Use of calcium in bareroot pine nurseries

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Abstract

Bareroot nursery managers may apply dolomite, gypsum, or Ca-nitrate to increase Ca in nursery soils. Although a few managers follow S.A. Wilde's recommendations and maintain soil at levels of 500 to 1,000 µg g^{-1} Ca, there is no need to keep Ca levels this high. In contrast, managers at sandy nurseries apply Ca when soil tests drop below 200 µg g^{-1} Ca. In fact, acceptable pine seedlings have been produced in irrigated soil with <100 µg g^{-1} available Ca. In plantations, asymptomatic wildlings grow when topsoil contains 17 µg g^{-1} Ca. In sandy soils, applying too much gypsum can result in a temporary Mg deficiency and too much lime will result in chlorotic needles.

Managers apply Ca when foliar levels fall below a published "critical value." The belief that the critical value for Ca varies by stock type is not valid. In fact, numerous "critical" values are invalid since they were not determined using growth response curves. Critical values determined for small seedlings using $CaCl_2$ in sand are apparently not valid for use in bareroot nurseries.

At bareroot nurseries, the soil extractable Ca level can decline during a year by 30 µg g^{-1} or more. Harvesting 1.7 million pine seedlings may remove 20 kg ha^{-1} of Ca but irrigation can replace this amount or more. When water contains 5 mg l^{-1} Ca, 600 mm of irrigation will add 30 kg ha^{-1} Ca. In some areas, 1,000 mm of rainfall will supply 7 kg ha^{-1} Ca. Even when a Mehlich 1 test shows no exchangeable Ca in the topsoil, pine needles on tall trees may exceed 2,000 µg g^{-1} Ca due to root growth in subsoil.

There are few documented cases of deficient pine needles (<300 µg g^{-1} Ca) in irrigated nurseries in Australia, New Zealand, Scotland and in the Americas. Even when soil fumigation delays the inoculation of ectomycorrhiza, bareroot pines have adequate levels of Ca. Typically, foliage samples from pine nurseries contain at least 1,000 µg g^{-1} Ca. Samples from 9-month-old seedlings range from 300 to 11,000 µg g^{-1} Ca. Although the "critical value" for *Pinus echinata* foliage is not known, seedlings with 300 µg g^{-1} Ca were not stunted and apparently grew well after outplanting.

Keywords

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

Contents

1 Introduction

The term calcium originates from the Latin word calx which means lime. Due to the quantity of limestone, calcium (Ca) is the fifth most common element in the Earth's crust and the third most common element in pine seedlings. Limestone contains calcite and aragonite which are forms of $CaCO_3$. When limestone contains $MgCO_3 \cdot CaCO_3$ it is referred to as dolomite while sources with low levels of Mg are called agricultural lime (https://www.lime.org/about-us/faqs/). Both types have been used in bareroot nurseries but most managers prefer to apply dolomite since it contains Mg. Details about the role of Ca in plants have been reviewed previously (Hawkesford et al. 2012; Bryson and Mills 2014; White 2015; Prado 2021). Ca moves easily with water to the top of trees and is sequestered in needles. Typically, Ca concentration in new needles increases during growing season. Since retranslocation from needles to the phloem is limited (Helmisaari 1992), concentrations of Ca in 18-month-old needles are typically higher than in 9-month-old needles. A literature review of Ca was undertaken to establish what has been learned from over a century of research and use in bareroot pine nurseries.

[Abbreviations: AA = ammonium acetate soil extraction. B = boron. Ca = calcium. CEC = cation exchange capacity. Cl = chloride. Fe = iron. K = potassium. LSD_{05} = Least significant difference, α= 0.05. meq = milliequivalent. Mg = magnesium. Mn =

manganese. N = nitrogen. P = phosphorus. pH = potential hydrogen. Pt = *Pisolithus tinctorius*. S = sulfur. TSP = triple superphosphate. Soil pH was measured in water.]

2 History

Most nursery managers in the 19th century did not apply fertilizers but a few spread lime before sowing cover-crops. At new nurseries located on nutrient-poor soils, organic matter was incorporated into soil before sowing seed and sometimes lime was added to assist in decomposition (Nicol 1820). However, on new land with no organic amendments, adding lime was found to do more harm than good (Nicol 1820).

Before 1892, agricultural experiment stations analyzed commercial fertilizers for N, P and K content but not for Ca content. At that time the terms "lime" and "calcium" were synonyms. In one bulletin, the words "lime", "gypsum" and "calcium" were mentioned 11, 2 and zero times, respectively (Scovell 1890). Fertilizer sold as raw bone manure might have an estimated nutrient value (1890) of \$0.038 kg^{-1}.

Schenck (1907) realized Ca was an essential element and he said pine seedlings contained about 19 kg Ca ha^{-1}. To replenish nutrients at his nursery, Schenck applied several fertilizers including bone meal (12% Ca). However, he admitted that results from tests with bone meal were uncertain. Although Schenck did not mention rate, 112 kg ha^{-1} of bone meal was applied at the Greenwood Nursery (PA) (Retan 1914). At two nurseries, he found that that acid phosphate (336 kg ha^{-1}) was the best fertilizer tested. In addition, sodium nitrate (168 kg ha^{-1}) and potash (168 kg ha^{-1}) were applied before sowing a cover crop.

In New York, managers believed that seedbeds of *Pinus strobus* "must be heavily fertilized but they should not be located on areas that have been heavily limed" (Steer 1915). The practice then was to apply fertilizers before sowing a cover-crop. Managers at the Syracuse Nursery (NY) applied sodium nitrate, potash, and bone meal, each at 140 kg ha^{-1}. In addition, a dilute phosphoric acid solution that was buffered with sodium, magnesium, and calcium salts (acid phosphate) was applied at 280 kg ha^{-1}.

Toumey (1916) also discussed nursery fertilization but did not mention calcium. For example, the term "phosphates of lime" (Scovell 1890, Fox 1904) means calcium phosphate. Toumey's list of chemical fertilizers included gypsum, lime, clay and sand. He said these four substances were "chiefly valuable in improving the physical qualities of certain soils."

Tillotson (1917) discussed the use of lime and fertilizers in Federal nurseries. He used the word "lime" 30 times and did not mention "calcium." He said that lime helps to decompose organic matter and "makes the soil lose and friable." Soil testing was considered expensive and inconvenient and test results were only good for only a few months. He said unslaked lime contains 90 to 95% lime and is generally used as part of a compost. In Minnesota, Hansen (1923) saw no consistent advantage of applying 4,000 kg ha^{-1} of lime one week before sowing pine seeds.

Jones (1925) said the life of the Savanac Nursery depended upon soil fertility and the fertilizers used were mainly concentrated commercial fertilizers. Blood meal (2,000 kg ha^{-1}) was used as a N source and bone meal (1,000 kg ha^{-1}) was used as a P source. Hydrated lime (3,900 kg ha^{-1}) was applied at the Savanac Nursery in order to increase soil pH (Jones 1925). Hydrated lime is calcium hydroxide [$Ca(OH)_2$] while dehydrated lime [CaO] is known as quicklime (Table 1).

Wahlenberg (1930) installed various fertilizer trials in hopes of advancing nursery management. In one trial he tested six sources of calcium. The best germination of pine occurred with calcium monohydrogen phosphate (355 kg ha^{-1}). He might have not been the first to test gypsum on pine seedbeds but he may have been the first in North America to publish test results. In California, several experiments were conducted to improve nursery management (Show 1930). At one nursery, fertilization was deemed unnecessary but at another, liming increased root mass of pine by more than 100%.

Wakeley (1935) said that fertilization of southern pine nursery had just begun and practically no fertilizer trials had been established. He mentioned N, P, K, bone meal and lime, but did not mention calcium. Managers realized that too much lime could increase damping-off fungi (Wilde 1938; Auten 1945; Stoeckeler 1949) and, therefore, applying lime was generally avoided in pine nurseries (Wilde 1942). When lime was recommended for pine seedbeds, the target acidity was generally pH 4.8 (Wilde 1942). Several university laboratories tested soil acidity before 1940 (Lunt 1938; Wilde 1938; Flaten 1939; Argetsinger 1941).

Table 1. A partial list of calcium (Ca) fertilizers. Powder (P): granules (G): liquids (L).

Ingredients	Name	Form	% Ca	% Other
Calcium oxide	Quicklime	P	65	
Calcium hydroxide	Slacked lime	P	54	
Calcium carbonate	Ag lime	G	32	3 Mg
Calcium chloride	De-ice	G	36	64 Cl
Phosphorite	Rock phosphate	G	33	33 P
Calcium sulfate	Gypsum	G	23	18 S
Calcium magnesium carbonate	Dolomite	G	22	11 Mg
Calcium nitrate	15.5-0-0	G	19	15.5 N
Calcium phosphate + $CaSO_4$	0-20-0	G	19	8 P 11 S
Calcium phosphate	0-45-0	G	15	19 P
Calcium magnesium nitrate	13.5-0-0	G	12	13 N 4 Mg
Calcium ammonium nitrate	17-0-0	L	9	17 N
Calcium EDTA	Calcium chelate	P	9	3 N
Calcium ammonium nitrate	27-0-0	G	8	27 N
Calcium glucoheptonate	Tracite GHEP	L	8	
Urea and $CaCl_2$	23-0-0	L	7	14 Cl
Limestone ammonium nitrate	LAN	G	4	28 N 2 Mg

In the 20th century, there were two schools of thought regarding how much Ca should be added to nursery soils. The "experiment" school established fertilizer trials while the "short-cut" school guessed at fertility needs of conifers and hardwoods. Making nursery recommendations base on fertility tests of virgin forest soils took less time than installing and measuring nursery fertility trials (Wilde 1940). As a result, Wilde set high Ca target levels for nursery soil and varied fertility targets by species. His soil Ca targets were 500, 750, and 1,250 µg g^{-1} for *Pinus banksiana*, *Pinus resinosa* and *Pinus strobus*, respectively (Wilde 1938). Once he published tentative standards for conifers in nurseries, many accepted these "short cut" standards without asking about the benefit/cost ratio. As a result, individuals likely applied Ca to *Pinus strobus* seedbeds while applying no Ca in adjacent seedbeds sown with *Pinus banksiana*. The belief that pine seedbeds should contain 500 to 1,000 µg g^{-1} Ca continued into the 21st century (Briggs 2008; VandeHey 2007; Bueno et al. 2012). In contrast, pines can grow well in irrigated nursery soil with >50 µg g^{-1} available Ca (Table 2) and in non-irrigated sites when soil contains 30 µg g^{-1} available Ca (NCSFNC 1991).

Table 2. Height (Ht), root-collar diameter (RCD), green root mass (Root), green total mass (Total) and % short roots with ectomycorrhiza (Ecto) for seedlings growing in sandy soil with less than 140 µg g^{-1} calcium (Mehlich 1). Soil samples were collected before sowing (Marx et al. 1984). Nurseries are arranged in order of increasing soil Ca at time of sowing.

Species	Nursery	State	pH	Sand	Ca	Ht	RCD	Root	Total	Ecto
				%	µg g^{-1}	cm	mm	g	g	%
Pinus taeda	Champion	SC	5.1	88	56	21.4	4.9	3.7	12.9	20
Pinus taeda	Westvaco	SC	4.7	86	80	26.6	7.9	13.0	34.4	61
Pinus taeda	Weyerhaeuser	OK	5.2	89	89	20.3	3.9	2.4	11.4	37
Pinus elliottii	Buckeye	FL	4.7	88	91	22.6	4.8	1.8	13.5	23
Pinus resinosa	Toumey	MI	4.7	86	96	21.4	4.7	5.4	26.3	44
Pinus elliottii	Buckeye	FL	5.0	94	101	27.0	4.5	2.3	13.9	27
Pinus taeda	Weyerhaeuser	OK	4.7	91	103	24.1	4.8	3.0	14.7	18
Pinus virginiana	Vallonia	IN	4.3	82	105	20.8	4.5	8.9	21.8	19
Pinus taeda	Weyerhaeuser	OK	5.5	90	106	28.2	4.4	3.4	14.0	43
Pinus resinosa	USDA	MI	4.8	88	114	14.1	4.1	2.5	13.1	46
Pinus virginiana	Vallonia	IN	5.1	81	131	25.1	4.0	5.1	14.9	43
Pinus elliottii	Buckeye	FL	5.2	95	139	19.1	3.0	1.2	6.6	28

The experiment school of thought was led by researchers in Germany, New Zealand and the United Kingdom who based fertility recommendations on nursery experiments. German researchers believed guessing at Ca needs for pine was not as useful as fertilizer tests. In one experiment in 1925, liming soil (5,400 Mg ha^{-1}) resulted in a statistically significant reduction in seedling numbers (Steven 1928). Likewise, too much Ca acetate reduced growth of *Pinus echinata* (Chapman 1941).

3 Soil tests

Soils contain exchangeable and non-exchangeable Ca and the sum is referred to as total soil calcium. In some soils, the total may be 14,000 µg g^{-1} Ca while the exchangeable portion is 6,090 µg g^{-1} Ca (Hallett and Hornbeck 1997). Various methods (Mehlich 1, Mehlich 3, AA, etc.) are used to estimate the exchangeable amount (Alva 1993; Davey 2002; Mylavarapu et al. 2002). Extractions of identical soil samples might produce 100 µg g^{-1} Ca when using Mehlich 1 and 170 µg g^{-1} Ca when using Mehlich 3 (Mylavarapu et al. 2002). As a result, managers who use Mehlich 1 will likely apply more Ca fertilizers than those who rely on Mehlich 3 tests.

In theory, the Mehlich 3 tests should not vary among laboratories, but that is not the case. In one comparison, laboratory C extracted twice as much Ca as did laboratory B (Table 3). Therefore, those who use laboratory C will apply less Ca to their seedbeds than managers who send samples to laboratory A or B.

Table 3. Examples of calcium soil test results (Mehlich 3) using three soil samples. Two laboratories produced similar results but laboratory C extracted twice as much calcium than laboratory B.

	Laboratory		
Sample	A	B	C
	µg g^{-1}	µg g^{-1}	µg g^{-1}
9	63	93	308
12	71	89	191
16	49	102	203

When a soil test value is below a pre-determined "trigger," then managers usually incorporate Ca several months before sowing pine seed. Due to equipment and budget limitations, a "stair-step" recommendation curve may be adopted (Figure 1). When a soil test indicates low Ca at pH 5, most agronomists recommend lime but nursery managers usually apply gypsum since pines grow better in acid soils (Marx 1990; South 2017). Gypsum may be applied at 363 kg ha^{-1} (Sonne 2006), or 900 kg ha^{-1} or 1,500 kg ha^{-1}. In one nursery trial, gypsum (7,500 kg ha^{-1}) applied before sowing did not increase growth of *Pinus radiata* seedlings (Flinn and Waugh 1983).

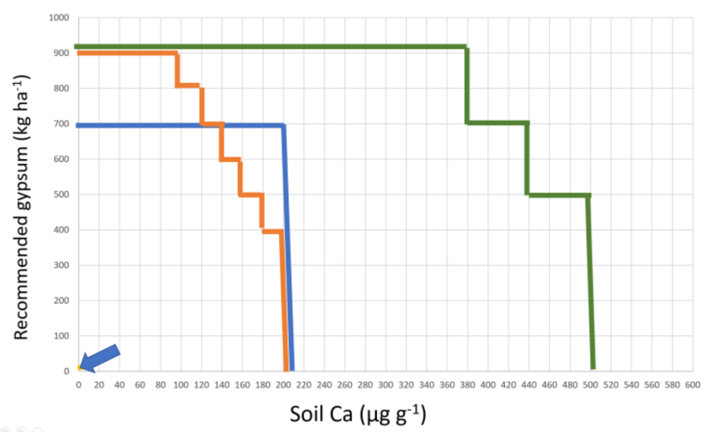

Figure 1. Various opinions exist regarding calcium (Ca) fertilization of pine seedbeds (White et al. 1980). Some researchers set 200 µg g^{-1} Ca as a satisfactory level (Woodwell 1958; South and Davey 1983) while others use a 500 µg g^{-1} (Briggs 2008; Bueno et al. 2012) or 600 µg g^{-1} target (van den Driessche 1984). When a Mehlich 3 test indicates a soil (pH 5.5) contains 165 µg g^{-1} Ca, one manger might apply 500 kg ha^{-1} of gypsum (orange line), another might apply 700 kg ha^{-1} (blue line) and a third might apply 900 kg ha^{-1} (green line). In contrast, some agronomists recommend no gypsum (arrow) and instead recommend raising soil pH by applying various rates of dolomitic lime.

Nursery managers apply Ca either from experience or from the recommendations of others. Some managers do not apply Ca since irrigation supplies more than required (Armson and Sadreika 1979; Argo et al. 1997). At nurseries where irrigation water is below 20 µg g^{-1} Ca, most managers apply the same rate of Ca to all pines even though Wilde (1938) recommend applying more Ca to *Pinus banksiana* than to *Pinus resinosa*. His logic for fertilizing with high rates of Ca included soil factors that did not relate to seedling nutrition (Wilde 1946, p. 196). In contrast, others recommend lower Ca levels which reduces expenditures for gypsum (Table 4).

Table 4. Recommended levels of extractable calcium for growing pine seedlings in bareroot nurseries vary by individual. Wilde (1938) and Stoeckeler and Jones (1957) varied the level by species and May (1984) varied it by sand content. Some values in this table were "tentative" and were subject to modification (Solan et al. 1979).

Species or soil texture	Minimum µg g^{-1}	Recommended µg g^{-1}	Upper value µg g^{-1}	Reference
--	100	-	300	Sadreika 1976
--	200	-	-	South and Davey 1983
Sand	200	-	300	May 1984
--	-	300	-	Hallet 1980
--	-	300	-	Bunting 1980
--	350	-	400	Kormanik et al. 1994
Sandy loam	300	-	450	May 1984
--	125	375	500	Knight 1978a
Pinus banksiana	-	400	-	Stoeckeler and Jones 1957
Pinus banksiana	-	500	-	Wilde 1938
--	-	500	-	Solan et al. 1979
Pinus sylvestris	-	600	-	Stoeckeler and Jones 1957
--	-	600	-	van den Driessche 1984
--	500	-	1,000	Youngberg 1984
Pinus resinosa	-	750	-	Wilde 1938
--	-	1,000	-	Landis 1988
Pinus strobus	-	1,250	-	Wilde 1938

4 Tissue analysis

Soil analyses are used to determine how much lime and gypsum to apply in bareroot nurseries (before sowing) while tissue analyses are used to diagnose deficiency and monitor uptake of nutrients. Except when extractable Ca is below 5 µg g^{-1} Ca (e.g. Chaves and Corrêa 2005), there typically is no relationship between soil Ca and foliar Ca concentration (South et al. 2017; Figure 2).

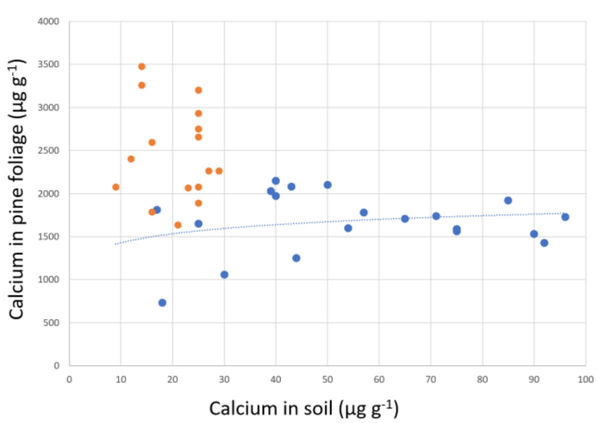

Figure 2. Irrigated *Pinus elliottii* seedlings in a greenhouse (16 orange dots; Steinbeck 1962) and non-irrigated *Pinus taeda* trees in plantations (20 blue dots and blue line; NCSFNC 1991) show no relationship between soil calcium and foliar calcium (blue r = 0.22). *Pinus elliottii* seedlings were irrigated using water containing 7.9 µg g^{-1} calcium while no irrigation was applied to the *Pinus taeda* plantations.

In nurseries, Ca in irrigation water can explain the lack of a relationship while root growth deeper than 15 cm may explain no relationship in pine plantations. Even when extractable soil Ca in the top 60 cm is below detectable levels (Mehlich 1), *Pinus palustris* trees with deep root may contain 2,900 Ca µg g^{-1} in needles (McLeod et al. 1979). In contrast, with lime rate studies, there can be is a high correlation between foliar Ca concentration and soil Ca (Carter 1987).

Pinus taeda seedlings with less than 1,000 µg g^{-1} Ca can be found in the southern United States (Table 5) while seedlings with more than 6,000 µg g^{-1} Ca in foliage occur in the Inland Mountain West (Mexal and Fisher 1987; Landis 1988). Although some claim the range of adequate % foliar Ca is greater for bareroot pines (versus container stock), data do not support the belief that bareroot pine foliage should contain 1,000 µg g^{-1} more Ca than foliage sampled from container-grown pines (Figure 3).

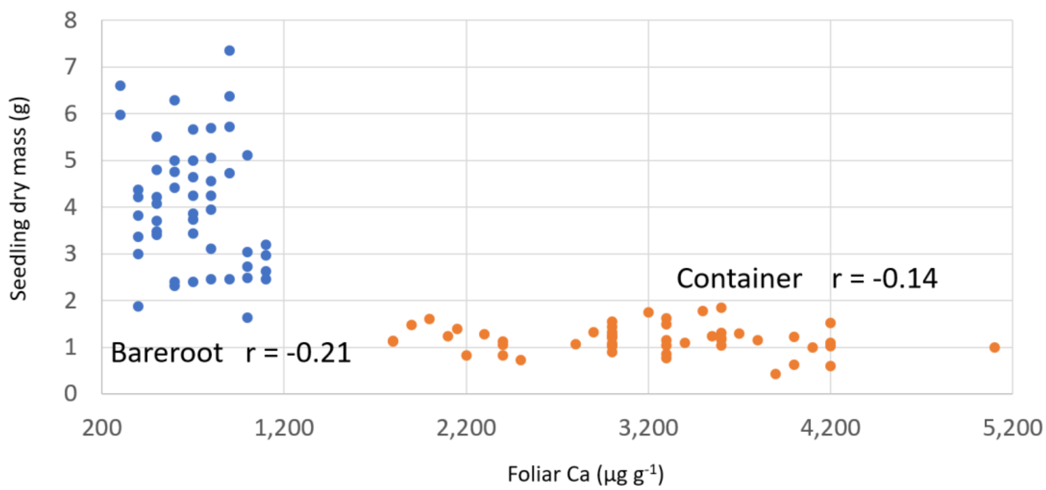

Figure 3. Seedling dry mass and calcium (Ca) concentration in foliage for 50 *Pinus echinata* seedlings (orange dots) grown in a greenhouse at the Stephen F. Austin State University (Bryson 1980). Blue dots represent 50 bareroot *Pinus echinate* seedlings lifted in November 1978 at the Ashe Nursery. There was no relationship (α = 0.10) between foliar calcium (Ca) and seedling dry mass for either stock type.

In theory, Ca concentrations in pine needles should increase with seedling age. For example, *Pinus taeda* seedlings in August contained 3,050 µg g^{-1} Ca while six months later the average was 3,750 µg g^{-1} Ca (Danielson 1966). Likewise, *Pinus radiata* needles sampled in fall may be 1,000 µg g^{-1} Ca lower than needles collected three months later (Menzies et al. 1981; Olykan et al. 1995). However, there are exceptions to theory. At some nurseries there is no trend (Sung et al. 1997) and sometimes June values were higher than concentrations in September (May et al. 1962; Baer 1984).

Table 5. The foliar calcium concentration of pine seedlings. Data compiled from Voigt 1955; Voigt 1958; Fowells and Krauss 1959; May et al. 1962; Steinbeck 1962; Beaton et al. 1965; Steinbeck 1965; Danielson 1966; Metz et al. 1966; Malavolta et al. 1970; Iyer et al. 1971; van Lear and Smith 1972; Woessner et al. 1975; Knight 1978b; Landis 1979; Hart and Widdowson 1981; Bryson 1980; Flinn et al. 1980; Baer 1984; van den Driessche 1984; Boyer and South 1985; Richardson and Perkins 1985; Landis 1988; Gleason 1989; Wall 1994; Andrews et al. 1998; Jose et al. 2003; Leski et al. 2010; Starkey and Enebak 2012; Hans 2013; Januszek et al. 2014.

			Foliar calcium (µg g^{-1})			
Species	Year-Month	samples	Mean	Minimum	Maximum	Reference
Pinus banksiana	1948?	5	2,740	2,000	3,300	1958
	1969?	5	2,300	2,000	2,700	1971
Pinus caribaea	1979-6	21	1,945	1,300	3,600	1981
Pinus contorta	1961-1963	34	3,960	1,600	6,400	1965
	1968-78	53	3,200	1,900	5,200	1984
Pinus echinata	1978-11	50	724	300	1,100	1980
Pinus elliottii	1954-12	39	1,490	900	2,220	1962
	1959-6	54	3,510	1,860	7,920	1962
	1959-9	54	850	500	1,800	1962
	1959-12	54	2,460	1,720	3,580	1962
	1970	4	4,550	3,800	5,000	1970
	1969	12	9,460	4,100	19,200	1972
	1961-12	48	2,224	1,450	3,450	1962
Pinus palustris	2000-10	8	4,675	3,000	7,400	2003
Pinus ponderosa	1978-11	2	6,700	--	11,300	1979
	1979-5	9	3,060	1,200	5,000	1984
	1980-4	9	2,760	1,100	3,500	1984
	1981-4	9	5,230	1,300	9,500	1984
	1985-9	9	2,840	2,270	3,510	1989
Pinus radiata	1953?	17	5,465	1,900	7,600	1955
	1975	18	5,100	2,200	5,200	1978
	1971-1975	12	3,300	1,700	5,300	1980
	1983-4	7	3,330	1,700	5,800	1985
	2011-8	22	1,960	1,300	2,600	2013
Pinus resinosa	1969?	7	2,500	1,900	3,500	1971
Pinus strobus	1998?	78	5,000	3,000	8,000	1998
Pinus sylvestris	1963-1	45	4,130	2,200	7,700	1965
	2003-11	15	4,660	3,300	5,800	2014
	2006-9	15	4,260	3,600	4,800	2010
Pinus taeda	1955-1	162	2,130	1,430	3,830	1962
	1956-1	216	1,370	810	2,480	1962
	1957-12	12	1,420	900	2,500	1959
	1962-2	256	1,200	340	2,160	1966
	1965-8	4	3,050	2,700	3,400	1966
	1966-2	4	3,650	3,600	3,700	1966
	1973-4	19	1,384	800	2,000	1975
	1982-12	41	3,000	2,200	6,600	1985
	1989-1	5	3,780	3,600	4,100	1994
	2009-7	19	3,300	2,900	5,500	2012
	2009-10	19	3,500	2,100	4,800	2012
	2010-2	19	3,300	2,500	5,900	2012
Pinus virginiana	1957-12	12	2,030	1,600	2,500	1959

4.1 Hidden hunger

Since a hidden hunger for Ca might not occur in 99.9% of pine plantations (Snowdon and Waring 1985; Will 1985; Woollons et al. 1995; May et al. 2009), there is little need to fertilize pine plantations with Ca. Most researchers in Australia and North America do not recommend adding lime or gypsum to pine stands at planting or at mid-rotation. In Europe, lime may be applied in forests (Baule 1975), but this is due mainly to increase soil pH as part of a precautionary principle (Talkner et al. 2019). Growth gains from applying dolomite to a 9-year-old *Pinus taeda* plantation (pH 4.3) were likely due to a Mg-deficiency (<700 µg g^{-1} Mg in foliage) since foliage in control plots contained >1,100 µg g^{-1} Ca (Kyle et al. 2005). No hidden hunger was detected when a nursery soil contained 135 µg g^{-1} Ca (South et al. 2017) or when a silt loam soil contained 246 µg g^{-1} Ca (McKee 1978). In fact, no hidden hunger was detected when a piedmont soil contained 57 µg g^{-1} Ca (Moschler et al. 1970). In contrast, *Fraxinus pennsylvanica* exhibited a hidden hunger for Ca at a bareroot nursery in North Carolina (Deines 1973).

Some surveys suggest a positive relationship between foliar Ca and height growth of pines (Hoyle and Mader 1964; Jenkinson 1974) while others report a negative relationship (Wells et al. 1973). A cause-and-effect relationship is unlikely since these correlations are confounded with other nutrients. Likewise, a positive correlation between soil Ca and height growth of *Pinus taeda* in a bareroot nursery (South et al. 2018) does not prove seedlings have a hidden hunger for Ca.

A hidden hunger can be proved by establishing a rate trial and plotting a response curve. Response curves using nutrient-sand culture were developed by varying $CaCl_2$ (Mitchell 1938; Woodwell 1958). In one study (Figure 4), a 10% reduction in maximum growth occurred at about 80 µg g^{-1} soil Ca and 2,700 µg g^{-1} foliar Ca (Mitchell 1939). For *Pinus serotina* and *Pinus taeda*, response curves were nearly flat (Woodwell 1958). However, a response curve developed in a greenhouse using washed sand and deionized irrigation water may not be appropriate for use in an operational nursery (Bates 1971). In a greenhouse, good root growth of *Pinus taeda* occurred at 22 µg g^{-1} soil Ca (Lyle and Adams 1971) and good shoot growth occurred at 20 µg g^{-1} soil Ca (Woodwell 1958).

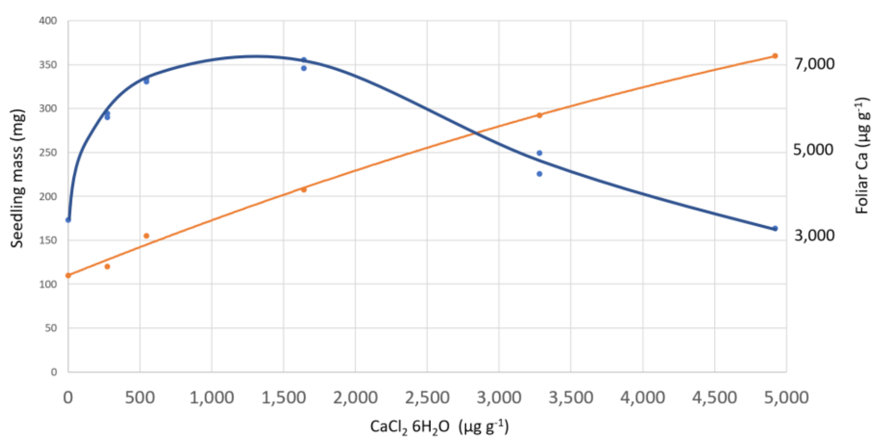

Figure 4. The effect of calcium chloride on dry mass (blue line) and foliar calcium concentration (orange line) of *Pinus strobus* seedlings growing in sand at the Black Rock Experimental Nursery (Mitchell 1939). Solution concentrations of 100 µg g^{-1} calcium (Ca) and 200 µg g^{-1} chloride (Cl) are equivalent to 546 µg g^{-1} $CaCl_2 \cdot 6H_20$. Seedlings with a 315 mg mass likely had 2,700 µg g^{-1} Ca in needles.

Due to fertility management and irrigation in nurseries, bareroot pine seedlings likely have flat response curves for Ca. As a result, pine seedlings can grow well at irrigated nurseries where the extractable soil Ca is 50 to 150 µg g^{-1} (Table 2). Even in a greenhouse, flat response curves have been observed in pots filled with sand (Steinbeck 1962; Figure 5). A growth response might result at locations where extractable soil Ca is below 5 µg g^{-1} (e.g. Chaves and Corrêa 2005).

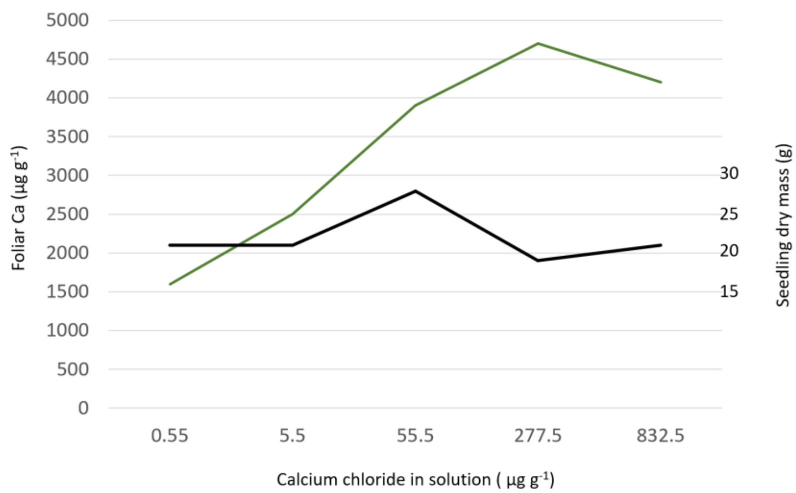

Figure 5. The effect of calcium chloride on dry mass (black line) and foliar calcium concentration (green line) of *Pinus virginiana* seedlings growing in sand in a greenhouse (Sucoff 1962). Due to unmeasured Ca in water, it was assumed that the solution concentration needed for good growth was 3 µg g^{-1} Ca. The nutrient solutions also contained 120 µg g^{-1} of magnesium sulfate as well as K, Na, N and P. Ca deficiency symptoms did not occur in any treatment. Increasing the concentration of $CaCl_2$ increase Ca in needles (LSD_{05} = 2,500 µg g^{-1} Ca) but did not affect seedling dry mass (LSD_{05} = 11 g).

4.2 Critical level in foliage

The "critical level" of foliar Ca is defined as the concentration that occurs at 90% of maximum yield; the probability of a growth response to fertilization is high when foliage is below this level (Bates 1971; Kumar and Shivay 2008). Most critical values for Ca in pine are guesses since the values were not determined from response curves. I see no reason to manage pine nurseries based on assumptions made using Ca ranges derived from foliage sampled from pine stands. Therefore, an accurate critical value for Ca has not been determined for *Pinus taeda*. During the 20th century, there was insufficient information to predict a pine response to Ca fertilization (Stone 1953; Allen 1987; Will 1985) and this situation has not changed. Although critical-values for pine foliage have been repeated numerous times, these values were not independently verified. Perhaps one estimate was equated with the average foliar Ca value for *Pinus taeda* (Metz et al. 1966). A "critical level" of 500 µg g^{-1} Ca for *Pinus ponderosa* was likely based on the optimum N/Ca ratio for *Betula verrucosa* (Ingestad 1974). Without complete explanations, we are left wondering what procedures were used to determine most critical values listed in Table 6.

When bareroot pines contained 800 µg g^{-1} Ca (Figure 3), I doubt growth in 1978 would have increased after seedlings received a foliar application of $CaCl_2$. I contend that for pine, critical levels >500 µg g^{-1} Ca (Table 6) can be ignored. Before managers top-dress pine seedlings based on foliar values of 2,000 µg g^{-1} Ca, researchers should first install tests to determine if bareroot seedlings with 800 µg g^{-1} Ca in foliage will respond to applications of $CaCl_2$.

Table 6. Estimated critical values for pine needles vary by species and reference. None of these values have been verified using Ca trials in bareroot nurseries.

Species	µg g^{-1} Ca	Method used	Reference
Pinus resinosa	350	Cited Swan 1972	Timmer and Armstrong 1987
Pinus spp.	500	Not provided	Zöttl 1973
Pinus caribaea	500	Cited Zöttl 1973	Vettorazzo and Couto 1997
P. ponderosa + P. jeffreyi	500	Cited Ingestad 1974	Powers 1983
Pinus ponderosa	500	Not provided	Allen 1987
Pinus ponderosa	500	Cited Powers 1983	Moore et al. 2004
Pinus radiata	600	Cited others	Boardman et al. 1997
Pinus contorta	800	Cited Swan 1972	Moore et al. 2004
Pinus contorta	800	Not provided	Binkley and Fisher 2013
Pinus contorta	800	Not provided	Allen 1987
Pinus elliottii	800	Not provided	Pritchett and Comerford 1981
Pinus sylvestris	900	Greenhouse data	Hacskaylo et al. 1969
Pinus sylvestris	900	Cited van den Burg 1990	Mellert and Göttlein 2012
Pinus banksiana	1,000	Response curve	Swan 1970
Pinus elliottii	1,000	Not provided	Allen 1987
Pinus radiata	1,000	Not provided	Knight 1978
Pinus palustris	1,000	Cited Blevins et al. 1996	Dickens et al. 2021
Pinus elliottii	1,200	Cited others	Boardman et al. 1997
Pinus taeda	1,200	Not provided	Allen 1987
Pinus taeda	1,200	Not provided	Gregoire et al. 2004
Pinus elliottii	1,400	Greenhouse data	Malavolta et al. 1970
Pinus taeda	1,500	Not provided	Jokela 2004
Pinus sylvestris	2,000	Cited Göttlein 2015	Talkner et al. 2019
Pinus strobus	2,700	Response curve	Mitchell 1939
Pinus nigra	2,700	Response curve	Kavvadias and Miller 1999
Pinus sylvestris	3,400	Response curve	Kavvadias and Miller 1999

When foliar Ca values fall below an accurate critical value and plants are in the "hidden hunger" zone (Mitchell 1939; Ritchey et al. 1982; Gregoire and Fisher 2004), then Ca fertilization will increase height growth. For example, when growing in acid-washed sand that was fertilized with N, seedlings with less than 80 µg g^{-1} Ca in foliage grew taller when fertilized with $CaCl_2$ (Figure 6).

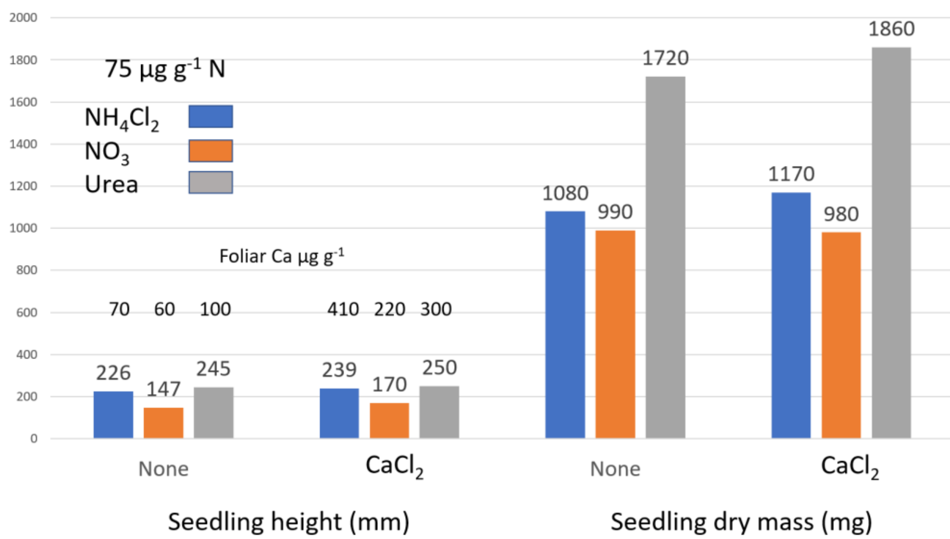

Figure 6. In a factorial trial, 18 pots containing *Pinus taeda* seedlings were fertilized with calcium chloride (200 µg g^{-1} Ca) and the remaining 18 pots (three pots per bar) were not fertilized with calcium (Pharis et al. 1964). Seedlings were fertilized three times a week using solutions of NH_4Cl_2 or urea or NO_3 ($NaNO_3$ then KNO_3). The $CaCl_2$ treatment increased height (α = 0.05) and foliar Ca (α = 0.01) but did not increase seedling mass (α = 0.05). Photos of seedlings represented by this graph appear on page 563 (Pharis et al. 1964).

4.3 Visible symptoms

When Ca-deficient seedlings are produced in greenhouses, symptoms vary with species. For *Pinus taeda* (Figure 7), a Ca deficiency caused resin to exude on needles and terminal buds (Lyle 1969). *Pinus taeda* needles were yellow with yellow-red splotches along the needle while *Pinus palustris* needles were delicate and had a pale green color (Pessin 1937). *Pinus sylvestris* seedlings had dead terminal buds and beads of resin (Figure 8). Beads of resin also formed on the tips of bracts surrounding the terminal bud of *Pinus radiata* (Purnell 1958). Ca-deficient *Pinus banksiana* had beads of exuded resin and contorted needles (Swan 1970). In regards to *Pinus radiata* plantations in South Wales, Australia, Humphreys (1964) said "One of the most important symptoms which we use is the appearance of a small resin drop on the young developing needles. This can be found by examining the plants with a hand lens." The lowest foliar Ca values reported for pine needles are 60-110 µg g^{-1} (Goslin 1959; Pharis et al. 1964; Chaves and Corrêa 2005) and these pines had visible deficiency symptoms.

Some say visual symptoms in Ca-deficient pine plantations include dieback of stem tips and branches and needle tortuosity (Rocha et al. 2019). A lack of photos illustrating these symptoms suggests documented cases of Ca-deficiencies in pine plantations are very rare (Bengtson 1968). Several traditional assumptions about Ca-deficiency are not valid (Saure 2014).

There are numerous photos of Ca-deficient crops but few if any photos illustrating symptoms on pine in irrigated bareroot seedbeds. In addition, there are no photos of Ca-deficient pines in either New Zealand (Will 1985; Davis et al. 2015), United Kingdom (Binns et al. 1980) or the United States. In contrast, photos from greenhouse trials have been published (Table 7).

Figure 7. *Pinus taeda* seedlings grown water culture in a greenhouse (photo taken August 1954 by Jack May). The Ca-deficient seedling had a dead terminal with some brown needles.

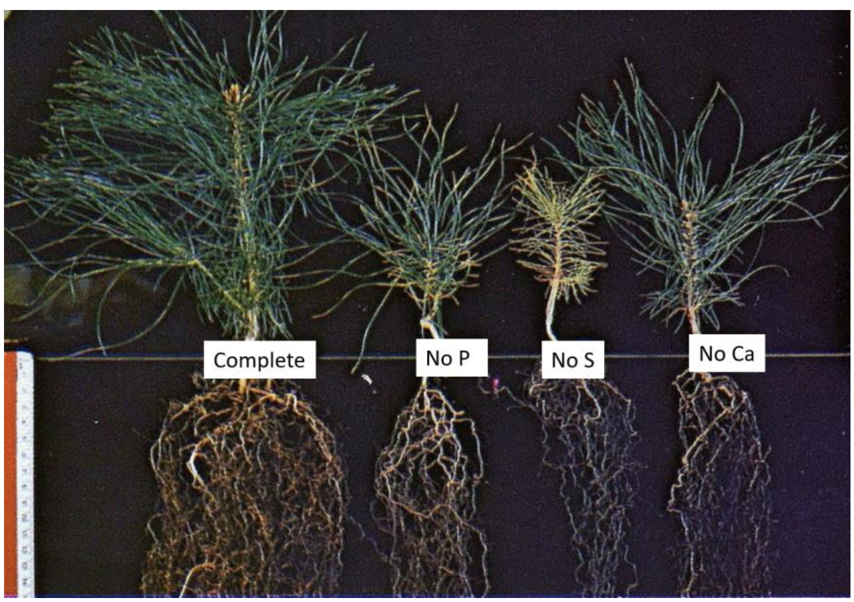

Figure 8. Seedlings of *Pinus sylvestris* were grown in sand in a greenhouse (Hacskaylo et al. 1969). Foliage sampled from complete nutrients, No P, No S and No Ca treatments were 4,800, 4,800, 6,300 and 900 µg g^{-1} Ca, respectively. Seedlings showing Ca deficiency symptoms had dead terminals. Growth of seedlings fertilized with no Ca was greater than seedlings not fertilized with N, P or S. Roots with no added Ca were exposed to $MgCl_2$, $MnCl_2$, $ZnCl_2$ and $CuCl_2$ (Photo permission by The Ohio State University Extension Publishing).

Table 7. A list of references that include photographs of calcium deficiencies in greenhouse-grown pines. Foliar concentrations of Ca-deficient seedlings were included in a few references.

Species	Medium	Photo on page	More than two rates?	Reference
Pinus banksiana	Sand	33	Yes	Swan 1970
Pinus banksiana	Perlite	152	No	Donald 1991
Pinus elliottii	Sand	27	No	Truman 1972
Pinus monticola	Sand	96	No	Murison 1960
Pinus nigra	Perlite	508	Yes	Kavvadias 1996
Pinus ponderosa	Sand	96	No	Murison 1960
Pinus radiata	Sand	86	No	Purnell 1958
Pinus sylvestris	Sand	47	No	Goslin 1959
Pinus sylvestris	Sand	51	No	Hacskaylo et al. 1969
Pinus sylvestris	Perlite	508	Yes	Kavvadias 1996
Pinus taeda	Sand	13	No	Sucoff 1961
Pinus taeda	Sand	562	No	Pharis et al. 1964
Pinus taeda	Water	Plate 18	No	Bengtson 1968
Pinus taeda	Sand	32	No	Truman 1972
Pinus virginiana	Sand	3	Yes	Sucoff 1962

5 Soils

Bareroot nurseries in the United States contain more than 40 µg g^{-1} Ca and those located on clay loam and sandy loam soils have more than 100 µg g^{-1} of exchangeable Ca in topsoil (Youngberg 1958; Dickson et al. 1960; McConnell and Klages 1969; South and Davey 1983; Marx et al. 1984). Since the correlation between Ca and sand content (r = -0.76) is negative (South and Davey 1983) sandy soils usually contain <150 µg g^{-1} Ca (Table 2). Some fine-textured soils may contain more than 400 µg g^{-1} Ca (Dickson et al. 1960; Tanaka et al. 1967; Bueno et al. 2012). In one survey, seedling quality of *Pinus strobus* was lower when nursery soil contained more than 200 µg g^{-1} Ca (Dickson et al. 1960). Typically, sandy topsoil in non-fertilized pine plantations contain less extractable Ca than in nursery topsoils (Figure 9).

Approximately 54% of the soils in 43 pine plantations in the southeastern United States contain more than 100 µg g^{-1} Ca (Mehlich 3) and 100% contain more than 15 µg g^{-1} Ca (NCSFNC 1991). In plantations, good growth occurs when topsoil contains 17 to 25 µg g^{-1} Ca (NCSFNC 1991). Although various row-crops exhibit Ca deficient leaves, soils in North America generally have enough Ca so that deficiency symptoms do not occur in pine plantations. As a result, calcium fertilizers are not applied at time of plantation establishment.

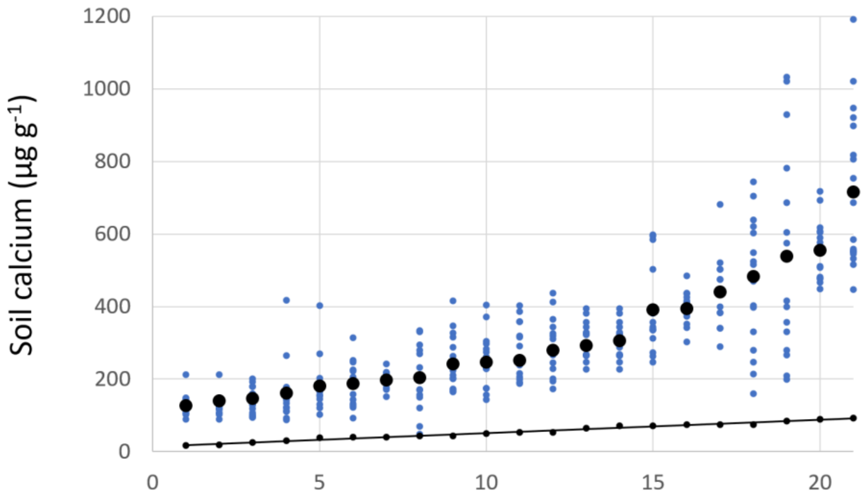

Figure 9. Soil calcium (Mehlich 3) from 21 nurseries and 21 non-fertilized pine plantations in the United States. Fields in nurseries vary from 49 to 1191 µg g^{-1} Ca (blue dots) and soils from the *Pinus taeda* plantations (black line) vary from 17 to 92 µg g^{-1} Ca (NCSFNC 1991). Each nursery is represented by a mean (black dot) of up to 15 soil samples. Calcium fertilizer was applied to nursery fields in March if the soil test was <200 µg g^{-1} (Mehlich 3). In comparison, Ca is typically not applied to pine plantations when extractable soil Ca is below 20 µg g^{-1}.

5.1 Soil pH

In nursery soil, Ca is positively related to pH mainly because lime is used to increase soil pH (Carter 1987; South and Davey 1983; South et al. 2017). In contrast, most pine plantations are not fertilized with lime and exchangeable Ca is not related to soil pH (NCSFNC 1991; Davis et al. 2007b).

5.2 Organic matter

Organic matter is positively correlated to soil Ca (r= +0.286; p = 0.059) in fertilized nursery soils (South and Davey 1983). Wilde (1958, p. 364) said that soils with low Ca may be “safely corrected by the addition of organic remains high in bases.” For example, adding leaves (2 cm depth) at the Vallonia Nursery (IN) initially increased soil Ca by 483 µg g^{-1} Mg (Davis et al. 2007a). Hardwood leaves may contain 22,700 µg g^{-1} Ca and pine bark and sawdust may contain 4,800 and 800 µg g^{-1} Ca, respectively (Mexal and Fisher 1987). Therefore, although more than 44,000 kg ha^{-1} of sawdust can be applied to seedbeds, available Ca levels might increase by <20 µg g^{-1} Ca (Munson 1982). Adding lime-amended horse manure at the Syracuse Nursery (NY) increased soil to pH 7.3, increased soil Ca to 1,300 µg g^{-1}, and reduced seedling quality (Bickelhaupt 1989).

5.3 Nitrogen

When nursery seedbeds are fertilized with ammonium fertilizers, Ca levels decrease due to leaching (Wilde and Kopitke 1940; Steinbeck 1962; Knight 1981; Boxman et al. 1991; Dobrahner et al. 2004; Bryson and Mills 2014). Fertilization with 224 kg ha^{-1} N (as AN) reduced soil Ca in Georgia by 17 to 38 µg g^{-1} Ca (Figure 10) and in Virginia Ca was reduced by 145 µg g^{-1} (Figure 11).

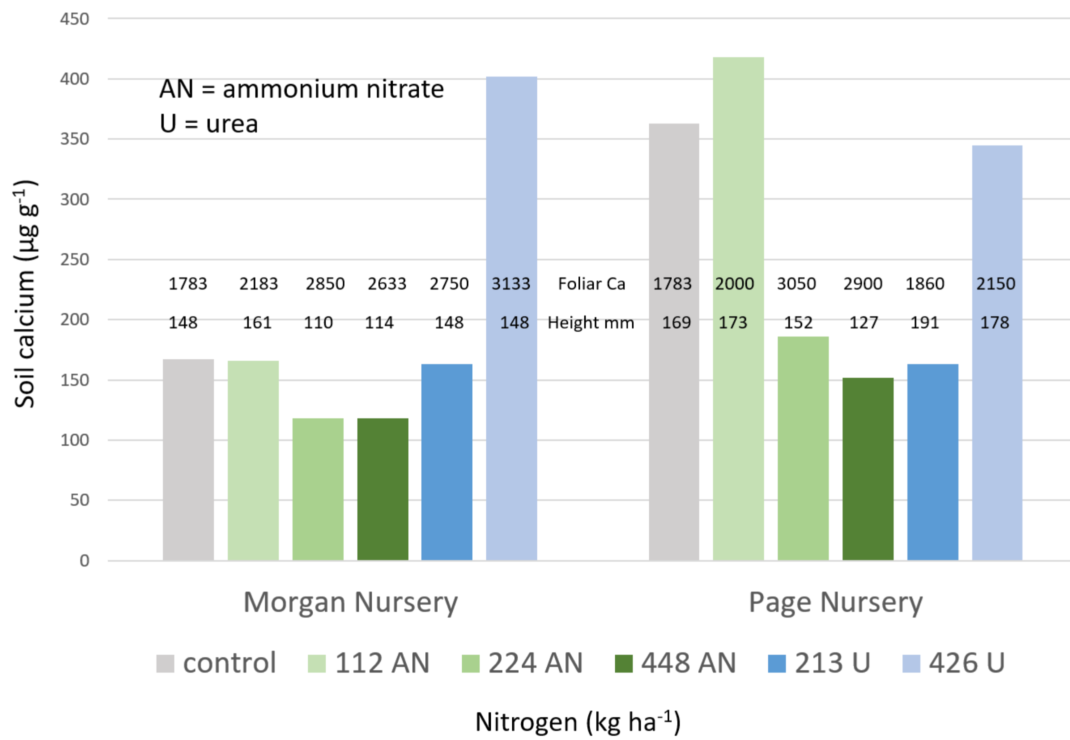

Figure 10. Fertilization of *Pinus elliottii* with ammonium nitrate (AN) increased foliar Ca levels and higher rates reduced the amount of extractable soil Ca (AA) when soil was sampled in December (Steinbeck 1962). This produced a negative relationship between soil Ca and foliar N (r= -0.56; α=0.01). The lowest N treatment (112 kg ha^{-1} of N; source was ammonium nitrate) and both urea treatments (U = Uramite) were applied before sowing (April 17 - Morgan Nursery; April 12 - Page Nursery). April soil samples indicated 87 and 343 µg g^{-1} Ca for the Morgan and Page nurseries, respectively. High rates of ammonium nitrate were applied using four top-dressings during the month of July. *Pinus elliottii* seedlings at lifting ranged in height from 110 mm to 191 mm and foliar Ca ranged from 1,783 µg g^{-1} to 3,133 µg g^{-1}. Urea fertilization resulted in “summer chlorosis” on 30 to 70 percent of seedlings from May through August. Fertilization with AN in July resulted in burning of foliage and increased seedling mortality (50% mortality at the Morgan Nursery and 30% at the Page Nursery). More than 70% of these seedlings remained chlorotic until cooler temperatures in October.

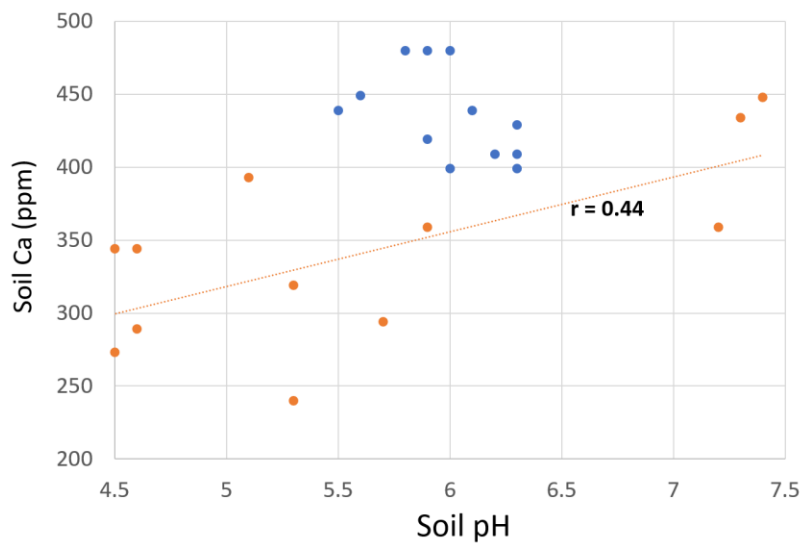

Figure 11. A trial at the Union Camp Nursery (VA) included four sources of N applied at 224, 336 and 448 kg ha^{-1} N during the growing season (Villarrubia 1980). On June 30, 1978, untreated plots (blue dots) averaged 436 µg g^{-1} Ca (Mehlich 1) and on September 12, 1978, N treated soil (orange dots) averaged 341 µg g^{-1} Ca. Soil treated with ammonium nitrate, ammonium sulfate, urea, and sodium nitrate averaged 279, 320, 357, and 414 µg g^{-1} Ca, respectively. Irrigation and rainfall leached some Ca and some Ca was taken up by seedlings. Fertilization with sodium nitrate reduced soil acidity to pH >7.1, while ammonium sulfate increased acidity to pH <4.7. Urea and ammonium nitrate treatments averaged pH 5.4 and pH 5.2, respectively.

5.4 Phosphorus

Adding $CaCO_3$ to a pH 5.5 soil increased available P in the soil but decreased foliar P concentrations in *Pinus sylvestris* seedlings to deficiency levels (Carter 1987). In contrast, adding $Ca(OH)_2$ to a pH 4.8 soil reduced Pt mycorrhiza but did not reduce foliar P of *Pinus taeda* (Marx 1990). If a mycorrhiza-lime interaction exists, this might explain why liming reduces foliar P concentration at some locations but not others. A positive growth response to P fertilization is unlikely when soil Ca is greater than 110 µg g^{-1} Ca (Wells et al. 1973). Some nursery soils exceed 2,000 µg g^{-1} Ca (Martian 1989; Bueno et al. 2012).

A foliar application of H_3PO_4 increased growth of *Pinus taeda* seedlings and reduced foliar Ca concentration by 500 µg g^{-1} (South et al. 1988). A similar response was observed in a greenhouse trial where sodium phosphate increased shoot mass to 23 g (Figure 12). At the Mt. Sopris Nursery (CO), stunted pine seedlings had P-deficient symptoms and foliage contained 1,000 µg g^{-1} P plus 11,300 µg g^{-1} Ca (Landis 1979). Readily available P can combine with Ca to produce an insoluble precipitate.

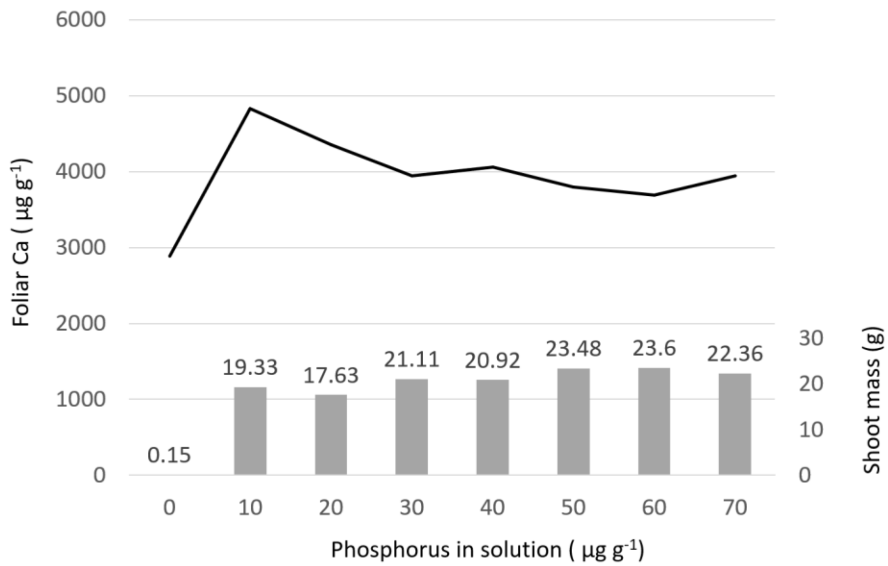

Figure 12. Shoot mass (bars and numbers) and calcium (Ca) in *Pinus taeda* needles (solid line) can be affected by the amount of sodium phosphate in nutrient solutions (Blackmon 1969). Each phosphorus solution also contained 100 µg g^{-1} of nitrogen and 100 µg g^{-1} of Ca.

5.5 Magnesium

Due to applications of dolomite, Mg and Ca are highly correlated in nursery soil (South and Davey 1983; South et al. 2018). At some nurseries, fertilizing with gypsum before sowing will lower soil Mg levels and induce a temporary Mg-deficiency in pine seedlings (South 2022a). At the Edwards Nursery (NC), fertilizing with $CaCO_3$ increased soil pH and did not lower soil Mg (Figure 13).

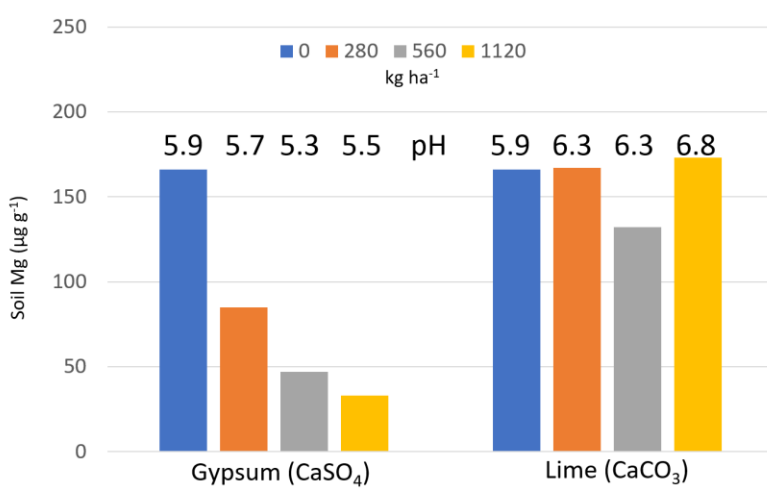

Figure 13. Adding 1,120 kg ha^{-1} gypsum (29% calcium) to a sandy soil lowered soil pH and reduced available Mg while adding 1,120 kg ha^{-1} lime (40% calcium) increased soil pH. Treatments at the Edwards Nursery (NC) (Deines 1973) were applied May 18, 1972 and soil was sampled in December 1972. [pH LSD_{05} = 0.33; Mg LSD_{05} = 32 µg g^{-1}].

5.6 Ca/Mg ratio

Soil nutrient ratios in this paper are determined using parts per million (µg g^{-1}); not milliequivalents. Those who prefer milliequivalents ratios may divide the Ca/Mg ratios presented here by 1.65.

Apparently, good bareroot pine seedlings were produced using soil Ca/Mg ratios of 12 (McConnell and Klages 1969; Wall 1994), 23 (Rowan 1971) and some "good" seedlings were produced with ratios >40 (Dickson et al. 1960; Landis 1988). In contrast, stunted bareroot pine seedlings occurred in New Zealand with a Ca/Mg ratio of 4 (Will 1961). At the New Zealand nursery, chlorosis had more to do with the absolute amount of Mg (12 µg g^{-1} Mg) and had little to do with a hypothetical imbalance between Ca and Mg. Even so, some believe the balance between Ca and Mg is more "important" than the absolute amount of Mg in the soil [Note: use of the word "important" is subjective without a mathematical basis]. Some say once the Ca/Mg ratio in soil exceeds 10, then managers must add Mg to prevent a reduction in chlorophyl production. While this might be true at some nurseries, there are several examples where ratios were greater than 10 and green seedlings were grown without Mg fertilization (Wall 1994; South 2022a).

Some have questioned the science behind a "Ca/Mg balance" for over a century (Lipman 1916) and data exist to cast doubt on the importance of a low Ca/Mg ratio. Although a soil with a Ca/Mg ratio of 11 can certainly produce yellow-tip needles, it is false logic to assume that all soils with a Ca/Mg ratio above 10 will produce Mg-deficient pine seedlings. Even Wilde questioned the Ca/Mg ratios proposed by Moser (1933). Wilde (1946; p. 83) said no concrete observations verifying such an assumption have thus far been reported in relation to tree growth. Nursery managers successfully grew pines in soil with Ca/Mg ratios as high as 67 (South 2022a). Several agronomists contend the "ideal" nutrient balance theory is flawed (Schulte and Kelling 1985; Kopittke and Menzies 2007; Gaspar and Laboski 2016; Chaganti et al. 2021).

5.7 Manganese

Translocation of Ca into the shoot apex is inhibited by high levels of soil Mn (Marschner 2012) and high soil Mn can stunt pine seedlings (South 2022b). Too much Mn may result in terminal death and resin exudation (i.e. Ca-deficiency) even though samples showed needles contained more than 2,000 µg g^{-1} Ca. In a greenhouse trial with saturated soil, applying 81 kg ha^{-1} Mn killed *Pinus resinosa* seedlings (Slaton and Iyer 1974). In one container trial, high levels of Mn and Zn reduced pine roots by 97% (Beyer et al. 2013). The Ca concentration in stunted roots was <70 µg g^{-1} and the concentration in needles was 280 µg g^{-1} (Figure 14). Adding dolomite to the soil can increase soil pH and will reduce the risk of a Mn toxicity (South 2022b; Figure 15).

Figure 14. High levels of manganese and zinc in soil reduced shoot and root growth and killed *Pinus strobus* seedlings (Beyer et al. 2013). In this soil (pH 4.1 – 3,200 µg g^{-1} Mn), pine needles had 1,800 µg g^{-1} Mn, 1,200 µg g^{-1} Zn and 280 µg g^{-1} Ca. Leaf mass was 14% of seedlings growing in uncontaminated media. Photo by Nelson Beyer, United States Geological Survey 2009.

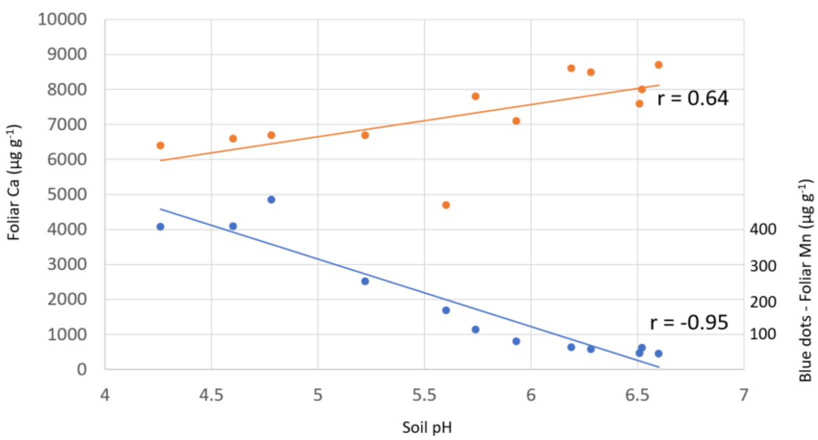

Figure 15. Adding dolomite to potting media increased soil pH, increased foliar Ca (orange dots) and reduced the uptake of manganese (Mn) in *Pinus rigida* foliage (Helm and Kuser 1991). Soil at pH 4.26 had no added lime while pH 6.6 soil was achieved by adding 40 g of dolomite per kg of soil. Seedling growth was maximum at pH 4.8.

6 Irrigation water

Ca in irrigation water at many nurseries is enough to meet the needs of pine seedlings (Carlson 1979; Landis 1979; Argo et al. 1997; Landis et al. 2009). When pines were growing in sand with low available Ca (14 µg g^{-1}) and were irrigated with water containing 8 mg L^{-1} of Ca, the needle concentration exceeded 4,000 µg g^{-1} Ca (Steinbeck 1962). About 93% of irrigation water samples from southern nurseries contain more Ca than 8 mg L^{-1} (Figure 16). Applying 600 mm of irrigation (at 10 mg L^{-1} Ca) is equivalent to applying 286 kg ha^{-1} of gypsum (21% Ca).

At one sandy location, irrigating non-fertilized soil for 16 years (632 mm year^{-1}) increased available soil Ca by 75 kg ha^{-1} (Albaugh et al. 2014). In addition to irrigation, 1,000 mm of rainfall may provide 3 to 38 kg ha^{-1} of Ca (Madgwick and Ovington 1959; Carroll 1962; Allen et al. 1968).

When growing plants in greenhouses, a few researchers believe "The calcium and magnesium ratio in the substrate solution (and in the irrigation water) should be 3 Ca to 1 Mg if expressed as meq/L or 5 Ca to 1 Mg if expressed as ppm Ca and Mg" (Bailey et al. 1999). Even so, there are insufficient data to make the Ca/Mg ratio "an evaluation factor when judging the suitability of a water for irrigation" (Ayers and Westcot 1985; South 2022a). At one *Pinus taeda* nursery, irrigation water contained 50 µg L^{-1} Ca and 2 µg L^{-1} Mg (McNabb and Heidbreder-Olson 1998). To avoid producing yellow-tip needles, foliar levels at that nursery were checked monthly and, if needed, Mg was applied over the top of seedlings in July.

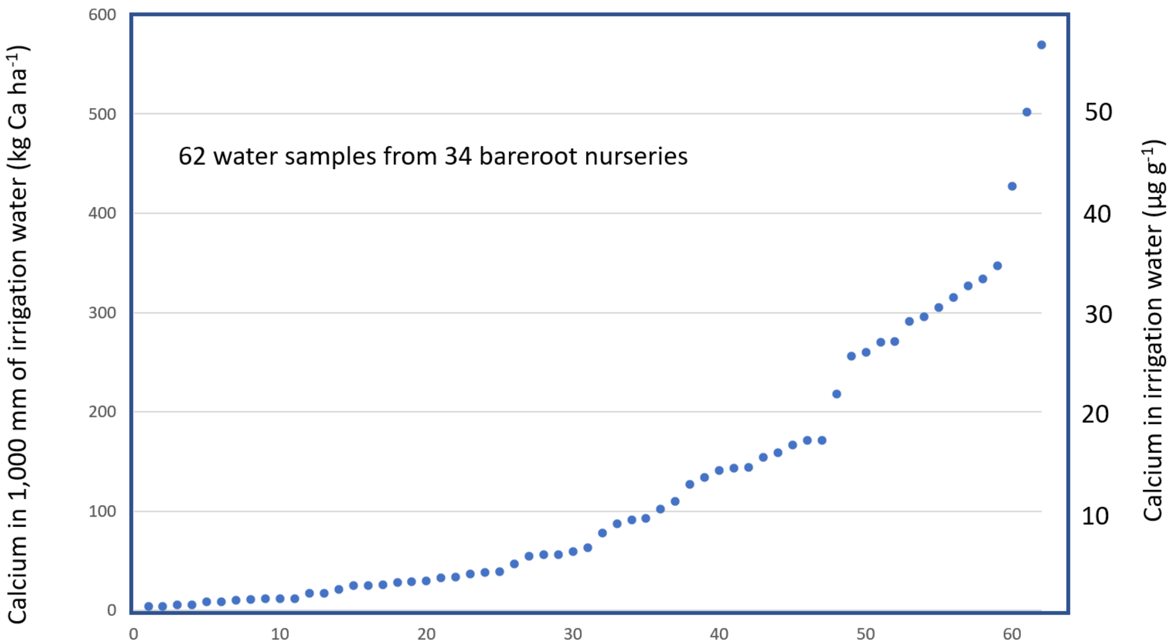

Figure 16. The amount of soluble Ca in irrigation water from 34 nurseries ranged from 4 to 57 mg L^{-1} (McNabb and Heidbreder-Olson 1998). When the level of Ca in irrigation water is 10 mg L^{-1}, then 60 cm of irrigation would add approximately 60 kg ha^{-1} $year^{-1}$. At four nurseries, the Ca/Mg ratio (µg) varied from 11 to 525.

7 Mycorrhiza

Pine seedlings without mycorrhiza do not become Ca-deficient (Ingestad 1962; Bücking et al. 2002). In a bareroot nursery, non-mycorrhizal *Pinus taeda* seedlings exhibited P deficiency symptoms while needles contained >3,000 µg g^{-1} of Ca (South et al. 1988). Adequate foliar Ca concentrations were also observed for non-mycorrhizal seedlings in greenhouse tests (Cumming and Weinstein 1990; Walker and McLaughlin 1997; Zhang and George 2010).

High levels of soil Ca can reduce the formation of Pt ectomycorrhiza (Marx 1990) and, in one trial, Pt ectomycorrhiza was inversely correlated (r = -0.36) with foliar Ca concentration (Mitchell et al. 1990). Likewise, a lack of mycorrhizal infection was noted when container-grown *Pinus sylvestris* seedlings were fertilized with Ca-nitrate (Kieliszewska-Rokicka 1991).

8 Calcium removed at harvest

Depending on species, cultural practices, and seedling age, a million pine 1-0 seedlings may contain 6 to 20 kg of Ca (Schenck 1907; Lunt 1938; Knight 1978b; Flinn et al. 1980; Donald and Young 1982; South and Boyer 1983; Nelson and Switzer 1985; Simpson 1985; Dobrahner et al. 2004). Harvesting 1.7 million pine seedlings might remove 26 kg ha^{-1} of Ca while harvesting *Zea mays* grain removes about a tenth of that amount (Heckman et al. 2003).

The Ca levels in topsoil decline over time when harvest rates exceed inputs from irrigation, fertilizers, and rainfall (Will and Knight 1968). Field #7, at the Ashe Nursery in Mississippi, had 380 µg g^{-1} Ca in 1969 and 68 µg g^{-1} in 1981 which equates to an average decline of 26 µg g^{-1} year^{-1}. Likewise, at the Lava Nursery (OR) and Duncan Nursery (BC), the decline was 33 µg g^{-1} year^{-1} (White et al. 1980; Youngberg 1984). At one area of the Westvaco Nursery (SC), rainfall and N-fertilization of cover-crops resulted in an average annual loss of 21 µg g^{-1} Ca from 1983 to 1990 (Figure 17).

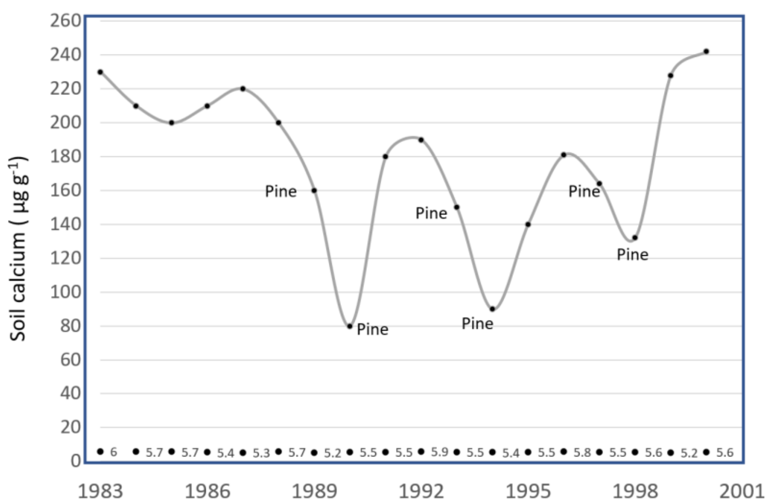

Figure 17. Soil calcium levels (Mehlich 1) at a bareroot nursery in South Carolina. Field B-1 was managed with cover-crops from 1983 to early 1989. *Pinus taeda* seed were sown in April of 1989, 1990, 1993, 1994, 1997 and 1998. Soil pH values adjacent to dots represent soil acidity in October-November. Dolomitic limestone was applied in 1988 (1,120 kg ha^{-1}), 1991 (2,240 kg ha^{-1}), 1992 (1,456 kg ha^{-1}) and 1998 (1,120 kg ha^{-1}).

9 Calcium concentration after transplanting

In general, outplanting performance is not related to the foliar Ca of pine seedlings at time of lifting (Madgwick 1964; Larsen et al. 1988; van den Driessche 1991). After tree planters cover roots with soil, pine seedlings take up enough cations to avoid a Ca-deficiency. In Texas, *Pinus echinata* needles had 724 µg g^{-1} Ca when outplanted in March and eight months later they contained 1,100 to 2,750 µg g^{-1} Ca (Bryson 1980). In 1979 and 1980, outplanted *Pinus ponderosa* seedlings ended the growing season at the same foliar concentration as at planting in late March (Baer 1984).

10 Toxicity

When pine needles contain less than 5,000 µg g^{-1} Ca (Table 5), seedlings do not show toxicity symptoms. However, stunted seedlings may result when the concentration in foliage exceeds 6,500 µg g^{-1} Ca (van Lear and Smith 1972; Carter 1987; Landis 1988; Potvin et al. 2014; Hachani et al. 2020; Figure 4). Occasionally pine foliage exceeds 9,000 µg g^{-1} Ca (Table 5). At the Mt. Sopris Nursery (CO), chlorotic, Fe-deficient, pine needles contained 11,300 µg g-1 Ca (Landis 1979).

Too much carbonates in soil can reduce height growth of pines (Erdmann 1966; Carter 1987) and too much Ca-acetate (3,735 µg g^{-1} Ca) can increase damping-off of *Pinus echinata* seedlings (Chapman 1941). Too much lime can cause deficiencies in Fe, B (Stone et al. 1982; Shorrocks 1997; South 2021) and Mn (Kishchuk 2000). Occasionally, too much gypsum will cause a temporary Mg deficiency in acid soils. When S is applied just before sowing, gypsum crystals may form on roots and this could reduce growth of pine seedlings (Carey et al. 2002). When soil contains more than 1,200 µg g^{-1} Ca, a B-deficiency may emerge (Gupta and MacLeod 1981; Stone et al. 1982; Landis 1988; South 2021). The toxicity threshold for Ca in irrigation water is 1,000 µg g^{-1} Ca (Landis et al. 1989).

High levels of Cl are toxic to pine seedlings, and therefore too much $CaCl_2$ can kill or stunt seedlings growing in sand (Mitchell 1939; Pharis et al. 1964; Timmer and Parton 1984). Chlorosis increased when a *Pinus resinosa* plantation was fertilized with 342 kg ha^{-1} $CaCl_2$ (Stone 1953). High rates of $Ca(OH)_2$ can increase soil pH and reduce growth of pine (Marx 1990). Most pines are not tolerant of soil with high salt levels and/or high soil pH and these soils often contain high levels of Ca (Carter 1987; Landis 1988; Hachani et al. 2020). Some say naturally high pH soils should never be selected for a forest nursery (Aldhous 1975; Landis 1988).

11 Ca Fertilizers

11.1 $CaCO_3$

When applied to a nursery soil at 1,100 kg ha^{-1}, agricultural lime ($CaCO_3$) increased a nursery soil pH by almost 1 unit (Figure 18). Although soil laboratories may suggest adding 2,000 kg ha^{-1} of lime when a nursery soil is at pH 5.0, this rate is not recommended for pine nurseries. In some cases, applying more than 1,500 kg ha^{-1} of lime can reduce growth of pine in greenhouses (Table 8).

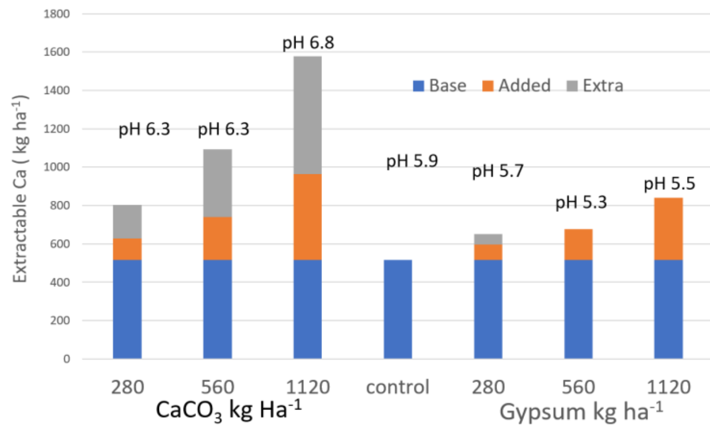

Figure 18. Fertilization (May 18, 1972) with calcium carbonate (agricultural lime – 40% Ca) and calcium sulfate (gypsum – 29% Ca) increased the amount of calcium in a silt loam soil in November at the Edwards Nursery in North Carolina (Deines 1973). Solubility may explain why soil Ca in November was lower than expected for gypsum treatments with pH<5.6. Solubility of calcium carbonate in water is 13 mg per liter and gypsum solubility may range from 2,000 to 2,500 mg per liter. Extra Ca in November (greater than amount applied) likely represents cations retained due to pH>6.0. LSD_{05} = 330 kg ha^{-1}

Table 8. The effect of $CaCO_3$ fertilization on heights (mm) and mass (g) of pines grown outside in soil (McIntyre and White 1930; Wahlenberg 1930; Lunt 1947) or in greenhouses. Recommended soil acidity for pine seedbeds is pH 4.5 to 5.5. pH = before treatment.

Species	pH	Rate	Control	$CaCO_3$	change	Reference
		kg ha^{-1}	-mm-	-mm-		
Pinus ponderosa	5.3	3,025	64	52	-19%	Wahlenberg 1930
Pinus radiata	6.3	40,000	64	57	-12%	Nakos 1979
Pinus strobus	--	2,240	55	47	-14%	McIntyre and White 1930
Pinus sylvestris	5.5	4,000	64	50	-22%	Carter 1987
Pinus taeda	3.0	2.337	96	78	-19%	Coultas et al. 1991
			-g-	-g-		
Pinus caribaea	5.8	1,792	8.09	4.68	- 42%	Richards and Wilson 1963
Pinus caribaea	6.3	1,792	7.18	7.61	+6	Richards and Wilson 1963
Pinus elliottii	4.3	2,694	13.5	13.2	-2%	McKee 1978
Pinus resinosa	5.0	8,960	40.9	35.5	-13%	Lunt 1947
Pinus strobus	5.6	2,240	90.0	108.6*	+20%	McIntyre and White 1930
Pinus strobus	--	2,240	31.1	40.4*	+30%	McIntyre and White 1930
Pinus sylvestris	4.6	6,000	0.107	0.072	-33%	Wallander et al. 1997
Pinus taeda	6.7	3,136	2.18	0.67	- 69%	Richards 1965
Pinus taeda	3.5	2,240	14.1	13.1	- 7%	Barbour and Berenyl 1969

* Damping-off might have increased seedling mass

A target value of 200 µg g^{-1} Ca for bareroot pine seedbeds (South and Davey 1983) is supported by *Pinus strobus* data (Dickson et al. 1960) and by a greenhouse test with *Pinus elliottii* (Figure 19). In contrast, targets of 300, 500 or 1,250 µg g^{-1} Ca are based on assumptions. As a result, Ca applied to meet these targets could be a waste of time and money (Crowther 1950; Dickson et al. 1960; McKee 1978; Bickelhaupt 1989).

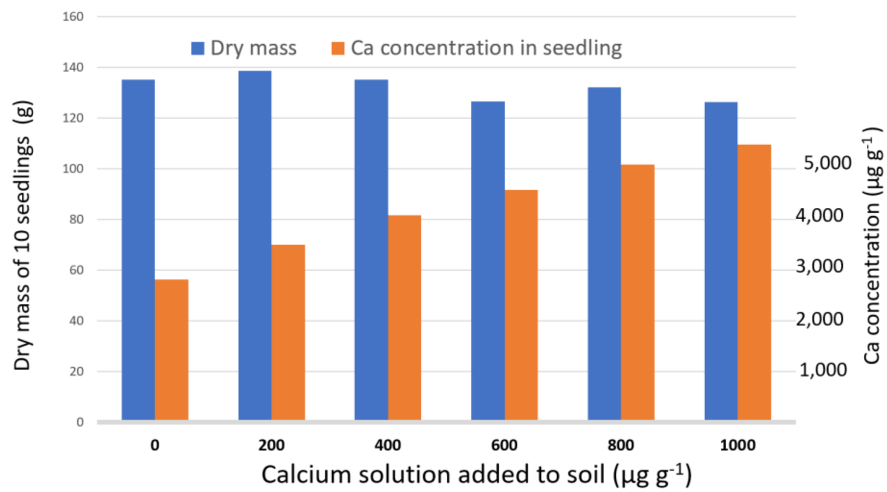

Figure 19. The effect of $CaCO_3$ on growth (dry mass) and foliar concentration of *Pinus elliottii* seedlings in a greenhouse (McKee 1978). Each pot contained 10 seedlings growing in a Caddo silt loam and untreated soil contained 318 µg g^{-1} Ca. Pots treated with 400 µg g^{-1} Ca (equivalent in this trial to 422 kg ha^{-1}), increased Ca concentration (total seedling) but did not improve seedling growth. In seems that increasing Ca concentration in foliage to more than 4,000 µg g^{-1} decreased growth (Y = 148 g – 0.0038* µg g^{-1} Ca in seedling; n = 6; r = -0.75). Soil averaged pH 4.3 at the start of the study and, after 51 weeks, soil with the highest rate of $CaCO_3$ was at pH 5.8.

11.2 $Ca(OH)_2$

Calcium hydroxide is typically not used by nursery managers but researchers sometimes apply it because it does not contain Mg, P or S (Crannell et al. 1994). In one trial, 2.85 Mg ha^{-1} of $Ca(OH)_2$ applied before sowing reduced growth of *Pinus taeda* (family 1-68) seedlings (Marx 1990). The treatment increased soil pH to 5.8 and seedling biomass was reduced by 21% (seedlings were also treated with 150 kg ha^{-1} of N). The increase in soil pH also reduced growth of Pt mycorrhiza.

11.3 $CaCO_3{\cdot}MgCO_3$

Soil and dolomite represent the primary sources of Ca in bareroot nurseries. The amount of dolomite applied varies with soil pH, CEC and year. Applying too much dolomite can increase Fe chlorosis (Shoulders and Czabator 1965) and damping-off (Wilde 1942; South 2017). At the Westvaco Nursery, dolomite was applied three times from 1988 to 1998 (Figure 16) which equates to 81 kg year^{-1} of Ca. Although contents vary with region and distributor, 1,000 kg of dolomite usually contains 220 kg of Ca.

11.4 $CaSO_4{\cdot}2H_2O$

Sometimes gypsum might initially decrease soil pH by 0.4 unit (Fried and Peech 1946; Figure 18) but in other soils pH might increase by 0.4 unit (Marx 1990). No effect on pH is expected when gypsum is applied to nursery soils above pH 4.5-5.0. Although some researchers apply gypsum at >1,700 kg ha^{-1}, nursery managers are reluctant to apply more than 800 kg ha^{-1} since higher rates might result in a Mg deficiency in sandy soils (South 2022a). Several nursery trials with gypsum have failed to demonstrate an increase in pine biomass (Table 10). Since gypsum is soluble, Ca does not last very long in sandy topsoils (Figure 18).

Applying gypsum before sowing will reduce the risk of a S deficiency. A rate of 870 kg ha^{-1} would provide 200 kg ha^{-1} S (Table 1). A S-deficiency might partly explain why lowering soil pH with H_2SO_4 increased growth of *Pinus strobus* seedlings (Wood and Bormann 1977). S-deficiencies have been reported at a few conifer nurseries (Lyle and Pearce 1968; Bolton and Benzian 1970; Morris 1979).

Some managers notice yellow-tip needles on pine seedlings growing in fields fertilized with N and gypsum ($CaSO_4 \bullet 2H_2O$). To reduce the risk of a Mg-deficiency at sandy nurseries, the rate of gypsum can be lowered (e.g. <800 kg ha^{-1}). However, the risk of yellow-tip symptoms is low at nurseries with CEC >50 meq kg^{-1}. At some nurseries, applying 1,500 kg ha^{-1} of gypsum (Table 9) did not produce a Mg deficiency.

It seems doubtful that applying gypsum to nursery soil will increase freeze tolerance of conifers. For example, applying gypsum to potted saplings did not increase freeze tolerance of *Picea rubens* (Schaberg et al. 2000) and applying extra Ca to *Pinus elliottii* did not increase cell wall thickness (Malavolta et al. 1970).

Table 9. The effect of calcium sulfate (gypsum) fertilization on heights (mm) or mass (g) of pines in bareroot nurseries.

Species	Rate	Control	Gypsum	change	pH	Reference
	kg ha^{-1}	-mm-	-mm-			
Pinus ponderosa	4,116	64	70	+10	5.3	Wahlenberg 1930
Pinus ponderosa	8,232	64	70	+12	5.3	Wahlenberg 1930
Pinus radiata	140	188	188	0%	5.0	Will 1961
Pinus taeda	6,776	278	238	-14%	5.4	South 2021
		-g-	-g-			
Pinus palustris	1,568	13.5	11.2	-17%	--	Maki and Henry 1951
Pinus palustris	1,568	12.7	13.6	+7%	--	Maki and Henry 1951
Pinus radiata	1,500	2.62	2.34	-11%	5.0	Flinn and Waugh 1983
Pinus taeda	5,300	9.4	9.7	+3%	5.1	Marx 1990
Pinus taeda	10,600	9.4	9.7	+3%	5.3	Marx 1990

11.5 $Ca(NO_3)_2$

As with most fertilizers, application rate is important. In one container trial, applying 2,665 ha^{-1} of Ca-nitrate reduced average height of 18-week-old *Pinus sylvestris* (Holopainen et al. 1995). Likewise, dipping needles in a solution containing 4,000 ppm N produced slight burning of needle tips (Eberhardt and Pritchett 1971). Nursery managers, however, routinely apply Ca-nitrate without causing foliar injury (Dumroese and Wenny 1997). At one bareroot nursery with high soil Ca, the annual amount of Ca-nitrate applied to *Pinus strobus* totaled 1,160 kg ha^{-1}; 180 kg ha^{-1} N and 220 kg ha^{-1} Ca (Dobrahner et al. 2004). The product was sprayed over the top of pine seedlings at a rate of 22 kg ha^{-1} of Ca. In 1982, a similar rate was applied over *Pinus taeda* seedlings at the Ft. Towson Nursery (OK).

In greenhouse trials using soil, pines fertilized with Ca-nitrate grew the same or better than those fertilized with ammonium nitrate or ammonium sulfate (Addoms 1937; Pharis et al. 1964; Kieliszewska-Rokicka 1991). Some say Ca-nitrate is the proper source when applying N in the autumn (Landis 1996). Even so, some believe nitrate is an inefficient source of N (Weetman and Algar 1974; Davey 1988).

Since Ca-nitrate has 15.5% N compared to 32% N for 32-0-0, most bareroot managers use economics to decide which form of N to purchase. When both products cost the same per tonne, most bareroot managers will choose 32-0-0 since a dollar will purchase twice the amount of N as Ca-nitrate.

Applications of Ca-nitrate increased freeze tolerance of deciduous trees (Percival and Barnes 2008) and applications of ammonium nitrate increased freeze tolerance of *Pinus palustris* and *Pinus halepensis* (Davis et al. 2011; Toca et al. 2018). In contrast, applying $CaCl_2$ did not increase freeze tolerance of *Pinus sylvestris* (Christersson 1973, 1975). It follows that if Ca-nitrate increases freeze tolerance, it likely is due to added N.

11.6 CAN

Calcium ammonium nitrate (CAN) exists in several forms. Some contain limestone, some contain dolomite and others contain calcium carbonate (Maxwell 2012). When calcium carbonate is added to AN, a granular product (26% or 27% N) is sold as “Nitro-Chalk” in the United Kingdom (Benzian 1959; Atterson 1969; O'Reilly et al. 2008), CAN in New Zealand (Ballard and Will 1978) and Cal-am in Australia (May et al. 2009). Adding calcium carbonate reduces the sensitivity of ammonium nitrate to detonation. The granular product (27-0-0) has been applied at rates up to 600 kg ha^{-1} (O'Reilly et al. 2008). A liquid product (17-0-0), made by adding Ca-nitrate to AN, is used to grow seedlings in containers (Dumroese and Wenny 1997). Since soil typically contains sufficient Ca, bareroot nursery managers tend to favor N fertilizers that lower soil pH but do not contain Ca. In contrast, use of CAN has little effect on soil acidity. In 1975, CAN represented about 6% of the N fertilizers used in New Zealand forestry (Ballard and Will 1978).

11.7 $CaCl_2$

An application of 22 kg ha^{-1} Cl is applied to certain row-crops when topsoil contains <15 µg g^{-1} Cl (Diaz 2019) but low Cl levels is not a concern in tree nurseries (Donald 1991). In greenhouses, $CaCl_2$ has been applied to pines 5 weeks after sowing (Timmer and Parton 1984; Dumroese and Wenny 1997) but a few managers prefer CAN which contains no Cl_2^-. Applying too much Cl_2^- can damage or kill pine seedlings in greenhouses (Sucoff 1962; Pharis et al. 1964; Heidmann and Thorud 1976; Sands and Clarke 1977). Applying $CaCl_2$ can increase freeze tolerance of *Pyrus communis* (Rease 1996) but does not increase freeze tolerance of pine (Pellett and Carter 1981).

Pinus taeda seedlings were affected by too much Cl_2^- when they were grown in pots containing white sand for 4.5 months (Pharis et al. 1964). Ten fertilizer treatments had 100% survival but seedlings treated with a double dose of Cl_2^- (ammonium chloride plus calcium chloride) had 46% mortality (11/24). Likewise, 17% died (4/24) when treated with a high rate of ammonium chloride.

In a greenhouse trial with *Pinus virginiana*, seedlings were fertilized with 5 rates of Ca and 3 rates of Mg (Sucoff 1962). The best growth occurred with 20 µg g^{-1} Ca and 24 µg g^{-1} Mg (Figure 20).

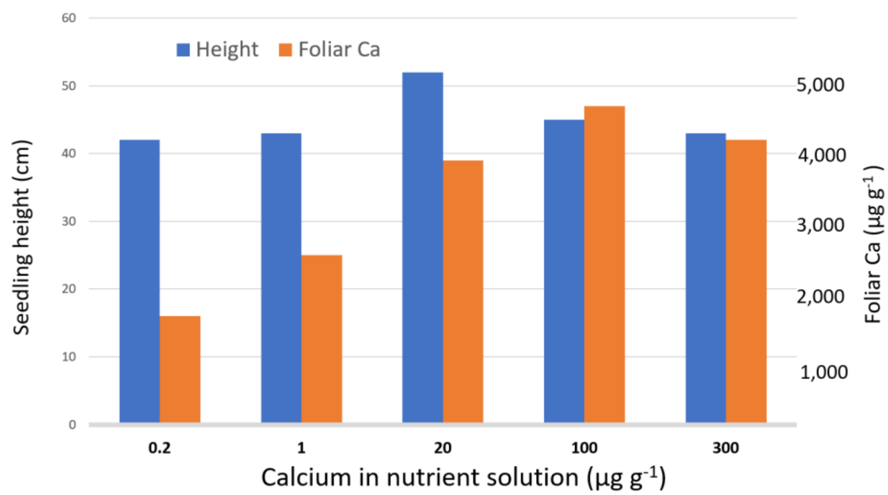

Figure 20. The effect of calcium chloride on height growth of *Pinus virginiana* growing in sand when magnesium is solution is 24 µg g^{-1} (Sucoff 1962). There was no significant difference in seedling height (α =0.05). The two highest Ca solution rates contained 278 µg g^{-1} Cl and 833 µg g^{-1} Cl.

11.8 $Ca(H_2PO_4)_2 \cdot H_2O$

In 1992, more than 34,400 kg of TSP were applied to nursery soils in the southern United States which was equivalent to 10 kg Ca per million seedlings (South and Zwolinski 1996). Prior to sowing, the IFA Nursery (WA) applied 224 kg ha^{-1} of TSP which supplied 33.6 kg ha^{-1} Ca (Marx et al. 1984). More than 500 kg ha^{-1} of TSP was applied to fallow fields at the Big Sioux Nursery (SD) (Martian 1989). The Bend Nursery (OR) and Griffith Nursery (NC) also applied TSP over the top of seedlings (Gleason 1989; Hinesley and Maki 1980).

Application of TSP increased available P to more than 50 µg g^{-1} P (Mehlich 3) at several nurseries. Although TSP use in North America has declined, it is still used to fertilize pine plantations in some countries (May et al. 2009).

11.9 $Ca(H_2PO_4)_2 \cdot CaSO_4$

In 1977, 224 kg ha^{-1} of ordinary super phosphate (OSP) was applied before sowing at nurseries in Florida and Louisiana (Marx et al. 1984). This rate supplied 43 kg ha^{-1} Ca, 18 kg ha^{-1} P and 25 kg ha^{-1} S. When managers stopped using OSP, a S deficiency occurred at several nurseries. As a result, use of gypsum in bareroot nurseries has increased since 1960.

When applied before sowing at two nurseries in Georgia, OSP increased height growth at one nursery (Figure 21). In contrast, applying OSP before sowing did not improve growth at two *Pinus taeda* nurseries (Rosendahl and Korstian 1945; Switzer and Nelson 1956). Due to a low P content, OSP is rarely used at bareroot nurseries in North America but it is used in Africa, Asia and South America.

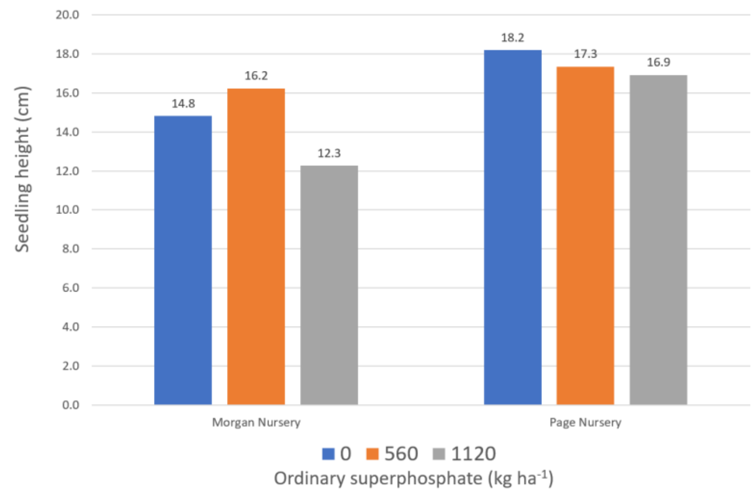

Figure 21. Fertilization (March-April, 1961 prior to sowing) with ordinary superphosphate (560 kg ha^{-1}) increased height growth of *Pinus elliottii* at the Morgan Nursery (88 µg g^{-1} P in soil) and had no effect at Page Nursery (129 µg g^{-1} P in soil) in Georgia (Steinbeck 1962). The 1,120 kg ha^{-1} rate added approximately 224 kg ha^{-1} Ca and 123 kg ha^{-1} S.

11.10 Chelates

Researchers may test Ca-chelates when row-crops show deficiency symptoms. However, a lack of deficiency symptoms in pine nurseries explains why few if any chelate experiments have been installed in bareroot nurseries. Most managers see no reason to apply Ca-chelates to bareroot pines. Pine needles have a thick epicuticular wax layer. In addition, due to near immobility of Ca, foliar applications are likely not adequate to correct a deficiency (Prado 2021).

11.11 Unknown anions

Several researchers published Ca experiments without including the associated anion (e.g. Cl_2^-, NO_3, OH). Some likely believed Cl is an inert element and they saw no need to mention it in the methods section. When the rate of Ca-x increased root length of *Pinus massoniana*, was extra growth due to Cl_2^-, or NO_3 or Ca? Likewise, when a researcher concludes that $CaNO_3$ is not a good fertilizer for pine, was it because the researcher cited hydroponic trial with $NaNO_3$? Invalid conclusions have been published because someone assumed pine growth was not affected by anions.

12 Costs

Fertilizer costs vary by region, shipping distance, year, and distributor. Cost comparisons are time sensitive and vary by region. To keep Ca costs below \$2 kg^{-1}, managers in the United States typically fertilize with dolomitic limestone to increase soil pH and apply gypsum when pH is near optimum. When gypsum costs \$0.26 kg^{-1}, the price of Ca would equal \$1.13 kg^{-1} (assuming no value for S). When Mg and Ca have equal value, then Ca from dolomite may cost \$0.75 kg^{-1}. In comparison, Ca might cost \$2 kg^{-1} when applied as Ca-nitrate (assuming N has the same value as N in urea). At nurseries that sell pine seedlings for 7 cents each, managers often purchase low-cost sources of Ca and N fertilizers.

13 Conclusions

(1) When nursery soil pH is above 5.0, no beneficial effect has been demonstrated by applying $CaCO_3$ to pine seedbeds.
(2) Most published critical values for Ca in needles (i.e., low foliar concentration resulting in a 10% growth reduction) were not determined using fertilizer response curves. The assumption that all conifers have foliage with a "greenhouse" critical value of 1,200 µg g^{-1} Ca is invalid.
(3) Due to taking a short-cut method, recommendations of 2,800 kg ha^{-1} Ca for nursery soils (Wilde 1938) are about 2,000 kg ha^{-1} too high for *Pinus strobus* seedbeds.
(4) When irrigation water provides more than 80 kg ha^{-1} Ca during a year, there is no need to apply Ca before sowing pine seed.
(5) When growing in soil, non-mycorrhizal pine seedlings do not become Ca-deficient.
(6) There is no proof of a hidden hunger for Ca when *Pinus taeda, Pinus elliottii, Pinus echinata, Pinus virginiana* and *Pinus palustris* are growing in irrigated bareroot nurseries.
(7) When lime increases damping-off of seedlings, growth of surviving pines may be increased due to a reduction in competition for light, water and nutrients.
(8) When irrigation water contains less than 3 µg g^{-1} Mg, applying too much gypsum before sowing can induce a Mg deficiency in pine seedlings.
(9) In rare cases when gypsum fertilization increases height growth, the pine seedlings were likely deficient in S.
(10) When pine needles contain >900 µg g^{-1} Ca, there is no need to apply $CaNO_3$ to bareroot pine seedlings during the hardening phase in the fall. However, it is not known what might happen when pine needles contain 300 µg g^{-1} Ca.
(11) Chloride is not inert and too much in hydroponics can kill pine seedlings. Some conclusions were invalid because authors assumed pine growth was not affected by anions.
(12) Fine-textured soils with >3,000 µg g^{-1} extractable Ca should not be selected for a bareroot pine nursery.

14 Acknowledgments

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