries, S-deficiencies have occurred in Alabama, Oklahoma, Wisconsin and possibly New York and North Dakota. The risk of a deficiency is greatest when irrigation water contains no S.

(5) When irrigation water provides more than 15 kg ha^{-1} S during a year, there is no need to apply S to grow bareroot seedlings when soil pH is less than 5.0.

(6) At sandy nurseries, a hidden hunger for SO_4 may exist when N-fertilized seedlings are irrigated with S-free water.

(7) Non-mycorrhizal pine seedlings do not become S-deficient when seedbeds are irrigated with water that contains more than 2 $\mu g\ g^{-1}$ S.

(8) Purchasing 10 kg of S might cost \$2 while one soil test for SO_4 may cost \$6. Therefore, some managers forgo SO_4 testing and, instead, annually fertilize with 10 to 30 kg ha^{-1} S.

(9) Except for *Pinus sylvestris*, published critical values for total S in pine needles (i.e., low enough to cause a 10% growth reduction) were not determined using fertilizer response curves. The assumption that all pines are S-deficient at 1,200 $\mu g\ g^{-1}$ S is not valid.

(10) Pine seedlings (with more than 1,100 $\mu g\ g^{-1}$ Ca in foliage) are likely S-deficient when gypsum fertilization increases seedling growth by more than 30%.

(11) When *Pinus taeda* trees are 12 years old and contain 400 $\mu g\ g^{-1}$ S in foliage, fertilization with 175 kg ha^{-1} S might not increase leaf area.

(12) *Pinus ponderosa* seedlings could be S-deficient if S fertilization increases diameter growth by 30%.

(13) For bareroot *Pinus strobus*, a hidden hunger for S existed since treating seedlings with sulphate fertilizes (Zn-sulphate and Cu-sulfate) exhibited increased growth.

(14) Too much sulphuric acid can injure roots of young bareroot seedlings.

(15) When pine needles have a N/S ratio of 18 in July, there is no need to stop fertilizing bareroot seedlings with N.
(16) Sodium is not inert and too much in hydroponics can reduce growth of pine seedlings. Some conclusions regarding S toxicity symptoms in pine were invalid because authors assumed high sodium levels in water were not toxic.

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