Use of magnesium in bareroot pine nurseries

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Abstract

Pines with visible magnesium (Mg) deficiencies (i.e. yellow tips on needles) occur in bareroot nurseries throughout the world. The occurrence of "yellow-tips" is rare when soil pH is above 6.5 but they have occurred on sands (pH < 6.0) with less than 25 µg g^{-1} Mg. If yellow-tips occur in the summer, the foliar content of yellow tips is usually less than 1,000 µg g^{-1} Mg. Some nurseries do not produce "yellow-tip" seedlings when irrigation water contains sufficient Mg. Factors favoring a deficiency include low soil pH, high calcium in irrigation water, frequent fertilization with nitrogen and potassium and applying too much gypsum. Although various Mg fertilizers are available, many nursery managers apply dolomite or potassium-magnesium sulfate before sowing seeds and a few also apply magnesium sulfate in July or August. Soil tests are used to determine when to fertilize before sowing and foliage tests determine when to apply Mg to green seedlings. Nursery managers who follow S.A. Wilde's forest-based soil recommendations may apply magnesium sulfate to green seedlings even when seedbeds contain adequate levels of Mg. When deficiency is minor, chlorosis on needle tips usually disappears before the fall equinox and, when applied at this time, Mg fertilizers have little or no effect on height growth. This paper reviews some of the past and current uses of Mg in bareroot nurseries and highlights a need for additional research.

Keywords

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

Contents

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1 Introduction

Magnesium (Mg) is the fifth most commonly applied nutrient when fertilizing pine seedlings (South and Zwolinski 1996). Despite the importance of Mg for photosynthesis (Grzebisz 2015), there are only a few published trials that involved testing Mg in bareroot pine nurseries. Due to a lack of research, several myths regarding Mg have emerged. To some extent, Mg can be considered a forgotten element (Cakmak and Yazici 2010). For this reason, a literature review was undertaken to establish what is known about Mg fertilization practices in bareroot pine nurseries. This review includes literature from the 20th century since most research trials with Mg were conducted prior to 2000.

[Abbreviations: AA = ammonium acetate soil extraction. AN = ammonium nitrate. AS = ammonium sulfate. DOL = dolomitic limestone. Kainit = kainite ($KMgSO_4Cl{\cdot}3H_2O$). Kieserite = $MgSO_4{\bullet}H_20$. MAP = magnesium ammonium phosphate. MS = magnesium sulfate heptahydrate; $MgSO_4{\cdot}7H_2O$ or $MgSO_4$. SPM = langbeinite (K_2SO_4-$2MgSO_4$). B = boron. Ca = calcium. Cl = chloride. Fe = iron. K = potassium. LSD_{05} = Least significant difference, α= 0.05. Mg = magnesium. Mn = manganese. N = nitrogen. P = phosphorus. pH = potential hydrogen. S = sulfur. Soil pH was measured in water. All reported correlation coefficients are significant at α = 0.05.]

2 History

In the past, temporary or “shifting” or “flying” nurseries produced one or two crops of seedlings without applying any fertilization (Fox 1904; Schenck 1907; Anderson 1949). Typically, these small nurseries were located near reforestation sites to reduce the cost of shipping. Usually only two crops of seedlings could be harvested without adding any Mg fertilizers (Toumey 1916). In Germany, however, the second crop of seedlings was sometimes fertilized with kainit (Fox 1904).

Soil fertility in “permanent” nurseries could be maintained using purchased fertilizers or organic amendments (Ross 1929). Many managers unknowingly applied enough Mg when irrigating seedbeds (McNabb and Heidbreder-Olson 1998) so that deficiency symptoms for Mg did not occur. At some permanent nurseries, kainit might be applied before sowing or between nursery rows (Fox 1904; Schenck 1907).

During the first half of the 20^{th} century, chemical fertilizers were rarely used in forest nurseries in the United States (Sudworth 1900; Toumey 1916; Show 1930; Wahlenberg 1930; McDaniel 1931) and when they were used, most did not contain Mg. Sometimes conifers were grown in research nurseries with soil that contained less than 5 $\mu g\ g^{-1}$ Mg (Flaten 1938; Argetsinger 1941). Some fertilizers supplied low rates of Mg only because kainit was included to supply K (Stewart and Hite 1903). Lime was sometimes applied in nurseries, but the recommendation was to apply it only as an ingredient in compost or in cases where soils were clearly deficient (Toumey 1916). Kainit and wood ash were used as fertilizers to add K, but few saw any need to apply Mg. In fact, Engstrom was against the use of chemical fertilizers (Spilsbury 1949). Although more than 15 chemical fertilizers were evaluated for pine (Wahlenberg 1930; Huberman 1935), MS was not among those tested since soils typically contained sufficient levels of Mg.

Over time, soil fertility at sandy nurseries declined and chlorosis appeared on pine seedlings (Tillotson 1917; Benzian 1965). In some cases, chlorosis was an Fe deficiency symptom (i.e. high soil pH) but sometimes yellow tips of needles appeared on N-fertilized conifers growing in acid, sandy seedbeds (Ingestad 1960; Benzian 1965). In England, nursery managers refer to Mg deficiency as “hard yellows” and in other regions the deficiency is known as “yellow-tip”.

After 1930, several researchers began testing Mg in nurseries and greenhouses (Table 1). Pot studies using either sand or washed sand, proved that Mg needed to be included in research solutions (Möller 1904; Addoms 1937; Inglestad 1962) or height growth would be reduced (Figure 1). In one trial, applying a nutrient solution without Mg reduced dry mass of *Pinus palustris* seedlings by 60% (Pessin 1937). Interest in Mg fertilization increased after yellow-tip symptoms (Table 2) occurred in pine nurseries in Wisconsin (Voigt et al. 1958) and New Zealand (Will 1961, 1962).

In the 20th century, there were two schools of thought regarding how much Mg should be added to nursery soils. Wilde (1938) said “the nutrient content of productive forest soils is a satisfactory criterion for establishing soil-fertility standards in forest nurseries.” As a result, Wilde set high target levels for Mg and K based on soil sampling in virgin natural stands. This explains why he varied fertilization rates depending upon species. His Mg nursery soil targets were 75, 150, and 225 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 standards without question. As a result, the idea that pine seedbeds should contain 150 µg g^{-1} Mg continued into the 21st century (Briggs 2008; Bueno et al. 2012).

The second 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 seedling needs with soil tests was not as useful as fertilizer tests in nurseries (Wahlenberg 1930). Those from this school established a fertility test in Scotland in 1922 using five treatments, five replications and an alpha value of 0.05 (Steven 1928). Subsequent research demonstrated that MS (applied before or after sowing) could improve needle color (Will 1961; Benzian 1967) and might increase seedling growth in a few cases (Table 1).

Table 1. The effect of magnesium sulfate (MS) fertilization on heights (mm) or mass (g) of conifers in bareroot nurseries and greenhouses (GH). Benzian (1965) applied kieserite ($MgSO_4 \bullet H_2O$, 17% Mg) while others applied Epsom salts ($MgSO_4 \bullet 7H_2O$, 9.6% Mg). Soil pH measured before fertilization and needle chlorosis relates to control seedlings.

Species	Product	Control	MS	change	pH	Chlorosis	Reference
	kg ha^{-1}	-mm-	-mm-				
Pinus radiata	224	188	319	+70%	5.0	Yes	Will 1961
Pinus radiata – GH	312	47	57	+21%	5.6	No	Mitchell 2000
Pinus radiata	224	190	210	+11%	5.2	No	Will 1962
Pseudotsuga menziesii	1,120	43	47	+9%	5.9	No	Schaedle 1959
Pinus echinata	672	195	211	+8%	6	No	Auten 1945
Pinus elliottii – GH	224	206	212	+3%	4.7	No	Steinbeck 1962
Pinus taeda – GH	536	272	279	+3%	5.3	No	Edwards et al. 1990
Pinus contorta	211	30	31	+3%	--	--	Benzian 1965
Pinus contorta	211	46	48	+3%	--	--	Benzian 1965
Pinus banksiana	1,120	stunted	stunted	0?	4.0	Yes	Voigt et al. 1958
Pseudotsuga menziesii	3,360	198	???	0?	5.1	No	van den Driessche 1963
Pinus resinosa	211	220	???	0?	6	No	Lunt 1938
Pinus contorta	211	38	37	-1%	--	--	Benzian 1965
Pinus taeda	876	257	254	-1%	5.2	No	Wall 1994
Pinus contorta	211	50	49	-2%	--	--	Benzian 1965
Pinus contorta	211	44	43	-3%	--	--	Benzian 1965
Pinus resinosa – GH	672	42	41	-3%	5.2	No	Cotton 1964
Pseudotsuga menziesii	280	213	199	-6%	5.2	No	Schaedle 1959
Pinus elliottii – GH	224	223.5	203	-9%	5.8	No	Steinbeck 1962
Pinus contorta	359	45	40	-10%	--	--	Benzian 1965
		-g-	-g-				
Pinus taeda – GH	466	2.0	2.5	+25%	--	No	Berenyi et al. 1971
Pinus palustris	1,568	13.5	16.4	+21%	--	No	Maki and Henry 1951
Pinus palustris	1,568	12.7	14.8	+16%	--	No	Maki and Henry 1951
Pinus taeda – GH	466	3.9	4.1	+5%	--	No	Berenyi et al. 1972
Pinus taeda – GH	466	3.45	3.5	+1%	--	No	Berenyi et al. 1972
Pinus taeda – GH	466	2.55	2.37	-7%	--	No	Berenyi et al. 1971
Pinus taeda – GH	466	4.9	4.5	-8%	--	No	Berenyi et al. 1972

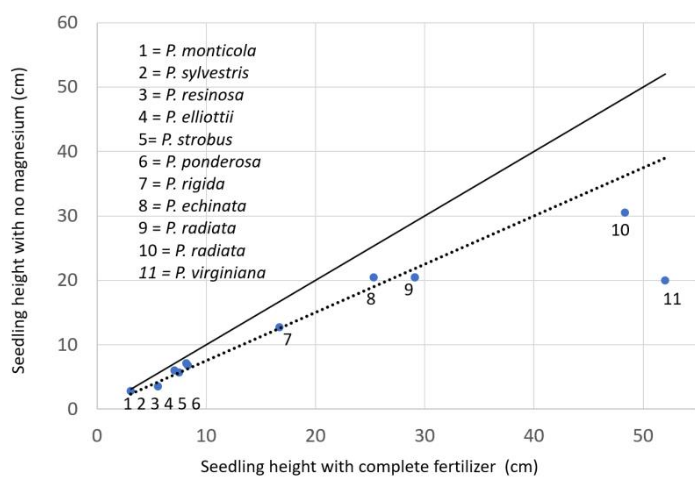

Figure 1. Height growth of pine seedlings in greenhouses is reduced about 25% (dashed line) when nutrient solutions do not contain magnesium sulfate (Hobbs 1944; Purnell 1958; Goslin 1959; Murison 1960; Sucoff 1962; Payn et al. 1995) or magnesium chloride (Van Lear and Smith 1972).

Table 2. A selected list of photographs of magnesium deficiencies in pines.

Species	**Location**	**Photo on page**	**Reference**
Pinus	Nursery	41	Baule and Fricker 1970
Pinus banksiana	Greenhouse	25	Swan 1970
Pinus banksiana	Greenhouse	152	Donald 1991
Pinus echinata	Greenhouse	597	Hobbs 1944
Pinus nigra	Field	313	Bengtson 1968
Pinus nigra	Field	18	Binns et al. 1980
Pinus ponderosa	Greenhouse	96	Murison 1960
Pinus radiata	Greenhouse	86	Purnell 1958
Pinus radiata	Nursery	44	Will 1985
Pinus radiata	Nursery	157	Will 1961
Pinus radiata	Nursery	96	Davis et al. 2015
Pinus sylvestris	Greenhouse	50	Goslin 1959
Pinus sylvestris	Field	135	Van Goor 1963
Pinus sylvestris	Greenhouse	51	Hacskaylo et al. 1969
Pinus sylvestris	Field	77	Van Goor 1970
Pinus taeda	Greenhouse	9	Sucoff 1961
Pinus taeda	Nursery	63	South 2018

3 Soil tests

Soils contain exchangeable and non-exchangeable Mg. In some soils, the non-exchangeable portion may contain several times more Mg than the amount reported by various soil tests (Benzian and Smith 1973; Šrámek, et al. 2012). Over time, a small portion of the non-exchangeable Mg is weathered and becomes available to crops (Salmon and Arnold 1963). Various extraction methods (Mehlich 1, Mehlich 3, AA, etc.) have been used to estimate the level of exchangeable nutrients (Alva 1993; Davey 2002; Mylavarapu et al. 2002).

Extractions of identical soil samples might produce similar Mg values when using Mehlich 1 or Mehlich 3 (Mylavarapu et al. 2002) but the AA method extracts less Mg (Alva 1993; Culman et al. 2019). For Mehlich 3 tests, levels deemed "adequate" vary by crop, but in general, 30 $\mu g\ g^{-1}$ Mg is "adequate" while values below 14 $\mu g\ g^{-1}$ Mg are "very low." Even when using the same extraction procedure, different laboratories will report different values for the same soil sample. As a result, managers who use laboratory C (Table 3) will apply less Mg to their seedbeds than managers who send samples to laboratory A or B. In contrast, those who believe 30 $\mu g\ g^{-1}$ Mg is "inadequate" may waste time and money on superfluous applications of Mg.

During the 20th century, Wilde (1958) and others believed, without much evidence, that nutrient ratios were more important than absolute contents. Wilde said a nursery growing *Pinus strobus* should have a 1 to 12 ratio of available N to available Mg (Wilde 1946; p 946). Although nutrient ratios are no longer deemed necessary (Kopittke and Menzies 2007) some private soil laboratories continue to use milliequivalents to calculate K/Mg and Ca/Mg ratios.

Most managers use soil tests to determine when to apply Mg fertilizers before sowing. When the soil test result is below a pre-determined "trigger" value, then fertilizer is applied. In contrast, a "target value" is used to determine how much fertilizer to apply. Since target values for pines of 50, 75 or 225 $\mu g\ g^{-1}$ Mg (Table 4) were not based on science (Berenyi et al. 1971; Wall 1994), the fertilizer applications required to meet these targets could be a waste of time and money. For example, results from a trial from one nursery (Wall 1994) suggest there is no need to adopt a target value of 50 µg g^{-1} Mg. In fact, even 12 µg g^{-1} Mg (Mehlich 3) can be sufficient for growth of pines at some locations (Steinbeck 1962; Berenyi et al. 1971; Munson 1982; Manikam and Srivastava 1980; Marx et al. 1984; Edwards et al. 1990). Target soil values vary from a low of 20 µg g^{-1} to 150 µg g^{-1} Mg (Figure 2) but most were set without establishing nursery trials (Youngberg 1952). Target values as high as 225 µg g^{-1} Mg were based on soil Mg values in virgin stands (Wilde 1938) while a 25 µg g^{-1} Mg target was based on greenhouse trials (Woodwell 1958).

Table 3. Examples of magnesium soil test results (Mehlich 3) using three soil samples. Two laboratories produced similar results but laboratory C extracted three times more magnesium than the other laboratories.

	Laboratory		
Sample	A	B	C
	µg g^{-1}	µg g^{-1}	µg g^{-1}
9	8	8	30
12	13	12	30
16	9	8	26

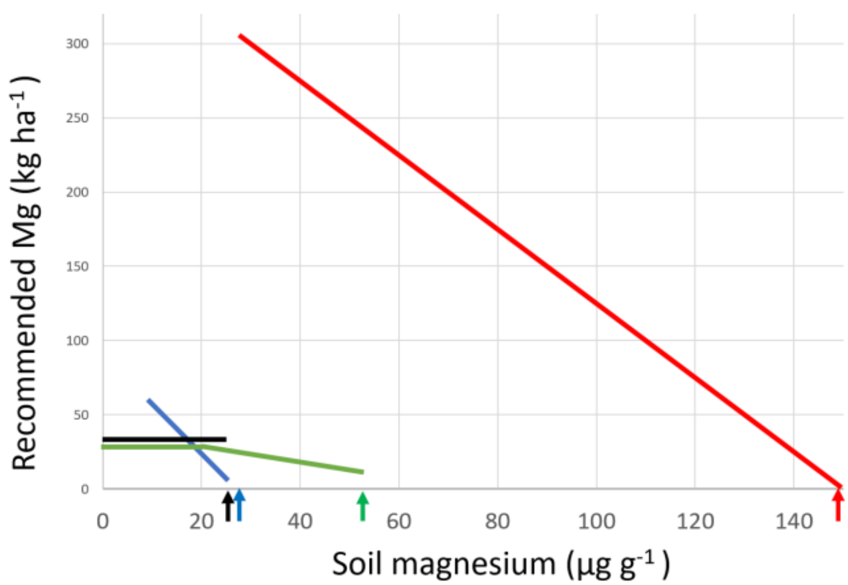

Figure 2. For pine seedbeds, various opinions exist regarding the trigger level for fertilizing with magnesium (Mg) (White et al. 1980). Some agronomists set 60 µg g^{-1} Mg as a satisfactory level (Hardy et al. 2014) while others use a 27 µg g^{-1} trigger value (blue arrow – line). Another group suggests no need to add Mg to pine seedbeds when soil levels exceed 24 µg g^{-1} (black arrow – line; South and Davey 1983) while a fourth group says 52 µg g^{-1} Mg is sufficient (green arrow - line). Some (Wilde 1958; Slone et al. 1979; White et al. 1980; van den Driessche 1984; Briggs 2008; Bueno et al. 2012) believed Mg should be applied when soil extraction levels are below 150 µg g^{-1} Mg (red arrow - line). For pine seedlings growing in soil, published data do not show a significant growth response to Mg application when seedlings have a normal green color with no “yellow tip” needles (Table 1).

Table 4. The concentration of soil Mg recommended for growing pine seedlings varies by individual, soil texture and species. For example, Wilde (1938) recommended 75 µg g^{-1} for *Pinus banksiana*and 225 µg g^{-1} for *Pinus strobus* while Sadreika (1976) recommended 18 µg g^{-1} for *Pinus banksiana*and 60 µg g^{-1} for *Pinus strobus*. Some values were "tentative" and subject to modification (Solan et al. 1979).

Soil texture	Minimum µg g^{-1}	Recommended µg g^{-1}	Upper value µg g^{-1}	Reference
Sandy loam	-	18	-	Sadreika 1976
Sandy loam	20	30	35	Knight 1978b
Loamy sand	25	-	30	May 1984
Sand; loamy sand	25	-	-	South and Davey 1983
Sand; loamy sand	25	-	-	Aldhous and Mason 1994
Loam	30	-	45	May 1984
Sandy loam	-	36	-	Hallett 1980
Silt loam	40	-	-	South and Davey 1983
Sandy loam	-	50	-	Kormanik et al. 1994
Sand	25	50	100	Woodwell 1958
Sandy loam	-	60	-	Sadreika 1976
Sandy loam	-	75	-	Wilde 1938
Loamy sand; sandy loam	60	-	180	Stoeckeler and Jones 1957
Sand; sandy loam	96	-	180	Youngberg 1984
Loam; sandy loam	120	-	240	Martian 1989
Loam; sandy loam	-	150	-	Landis 1988
Loam; sandy loam	-	150	-	Solan et al. 1979
Sandy loam	-	225	-	Wilde 1938
Sand; sandy loam	-	225	-	Youngberg 1952

4 Tissue analysis

Tissue analysis is the preferred method to decide if Mg fertilization is needed (Carter et al. 2021) and pine seedlings may show yellow-tip needles when needles contain 1,000 µg g^{-1} Mg or less (Leaf 1968; Morrison 1974). Diagnostics may be improved by separating the yellow-tip of needles from the basal green portion and submit both for analysis (e.g. Stone 1953; Hunter et al. 1986). Routine sampling during the summer (Figure 3) provides an early warning system for yellow-tip needles.

Foliage of bareroot pine seedlings averaged 950 µg g^{-1} Mg in Australia (Flinn et al. 1980; Hopmans and Flinn 1983), 750 µg g^{-1} Mg in New Zealand (Knight 1978b) and 1,000 to 1,100 µg g^{-1} Mg in the southern United States (Boyer and South 1985; Starkey and Enebak 2012). At a nursery experiment in Fleet England, yellow-tip *Pinus contorta* seedlings had slightly more than 600 µg g^{-1} Mg but those treated with 6.7 kg ha^{-1} of MS contained 850 µg g^{-1} Mg (Aldhous and Atterson 1966). When soil was treated with 40 kg ha^{-1} of Mg, *Pinus contorta* foliage had 900 µg g^{-1} Mg at the Wareham Nursery in England (Benzian and Smith 1973).

The minimum foliar Mg concentration for a pot trial with *Pinus radiata* was 200 µg g^{-1} Mg (Will and Knight 1968) and the minimum for bareroot *Pinus taeda*, sampled in 1982 at a nursery in Arkansas, was 300 µg g^{-1} Mg (Table 5). Deficient bareroot *Pinus radiata* seedlings had 600 µg g^{-1} Mg in foliage (Will 1961) and bareroot *Pinus echinata* from the Ashe Nursery averaged 435 µg g^{-1} Mg in foliage (Bryson 1980).

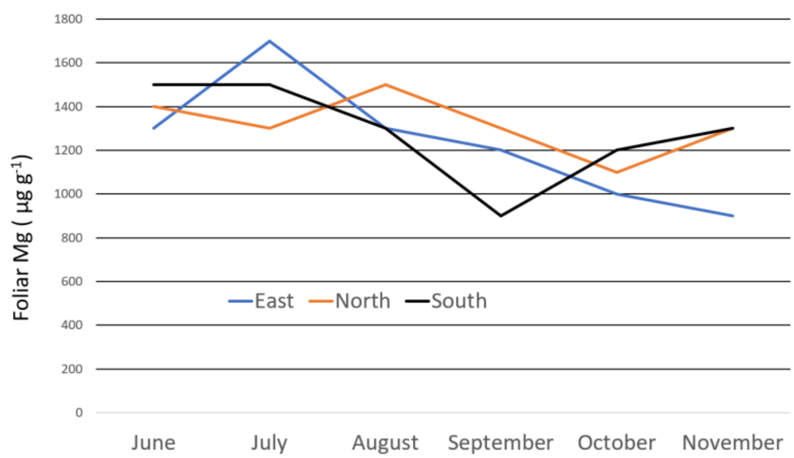

Figure 3. As *Pinus taeda* seedlings increase in mass, foliar concentrations of nutrients will sometimes decline from July to November (data from three fields provided for a bareroot nursery in Mississippi in 2020).

Due to "carbohydrate dilution," the Mg concentration in pine foliage declines during the growing season (Danielson 1966; Rowan and Steinbeck 1977; Wall 1994; Rowe 1996; Sung et al. 1997; Iyer et al. 2002; Dobrahner et al. 2004). In 1959, there was about a 50% decline for *Pinus elliottii* (Table 5) and in 2020, the decline from July to November was 0%, 20% and 47% for North, South and East fields, respectively (Figure 3).

5 Soils

Many soils in the United States are not sandy and therefore have adequate levels of Mg. For example, nurseries located on clay loam and sandy loam soils have topsoil with more than 100 µg g^{-1} of exchangeable Mg (Youngberg 1958; McConnell and Klages 1969; South and Davey 1983; Marx et al. 1984). In contrast, sandy soils can have topsoil with less than 25 µg g^{-1} Mg (Figure 4) and approximately 60 % of the pine plantations in the southern United States contain less than 30 µg g^{-1} Mg (Mehlich 3) (NCSFNC 1991). Transplanted *Pinus teada* seedlings grow well in soil with 12 µg g^{-1} Mg (Edwards et al. 1990) and good growth occurs even when topsoil contains 6 or 7 µg g^{-1} Mg (NCSFNC 1991). Since there is a negative correlation between Mg and sand content (South and Davey 1983; Figure 5), Mg fertilization is more likely to be needed for seedbeds with more than 75% sand.

5.1 Soil pH

In nurseries, soil Mg is positively related to soil pH (South and Davey 1983; South et al. 2017) partly because dolomite is used to increase soil pH and partly because Mg leaches when hydrogen ions are plentiful. Soils with pH greater than 6.0 often contain more than 100 µg g^{-1} of extractable Mg(Martian 1989; Bueno et al. 2012) and therefore have a low risk of developing a Mg deficiency (Landis 1996). In contrast, deficiencies may occur when soil pH is below 6.0 and when the soil contains less than 25 µg g^{-1} Mg (Will 1963). At a nursery in Wisconsin, yellow-tips occurred when soil pH was 4.0 to 4.3 and this type of chlorosis was reduced by fertilization with limestone (Stoeckeler 1949). Sometimes foliar Mg is positively related (r = 0.38) to soil pH (Davis et al. 2007b).

Table 5. The foliar magnesium concentration of pine seedlings. Data compiled from Voigt 1955; May et al. 1962; Danielson 1966; Iyer et al. 1971; Knight 1978b; Bryson 1980; Flinn et al. 1980; Hart and Widdowson 1979; Baer 1984; van den Driessche 1984; Boyer and South 1985; Gleson 1989; Starkey and Enebak 2012; Hans 2013; and Januszek et al. 2014. * The 6,230 $\mu g\ g^{-1}$ value for June 1959 (May et al. 1962) might be due to a typographical error or residual fertilizer imbedded in epicuticular wax.

			Foliar Magnesium ($\mu g\ g^{-1}$)		
Species	Year-Month	samples	Mean	Minimum	Maximum
Pinus banksiana	1954?	32	850	599	1,049
	1969?	5	1,400	1,200	1,700
Pinus caribaea	1979-6	21	1,176	700	2,200
Pinus contorta	1968-10	53	1,300	1,000	1,700
Pinus echinata	1978-11	50	435	320	560
Pinus elliottii	1954-12	39	1,100	800	1,420
	1959-6	54	1,960	1,130	6,230*
	1959-9	54	1,190	880	1,900
	1959-12	54	970	780	1,140
Pinus ponderosa	1979-5	9	1,500	1,200	1,800
	1980-4	9	1,300	1,100	1,500
	1981-4	9	1,400	1,300	1,500
	1985-9	6	1,840	1,930	1,730
	1985-10	3	1,510	1,480	1,560
Pinus radiata	1975	18	750	500	1,130
	1971-1975	12	950	800	1,100
	2011-8	72	704	200	1,300
Pinus resinosa	1969?	7	1,400	1,100	1,700
Pinus sylvestris	2003-11	15	910	800	1,000
Pinus taeda	1955-1	162	860	670	1,150
	1956-1	216	1,050	780	1,750
	1957-1	216	1,160	670	2,150
	1965-8	4	950	840	1,080
	1966-2	4	630	570	730
	1982-12	41	1,000	300	2,300
	2009-7	19	1,400	1,100	1,700
	2009-10	19	1,100	700	1,600
	2010-2	19	1,100	600	1,500

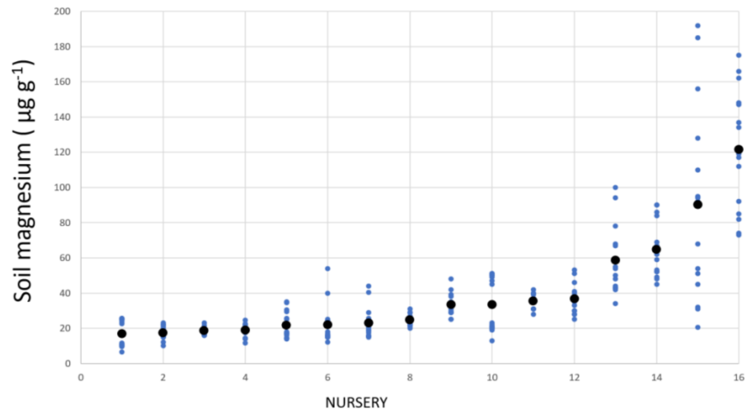

Figure 4. Soil magnesium (Mehlich 3) from 16 southern nurseries in the United States varies from 5 to 175 µg g^{-1}. Each nursery is represented by a mean (black dot) of 15 soil samples (i.e. 240 points on graph with many hidden points). Magnesium fertilizer was usually applied to fields in March when the soil test was < 25 µg g^{-1}.

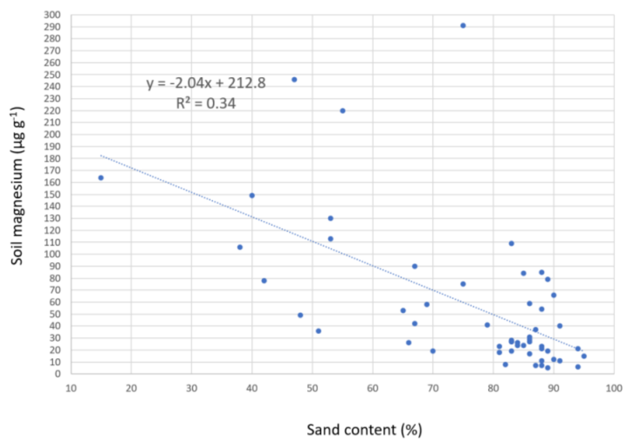

Figure 5. Soil magnesium (Mehlich 1) from 37 nurseries in the United States varied from 5 to 291 µg g^{-1} Mg (54 samples collected from 1977 to 1980). Each nursery is represented by one to four dots (1 point per mycorrhizal study). Before sowing, MS was applied to three fields and lime was applied to 14 fields (Marx et al. 1984). The nursery with the lowest sand content was at Natchez, Mississippi and the nursery at Chiefland, Florida had the most sand. The nurseries with 5 µg g^{-1} and 291 µg g^{-1} were at Ft. Towson, Oklahoma and Umpqua, Oregon, respectively. Sixteen fields (out of 54 points) had soil with less than 25 µg g^{-1} Mg.

5.2 Organic matter

Wilde (1958, p. 364) said that soils with critically low Mg may be “safely corrected by the addition of organic remains high in bases.” For example, adding leaves (2 cm depth) at the Vallonia Nursery (Indiana) initially increased soil Mg by 73 µg g^{-1} Mg (Davis et al. 2007a) and adding leaf mold at the Monico Nursery (Wisconsin) increased soil Mg by 50 µg g^{-1} Mg (Wilde and Krause 1959). Although leaves may contain 2,000 µg g^{-1} Mg, most organic amendments contain relatively low amounts of Mg. Pine bark and sawdust may contain 600 and 100 µg g^{-1} Mg, respectively (Mexal and Fisher 1987). Therefore, even though more than 44,000 kg ha^{-1} of sawdust can be applied to seedbeds, soil levels might increase by < 10 µg g^{-1} Mg (May 1957; Munson 1982). Likewise, incorporating peat at the FIA Nursery in Washington and at the

Toumey Nursery in Michigan did not affect soil Mg levels (Chen 1960; Koll 2009). At the Albuquerque Nursery (New Mexico), adding 43,000 kg ha^{-1} of sawdust had no effect on foliar Mg of pine (Mexal and Fisher 1987). Although adding 500 m^{-3} ha^{-1} of organic material (3 parts sawdust and 1 part sewage sludge) increased soil Mg at the Wind River Nursery in Washington, it also decreased growth and survival of outplanted *Pinus ponderosa* seedlings (Coleman et al. 1987).

Some researchers test different forms of organic matter without providing a comparison of cost data. As a result, managers are often hesitant to purchase composts without knowing the potential economic benefits (Coleman et al. 1987; Rahmani et al. 2004). Since costs of transport and handling composts are high (Crowther 1950), most bareroot nursery managers do not add compost to the soil. Adding low rates of dolomitic lime is a more economical way to increase soil Mg in nurseries (Munson 1982).

5.3 Nitrogen

When nursery seedbeds are fertilized with ammonium fertilizers, the amount of Mg leached can increase (Wilde and Kopitke 1940; Steinbeck 1962; Deines 1973; Knight 1981; Boxman et al. 1991; Bryson and Mills 2014). When managers install unfertilized check plots, they may observe yellow-tip needles on N fertilized seedlings while slow-growing seedlings in check plots have green needles (Stoeckeler and Arneman 1960). At two nurseries in Georgia, fertilization with N reduced the level of soil Mg but pine seedlings did not become Mg-deficient because soil levels in December were still greater than 20 µg g^{-1} Mg (Figure 6).

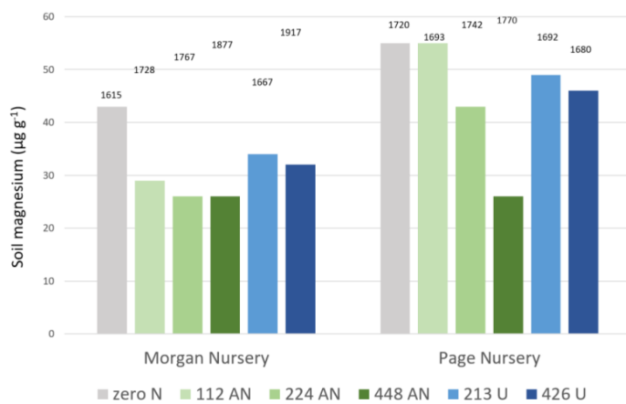

Figure 6. Nitrogen (N) fertilization increased foliar N levels and reduced the amount of soil Mg when sampled in December (Steinbeck 1962). This produced a negative relationship between soil Mg and foliar N (r= -0.296; α=0.01). The lowest N treatment (112 kg ha^{-1} of N; source was AN = ammonium nitrate) and both urea treatments (U = Uramite) were applied before sowing (April 17 - Morgan Nursery; April 12 - Page Nursery). April soil samples indicated 46 and 72 µg g^{-1} Mg for the Morgan and Page nurseries, respectively. Both rates (224 and 448 kg ha^{-1}) of N were applied using four top-dressings during the month of July. *Pinus elliottii* seedlings lifted from non-fertilized plots (zero N) had 1,615 µg g^{-1} Mg in foliage at the Morgan Nursery and 1,720 µg g^{-1} Mg at the Page Nursery. Urea fertilization resulted in "summer chlorosis" on 30 to 70 percent of seedlings from May through August. Fertilization with ammonium nitrate (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. Foliar Mg concentrations (numbers above bars) are not indicative of yellow-tip chlorosis.

At a loamy sand nursery in Wisconsin, the correlation between Mg and nitrates in the leachate was positive (r = 0.37) (Dobrahner et al. 2004). At a nursery in New Zealand, fertilizing pines with high rates of AS increased yellow-tip symptoms but lower rates sometimes reduced chlorosis and increased foliar concentrations of Ca, K, Mg (Will 1961). At one sandy nursery in South Carolina, seedlings fertilized with N in June and July exhibited yellow-tip symptoms (0.10% Mg in foliage) while foliage on slower-growing seedlings (no N applied before August) had 0.16% Mg in foliage. Perhaps the extra N increased growth and reduced Mg levels so that yellow-tip symptoms appeared (Stoeckeler and Arneman 1960). At a bareroot pine nursery with 31 µg g^{-1} extractable Mg, fertilization with N did not reduce foliar Mg and did not induce a Mg deficiency (Wall 1994).

In greenhouse trials, fertilizing sand with solutions containing ammonium and/or nitrate increased seedling growth and reduced the Mg concentration in pine needles (Steinbeck 1962; Blackmon 1969; Malavolta et al. 1970; Swan 1970; Majid 1984). For example, fertilization with solutions containing 100 µg g^{-1} N increased growth but higher N rates decreased growth and decreased foliar Mg (Figure 7). A similar effect was detected for soil ammonium in non-fertilized pine plantations in the southern United States. A survey of 41 sites detected a negative correlation (r= -0.41) between soil ammonium and foliar Mg concentration for *Pinus taeda* (NCSFNC 1991).

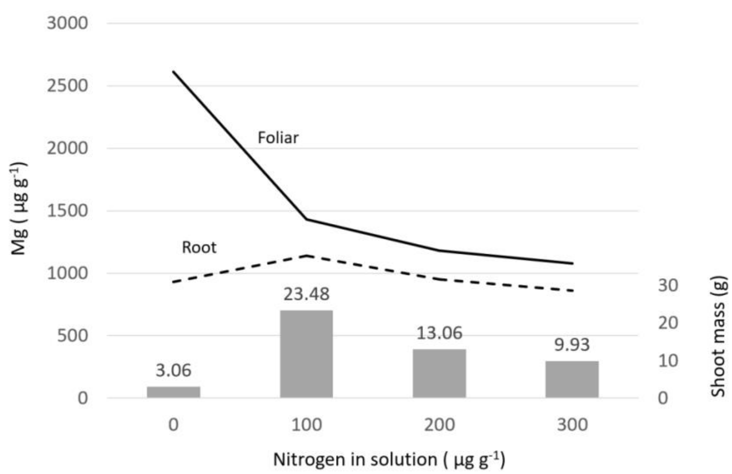

Figure 7. Seedling shoot mass (bars and numbers), and the concentration of magnesium (Mg) in *Pinus taeda* needles (solid line) and taproots (dashed line) can be affected by the amount of urea and ammonium nitrate in nutrient solutions (Blackmon 1969). Each nitrogen treatment also contained 50 µg g^{-1} of phosphorus and 50 µg g^{-1} of Mg.

5.4 Calcium

5.4.1 Gypsum

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, the rate of gypsum can be lowered (e.g. < 800 kg ha^{-1}) and an application of SPM can be applied before sowing. Likewise, increasing the amount of Mg in fertilizer solutions by just 1 µg g^{-1} could make a large difference in uptake of Mg in pine needles (Dumbroff and Michel 1967). At nurseries where gypsum treatments produced yellow-tip needles, the symptoms usually appear after mid-season and disappear before seedlings are lifted.

When gypsum (>4,100 kg ha^{-1}) was applied to nursery soils without any N fertilization, yellow-tips did not form on pine seedlings (Wahlenberg 1930; South 2021). When 2-0 *Pinus radiata* seedlings were already deficient in Mg, applying gypsum (168 kg ha^{-1}) in the spring had no effect on height growth or needle color (Will 1961). Likewise, adding gypsum to soil before sowing did not reduce growth of asymptomatic *Pinus taeda* seedlings, even with N fertilization (Table 6). Although N can lower both soil pH and soil Mg, gypsum lowers soil Mg without much effect on soil acidity (Flinn et al. 1980; Sumner et al. 1986). For example, 280 kg ha^{-1} of gypsum leaches more Mg than 224 kg ha^{-1} of AN (Figure 8).

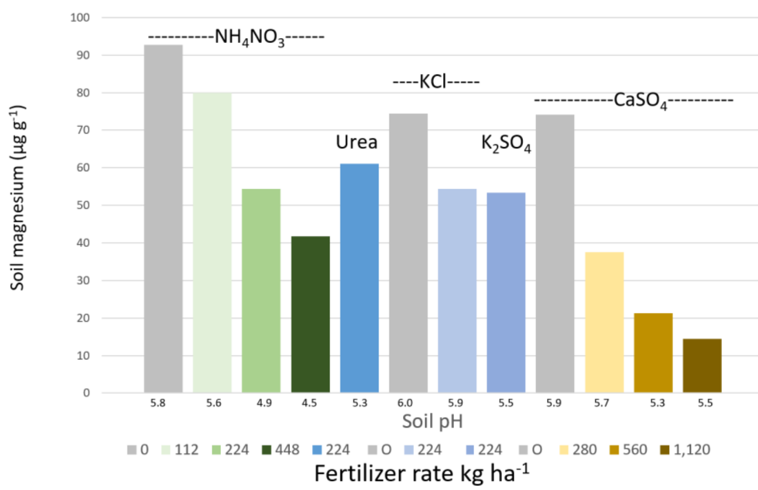

Figure 8. Fertilization with nitrogen (N), potassium (K) and calcium (Ca) reduced the amount of magnesium in a silt loam soil at the Edwards Nursery in North Carolina (Deines 1973). The K and Ca treatments below 54 µg g^{-1} Mg are significantly different from the K and Ca controls and N treatments below 70 µg g^{-1} Mg are significantly different from the N control (α=0.10).

Table 6. Growth of 1-0 bareroot *Pinus taeda* seedlings (family 1-68) growing in soil amended with pine bark, calcium sulfate (gypsum) and calcium hydroxide. Soil pH, calcium (Ca) and magnesium (Mg) were from soil samples collected in November 1986 (Marx 1990). The least significant differences (α =0.05) for height, shoot dry mass and root dry mass were 3.4 cm, 3.2 g and 0.6 g, respectively. There were no differences among treatments for soil Mg (mean = 42.5 µg g^{-1}).

$CaSO_4$	$Ca(OH)_2$	pH	Soil Ca	Ca/Mg	Height	Shoot mass	Root mass
kg ha^{-1}	kg ha^{-1}		µg g^{-1}		cm	g	g
0	0	4.9	204	5	32.5	7.4	2.0
5,300	-	5.1	592	14	-	7.6	2.1
10,600	-	5.3	1,092	25	-	7.7	2.0
-	2,850	5.8	686	16	31.0	6.4	2.1
-	5,700	6.8	1,210	28	28.1	5.1	1.9

5.4.2 Ca/Mg ratio

In this review, soil nutrient ratios are determined using parts per million ($\mu g\ g^{-1}$) and 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 $\mu g\ g^{-1}$ 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; Table 7).

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 with Ca/Mg ratios as high as 67 (Table 7). In fact, low Ca/Mg ratios in greenhouse trials showed a reduction in early root growth (Lyle and Adams 1971). 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).

Table 7. Growth of 1-0 bareroot *Pinus taeda* seedlings (family 1-68) growing in soil amended with pine bark, calcium sulfate (gypsum) and calcium hydroxide. Soil pH, calcium (Ca) and magnesium (Mg) were from soil samples collected in November 1986 (Marx 1990). The least significant differences (α =0.05) for height, shoot dry mass and root dry mass were 3.4 cm, 3.2 g and 0.6 g, respectively. There were no differences among treatments for soil Mg (mean = 42.5 $\mu g\ g^{-1}$).

Species	Nursery	State	pH	Sand	Ca	Mg	K	K/Mg	Ca/Mg	Ht	RCD	Mass	Ecto
				%	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$			cm	mm	g	#
P. taeda	Weyerhaeuser	OK	5.2	89	89	5	51	10	18	20.3	3.9	11.4	37
P. clausa	Andrews	FL	4.8	94	404	6	13	2	67	20.6	2.5	6.7	24
P. taeda	Champion	SC	5.1	88	56	7	49	7	7	21.4	4.9	12.9	20
P. taeda	Weyerhaeuser	AR	5.3	87	261	7	41	6	37	23.2	4.4	13.2	33
P. virginiana	Vallonia	IN	4.3	82	105	8	63	8	13	20.8	4.5	21.8	19
P. elliottii	Archer	FL	5.5	>85	149	8	24	3	19	23.5	5.6	**5.7**	34

5.5 Potassium

Applying 224 kg ha^{-1} of K_2SO_4 increased chlorosis of Mg deficient pine seedlings at a nursery in New Zealand (Will 1961) and high levels of exchangeable soil K (> 80 $\mu g\ g^{-1}$) have been correlated with Mg deficiency symptoms in pine plantations

(Beets et al. 2004). When too much K fertilizers are applied, the risk of a Mg deficiency increases (Boynton and Burrell 1944; Knight 1978a; South and Davey 1983; Grzebisz 2015). At the Morgan Nursery in Georgia, five applications of KCl (each at 112 kg ha^{-1}) reduced foliar Mg concentration in *Pinus taeda* to 580 µg g^{-1} (Rowan 1987). Likewise, applying K before sowing lowered soil Mg at a nursery in North Carolina (Figure 8). Although yellow-tipped pine seedlings occurred when soil K/Mg ratios were 4 (Voigt et al. 1958) and 5 (Will 1961), deficiencies were not reported when K/Mg ratios before sowing were 7, 8 or 10 (Table 7).

5.6 Irrigation water

At some nurseries, irrigation water contains enough Mg to meet needs of seedlings (Carlson 1979; Landis 1996). Applying 60 cm of irrigation (2 mg L^{-1} Mg) is equivalent to applying 120 kg ha^{-1} of MS (10% Mg). When pines were growing in sand (12 µg g^{-1} Mg) and were irrigated with water containing 2 mg L^{-1} of Mg, the concentration in needles exceeded 2,000 µg g^{-1} Mg (Steinbeck 1962). In contrast, when pine seedlings only received rainfall, foliar Mg was less than 1,000 µg g^{-1} (Benzian and Smith 1973). At some locations 1,000 mm of rainfall may provide only 1-5 kg ha^{-1} of Mg (Madgwick and Ovington 1959; Allen et al. 1968; Metson 1974; Hunter 1996).

At the Weyerhaeuser Nursery in Oklahoma, soil contained 5 µg g^{-1} Mg before sowing and harvested pine seedlings averaged 3.9 mm at the root-collar (Marx et al. 1984). If the irrigation water (60 cm) contained 5 mg L^{-1} Mg, then seedlings may have been supplied with 30 kg ha^{-1} of Mg during the growing season. About 33% of irrigation water samples from southern nurseries contain more than 4 mg L^{-1} of Mg (Figure 9). At some sandy locations, irrigating non-fertilized soil for 16 years (632 mm yr^{-1}) might increase soil Mg by 14 kg ha^{-1} (Albaugh et al. 2014).

When growing plants in greenhouses, some 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). For 27% of container nurseries surveyed, the Ca/Mg ratio was greater than 5 (Argo et al. 1997). To keep nursery soil “in balance,” Davey (2002) said managers must add Mg fertilizer when irrigation water contains >10 times more Ca than Mg. At one *Pinus taeda* nursery, irrigation water contained50 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 SPM and MS were applied over the top of seedlings in July.

5.7 Mycorrhiza

Typically, non-mycorrhizal pine seedlings take up Mg and do not become Mg-deficient. For example, slow-growing, non-mycorrhizal *Pinus taeda* seedlings exhibited P deficiency symptoms while needles contained >900 µg $g^{-1}$of Mg (South et al. 1988, 2018). Adequate foliar Mg concentrations were also observed for ectomycorrhizal and non-mycorrhizal seedlings in greenhouse tests (Cumming and Weinstein 1990; Walker and McLaughlin 1997; Zhang and George 2010). It is possible that activity of “rock-eating” ectomycorrhiza can assist in converting “unavailable” Mg to ions available to pines (van Schöll et al. 2008) but there is scant evidence this occurs in nursery soils (Metson 1974; Smits and Wallander 2017). In one pine trial, foliar Mg in needles was positively related to certain types of ectomycorrhizal fungi (Leski et al. 2010).

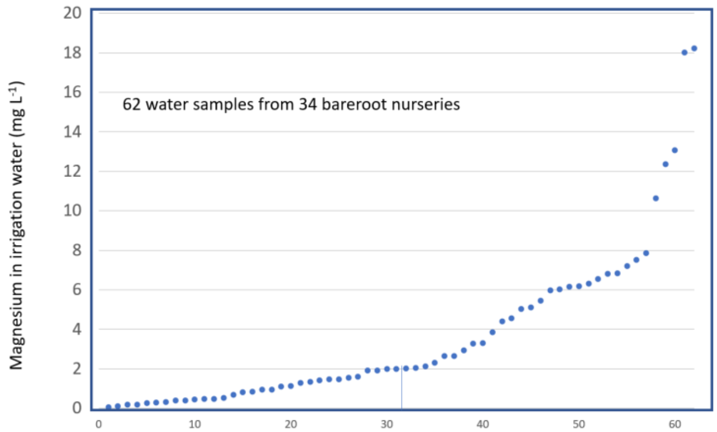

Figure 9. The amount of Mg in irrigation water from 34 nurseries ranged from 0.06 to 18 mg L^{-1} (McNabb and Heidbreder-Olson 1998). When the level of Mg in irrigation water is 1 mg L^{-1}, then 60 cm of irrigation would add approximately 6 kg ha^{-1} yr^{-1}. At four nurseries, the Ca/Mg ratio (µg) varied from 11 to 525.

5.8 Freeze tolerance

After a freeze occurred at a nursery at Inchnacardoch Scotland, conifers that received no MS were "frosted" during their first winter. Seedling injury appeared to be correlated with the degree of yellowing caused by magnesium deficiency (Aldhous and Atterson 1966). Seedlings with good color and less freeze injury received 162 kg ha^{-1} of Mg. In contrast, fertilization with MS or SPM did not increase freeze tolerance of *Pinus taeda* (Rowan 1987; Edwards et al. 1990). MS did not affect freeze tolerance of *Pinus sylvestris* growing in nutrient solutions (Christersson 1973). Likewise, MS fertilization did not seem to increase freeze tolerance of *Pseudotsuga menziesii* (Schaedle 1959).

6 Amount of Mg removed at harvest

Depending on species, cultural practices, and seedling age, a million pine seedlings may contain 4 to 14 kg of Mg (Knight 1978b; Flinn et al. 1980; Donald and Young 1982; South and Boyer 1983; Dobrahner et al. 2004). When 1.7 million pine seedlings ha^{-1} are harvested, this might remove 17 kg ha^{-1} of Mg. Likewise, harvesting a single crop of *Zea mays* grain removes about 14 kg ha^{-1} Mg (Heckman et al. 2003). To replenish some of the harvested nutrients, some managers fertilize with more than 17 kg ha^{-1} of Mg (Table 8).

The Mg 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 74 µg g^{-1} Mg in 1963 and 11 µg g^{-1} in 1980 which equates to an average decline of 3.7 µg g^{-1} yr^{-1}. In one year, soil Mg levels decreased 18 µg g^{-1} in Alabama (May 1957), 11 µg g^{-1} in Georgia (Marx 1990), 25 µg g^{-1} in Michigan (Koll 2009) and 7 µg g^{-1} in North Carolina (Danielson 1966). At one area of the Westvaco

Nursery in South Carolina, rainfall and N-fertilization of cover-crops resulted in a loss of 30 µg g^{-1} Mg from 1983 to 1984 (Figure 10).

Table8. Examples of operational applications of magnesium sulfate (MS), sulfate potash magnesium (SPM), and dolomitic limestone (DOL) at bareroot nurseries.

Nursery	Location	Source	Mg kg ha^{-1}	Reference
Before	**Sowing**			
Magnolia	Arkansas	MS	11	Marx et al. 1984
Toumey	Michigan	MS	11	Koll 2009
Orono	Canada	MS	11	Bunting 1980
Benalla	Australia	MS	18	Hopmans and Flinn 1983
Cracow	Poland	MS	20	Januszek et al. 2014
Ironhill	England	MS	34	Thomas and Jackson 1983
Coillte	Ireland	MS	37	Morrissey and O'Reilly 2002
Rotorua	New Zealand	MS	42	Knight 1981
Headley	England	MS	120	Moffat 1994
Rochester	Washington	SPM	31	Wang and Zabowski 1998
Andrews	Florida	SPM	37	Berry 1980
Archer	Florida	SPM	37	Irwin et al. 1998
Lee	Florida	SPM	37	Leach and Gresham 1983
Archer	Florida	SPM	43	Van Rees et al. 1990
Beauregard	Louisiana	SPM	49	Marx et al. 1984
Surry	Canada	SPM	49	Donald 1991
Bessey	Nebraska	SPM	50	Schmidt 1991
Andrews	Florida	SPM	62	Rodríguez-Trejo and Duryea 2003
Westvaco	South Carolina	DOL	123	Marx et al. 1984
After	**sowing**			
Milton	New Zealand	MS	6	Stockley 1969
SCS	Michigan	MS	2+2+2	Marx et al. 1984
Benalla	Australia	MS	5+4+4+4+5	Hopmans and Flinn 1983
Wilson	Wisconsin	MS	13+13	Dobrahner et al. 2004
Ashe	Mississippi	MS	170	Maki and Henry 1951 – research trial
Toumey	Michigan	SPM	10	Koll 2009
Nepco lake	Wisconsin	SPM	31	Marx et al. 1984
Flint River	Georgia	SPM	35	VanderSchaaf and McNabb 2004
Surry	Canada	SPM	35	Donald 1991
Andrews	Florida	SPM	25+18	Rodríguez-Trejo and Duryea 2003
Andrews	Florida	SPM	15-14-15	Berry 1980
Archer	Florida	SPM	30+30	Irwin et al. 1998
Bessey	Nebraska	SPM	25+25+25	Schmidt 1991
Kaingaroa	New Zealand	DOL	18	Will 1961 – research trial
Griffith	North Carolina	DOL	36	Hinesley and Maki 1980

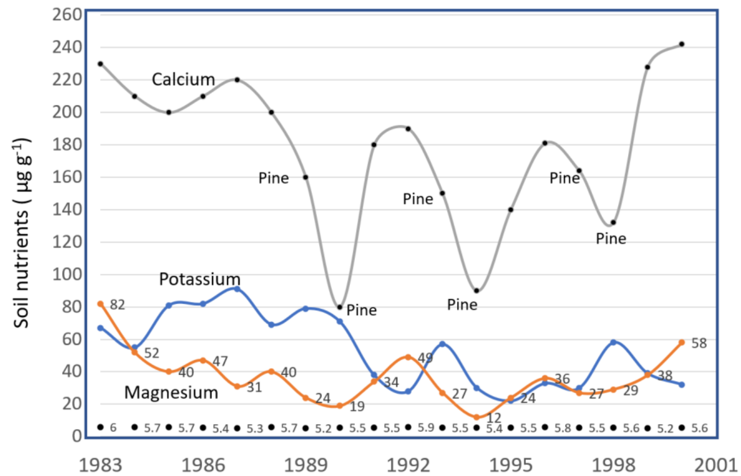

Figure 10. Trends in November-extracted soil cations (Mehlich 1) at a bareroot nursery in South Carolina. Field B-1 was managed with cover-crops from 1983 to early 1989. *Pinus taeda* seed were sown in April of 1989, 1990, 1993, 1994, 1997 and 1998. Soil pHvalues adjacent to dots represent soil acidity 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}). Magnesium sulfate and sulfate-potassium-magnesium were not applied over the top of seedlings.

7 Deficiency

Symptoms of Mg deficiency have occurred on fertilized pine seedlings at long-established nurseries in Australia, England, Germany, New Zealand, Sweden and the United States. In 1959, most bareroot nurseries in norther Sweden were producing seedlings with Mg deficiency symptoms (Ingestad 1960). The “yellow-tip” symptoms (e.g., Figure 11) typically occur between the summer solstice and a month after the autumn equinox (Benzian 1959). Soils prone to producing a visible deficiency include sands and loamy sands that have a low pH and low soil organic matter. Fertilization with Mg improved needle color of Mg deficient pines without increasing height or diameter growth. Likewise, when seedlings are chlorotic due to a deficiency in S (Leaf 1968; Lyle and Pearce 1968; Bolton and Benzian 1970), applying MS could improve needle color. However, when chlorosis is due to a Mn toxicity, fertilizing pine seedlings with Mg will not make needles green (Voigt et al. 1958).

Without yellow-tip symptoms and with no growth response to Mg fertilizers, a low soil test does not mean seedlings are Mg-deficient. A foliar test is more reliable than a soil extraction method that can underestimate the amount of available Mg. Even so, some authors say a soil is “deficient” when soil tests are below 150 µg g^{-1} Mg (Table 3). Except for a few nursery trials (Will 1961; Will and Knight 1968; Wall 1994), the minimum values listed in Table 3 were not derived experimentally. In fact, when there is adequate Mg in irrigation water, good seedling growth can occur when soil contains less than 9 µg g^{-1} Mg (Mehlich 1) (Table 6).

Figure 11. *Pinus taeda* seedlings (August 9, 2019) showing signs of Mg deficiency (foliage at 1,000 µg g^{-1} Mg) in a bareroot nursery in South Carolina (pH = 5.7; 22 milliequivalents of cations kg^{-1}; 1.4 µg g^{-1} Mg in irrigation water). Soil ratios at this location were 0.6 for K/Mg and 11 for Ca/K [24 µg g^{-1} Mg, 14 µg g^{-1} K and 263 µg g^{-1} Ca, Mehlich 3]. Older needles had chlorotic tips while new needles at the shoot tip showed no chlorosis. Slow-growing seedlings (in a nearby under-fertilized check plots) had no visible symptoms of a Mg deficiency and needles contained 0.16% Mg. The chlorotic tips on the needles turned green two weeks after this photo was taken. A similar deficiency occurred at a nursery in Virginia in 2021 where yellow tips were observed on August 16, 2021 (foliage 0.07% Mg) but symptoms disappeared by August 24.

7.1 Visible symptoms

Chlorosis on the tips of pine needles is the clue that allows Mg deficiencies to be easily diagnosed (Leaf 1968). The chlorosis on older needle tips occurs when Mg is translocated from these needles to the newly developing needles near the top of the seedlings.

Yellow-tip symptoms appeared on conifers at two Wisconsin nurseries in 1948 (Voigt et al. 1958). According to the authors, the “stock in certain sections of the nurseries showed marked discoloration. The symptoms appeared in July or August when the outer portion of the needles exhibited a bright yellow to gold color; the portion of the needle nearest the sheath retained the normal green color. In severe cases, however, nearly the entire needle turned yellow. The yellowing was most pronounced in beds where the soil reaction was pH 4.5 or below.” The chlorotic needles of *Pinus banksiana* contained 600 µg g^{-1}Mg and the soil (pH 4.1) contained 7.5 µg g^{-1} Mg (Voigt et al. 1958). Green seedlings in pH 5.1 soil had 1,800 µg g^{-1}Mg in foliage. Completely yellow seedlings were likely affected by Mn toxicity due to acid soil (< pH 4.2) and too much rain resulting in waterlogging of seedbeds (Slaton and Iyer 1974). This would explain why potted seedlings recovered when treated with dolomite (1,120 kg ha^{-1}) but remained chlorotic and stunted when treated with magnesium nitrate (1,120 kg ha^{-1}) or 224 kg ha^{-1} of magnesium oxide (Voigt et al. 1958).

At some nurseries, yellow-tips symptoms are ephemeral and are gone by the fall equinox. For this reason, some managers were not aware of the deficiency since foliage in August was not analyzed and seedlings in November appeared normal. The reason needles recover by late September maybe due to a reduction in N and K fertilization combined with a reduction in growth rate. At one nursery in North Carolina, seedlings lifted in February had foliage with 630 µg g^{-1}Mg (Danielson 1966) and at the Ashe Nursery (Mississippi), seedlings lifted in November in had 435 µg g^{-1}Mg (Bryson 1980).

7.2 Hidden hunger

A hidden hunger exists when there are no yellow-tip symptoms but growth is increased when seedlings are fertilized with Mg. Although Mg fertilization will sometimes increase growth in pine plantations (Stone 1953; Olykan et al. 2001), examples of increased growth from MS fertilization of asymptomatic bareroot pine seedlings are rare (Table 1). Very low Mg levels will stunt growth of pine seedlings in hydroponics (Hauer-Jákli and Tränkner 2019), in containers (Will and Knight 1968) and in nurseries (Will 1961), but transitory yellow-tip symptoms may not slow growth.

To demonstrate a true hidden hunger, researchers develop growth response curves under controlled conditions (Figure 12). However, various tests conducted on asymptomatic conifer seedlings do not show a significant height growth response from fertilizing with Mg (Auten 1945; Schaedle 1959; Benzian 1965; van den Driessche 1963; Rowan 1987; Wall 1994). Perhaps soil at these nurseries contained a sufficient level of Mg (Figure 13) or perhaps irrigation supplied sufficient amounts of Mg to seedlings. It is also possible that some fertilizers contained 1 to 3% Mg and growers may have unknowingly applied 2 to 6 kg ha^{-1} of Mg to seedlings (Munson 1982; Bailey et al. 2000).

At several nurseries, pines grew well when extractable soil Mg was less than 9 µg g^{-1} (Table 7). In greenhouse trials, fertilization with MS did not increase height growth of asymptomatic pine seedlings growing in soil with either 2.9 (Rowan 1971), 5.5 (Manikam and Sirvastava 1980) or 15 µg g^{-1} Mg (Cotton 1964). In another trial, fertilization with Mg (source not reported) increased growth of *Pinus radiata* (Will and Knight 1968). For *Pinus palustris*, treating seedlings with 1,568 kg ha^{-1} of $MgSO_4 \bullet 7H_2O$ at the Ashe Nursery might have increased green mass by 16 to 21% (Maki and Henry 1951).

In general, outplanting performance is not related to the Mg content of bareroot seedlings at time of lifting (Zarger 1964; Madgwick 1975; Baer 1984; Larsen et al. 1988; van den Driessche 1991). Although there are exceptions (e.g. Will and Knight 1968), most soils at field sites have adequate Mg and uptake begins either before or soon after new roots start to grow (Baer 1984; Kelly and Barber 1991). Bareroot *Pinus echinata* needles with 435 µg g^{-1} Mg (at planting in March) had twice that level eight months later (Bryson 1980).

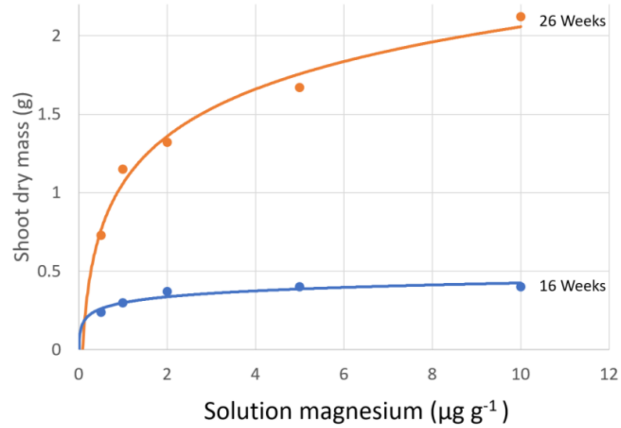

Figure 12. The effect of a magnesium fertilizer (source not reported) on the growth of *Pinus banksiana* seedlings growing in sand in a greenhouse (Swan 1970). At age 16 weeks, yellow-tipped needles were noted at zero and 0.5 µg g^{-1} treatments but chlorosis did not occur at higher solution concentrations. The hidden hunger zone may have ranged from 1 to 5 µg g^{-1} Mg-solutionfor the 16-week-old seedlings.

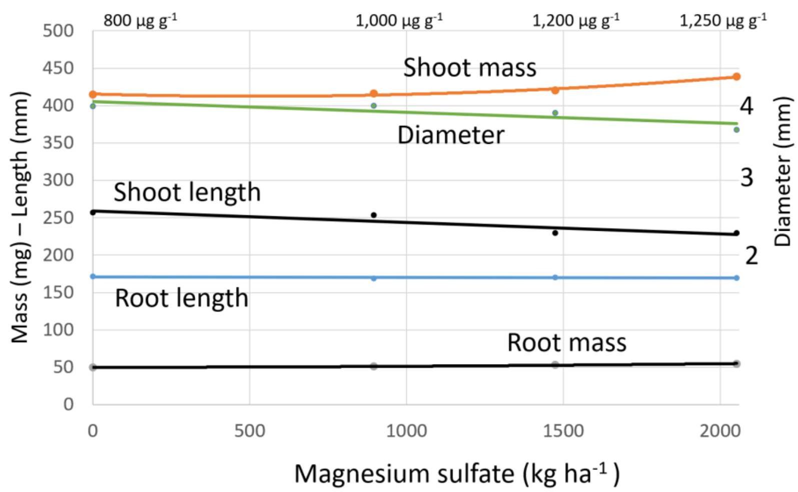

Figure 13. The effect of magnesium (Mg) sulfate on growth and foliar Mg concentration of *Pinus taeda* seedlings at a nursery in Texas (Wall 1994). Before sowing, soil contained 31 µg g^{-1} Mg. Beginning six weeks after sowing, applications of Epsom salts ($MgSO_4 \bullet 7H_2O$) were made every three weeks for a total of five applications. Mg treatments had no significant effect on shoot or root mass, root-collar diameter, shoot or root length ($\alpha = 0.05$). Foliar Mg at lifting in January 1989 (indicated at the top of the graph) was increased by top-dressings greater than 1,000 kg ha^{-1}.

8 Toxicity

In 1618, a farmer at Epsom England noticed that although his cows would not drink water from his well, the Epsom salts in the water seemed to heal scratches and rashes (Classen et al. 2004). Although little scientific evidence supports a "detoxifying effect" from water that contains Epsom salts (Deshmukh and Ray 2019), some people continue to take baths containing MS. Even so, nursery applicators should take precautions when handing MS. Since MS is a strong purgative, workers should minimize inhalation and ingestion while preparing fertilizer solutions (Davey and McNabb 2019).

Regarding nursery stock, Wilde (1946; p 86) said "Magnesium salts in excess produce harmful effects." It is true that too many Cl ions can kill pine seedlings (Sucoff 1962; Franklin et al. 2002; Goodrich and Jacobi 2012) but damage caused by high rates of MgCl doesn't prove that high rates of Mg will harm pine seedlings. Greenhouse trials (Howell 1932; Sucoff 1962; Miller and Cumming 2000) and observations with nursery-grown conifers undermine the "harmful effects" assumption. Apparently, Wilde (1946) was referring to white alkaline soils (pH 8 to 9) that contain "chlorides of sodium, magnesium, and potassium, as well as calcium chloride" (Engstrom and Stoeckeler 1941; p. 45). Pines seem to be relatively tolerant of chloride-free Mg fertilizers.

Na and Cl are toxic to pine seedlings and the upper limits for irrigation water might be 69 µg g^{-1} for Na and 71 µg g^{-1} for Cl (Bailey et al. 1999). Even though Mg is less toxic than Na, some suggest the upper limit for Mg is less than 69 µg g^{-1} (Landis et al. 1989; Argo et al. 1997). Although the maximum limit for Mg is not known, one nursery in California irrigated with water that contained 113 µg g^{-1} Mg (Landis et al. 2009).

The consequences of irrigating sandy nursery soils with water containing more than 50 µg g^{-1} Mg is not clear since most irrigation water contains less than 40 µg g^{-1} Mg (Argo et al. 1997; Figure 9). Pine seedlings in fertilizer trials were not injured when they were fertilized using solutions that contain more than 70 µg g^{-1} Mg (Giertych and Farrar 1961; Schomaker 1969; Brix and van den Driessche 1974). Perhaps the true concern is with a buildup of $MgCO_3$ in soil, and not with Mg, per se. Applying too much $MgCO_3$ will increase soil pH (Pierce et al. 1999) and too much dolomite can reduce growth of pine seedlings (Wall 1978).

A single top-dressing of MS (170 kg ha^{-1} of Mg) did not harm *Pinus palustris* seedlings (Maki and Henry 1951) and 210 kg ha^{-1} of Mg (applied as MAP before sowing) did not harm *Pinus taeda* seedlings (Zarger 1964). Some believe it is safe to apply more than 270 kg ha^{-1} of Mg before sowing pine (White et al. 1980; Bueno 1991). Several fields at the Syracuse Nursery produce seedlings when soil contains more than 200 µg g^{-1}Mg (Bueno 1991) and in one greenhouse study, high soil Mg (1,198 µg g^{-1}) did not harm pine seedlings (Hart et al. 1980). However, adding 1.5 kg of MS m^{-3} to a bark-peat moss mix (e.g., 1,500 kg ha^{-1} at a soil depth of 10 cm) reduced height growth of transplanted pines by 3% to 8% (Mason et al. 1995).

Although a few authors say pine needles with Mg levels greater than 1,600 µg g^{-1} is above the "acceptable range" and "extreme" (Mellert and Göttlein 2012) this belief is not supported by the literature (Sucoff 1962; Schomaker 1969; Maxwell 1988; Landis et al. 1989). Foliar values of 2,200 µg g^{-1} Mg were not toxic to *Pinus caribaea* (Hart et al. 1980), *Pinus elliottii* (Steinbeck 1962*), Pinus banksiana* (Swan 1970), *Pinus ponderosa* (Baer 1984), *Pinus strobus* (Iyer 1965; Schomaker 1969), *Pinus taeda* (Boyer and South 1985), *Pinus virginiana* (Sucoff 1962) or *Pinus contorta* (Goodrich and Jacobi 2012). In fact, growth of some pines was not reduced even when foliar concentrations reached 3,700 ug g^{-1} Mg (Goodrich and Jacobi 2012). There are no data to suggest seedlings with luxury consumption of Mg are not acceptable and should be culled before outplanting.

Researchers did not report any injury when applying either SPM (Rowan 1987) or MAP to seed (Bridger et al. 1962) or seedbeds (Benzian 1967; Bean 1965; Zarger

1964; Knight 1978; Menzies et al. 2001). When applied just prior to sowing, $MgCO_3$ might increase soil pH which could increase damping-off. For example, a pre-sowing application of 1,120 kg ha^{-1} of $MgCO_3$ reduced seedbed densities of *Pseudotsuga* by 19 to 29% (van den Driessche 1963). However, when applied one month before sowing, even 3,360 kg ha^{-1} of $MgCO_3$ did not affect seedling growth of *Pseudotsuga* (van den Driessche 1963). This casts doubt on the belief that high levels of $MgCO_3$ are toxic to pines (Wilde 1946).

Although $MgCl_2$ can certainly produce harmful effects to seedlings, this does not mean all Mg salts cause injury (Devitt et al. 2005). In fact, adding $MgSO_4$ can increase survival of pines treated with solutions containing 1,367 µg g^{-1} of Cl (Sucoff 1962). Instead of decreasing growth, adding $MgSO_4$ to $CaCl_2$ solutions increased height growth (Figure 14).

Although it is possible 672 kg ha^{-1} of MS (just prior to sowing?) reduced germination of *Pinus echinata* by 17% (Auten 1945), this non-significant (LSD_{05} = 47%) reduction might have been due to unrelated damping-off resulting in unusually high random variation.

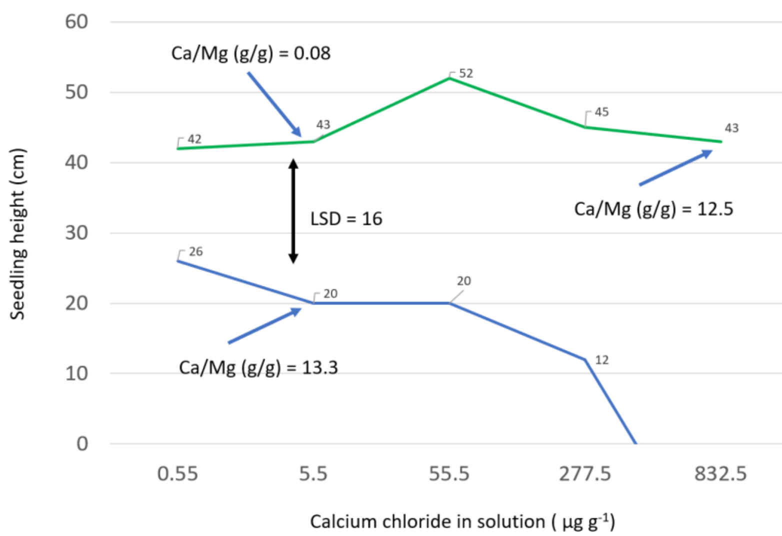

Figure 14. When availability of magnesium (Mg) is low (blue line = 0.15 µg g^{-1} Mg in solution), adding additional chloride to nutrient solutions reduces height growth of *Pinus virginiana* and too much chloride killed seedlings(Sucoff 1962). Adding additional $MgSO_4$ (green line – 24 µg g^{-1} Mg) reduced injury from calcium chloride. Heights are the average of four seedlings except for the container where all seedlings died (high calcium + low Mg). LSD_{05} is estimated using results from a Duncan's multiple range test.

9 Costs

Fertilizer costs vary by region, shipping distance, year, and distributor. Cost comparisons, therefore, will vary over time and region. To keep Mg costs low, bareroot nursery managers in the United States typically fertilize with dolomitic limestone or SPM. When liming to increase soil pH, managers usually choose dolomitic limestone, since it is a cost-effective way to increase Mg. Assuming minimal benefit from Ca, a kg of Mg might cost \$0.30 for regular dolomite (ag grade) or \$3.00 for pelletized dolomite. In contrast, Mg in some of the low-concentration products (Table 9) may cost more than \$100 kg^{-1} of Mg.

At the Kaingaroa Nursery, applying a top-dressing of dolomite (168 kg ha^{-1}) to yellow-tipped *Pinus radiata* seedlings improved seedling color (Will 1961) but the chlorosis was eliminated in plots treated with, more soluble, MS. When dolomitic lime is incorporated about a year before sowing pines, a rate of 1,000 kg ha^{-1} will initially add about 110 kg ha^{-1} of Mg.

Table 9. A partial list of magnesium (Mg) fertilizers. soluble (So): granules (G): liquids (L).

Ingredients	% Mg	Tradename	Form	% Mg	% S	% N
magnesium oxide + magnesium sulfate	50-55	ProMag®	G	36	6	
magnesium oxysulfate	36	Magnesium 36%	G	36	6	
magnesium sulfate	18	Southern Ag®	So	15	16	
magnesium ammonium phosphate	15	MagAmp	G	15		7
magnesium – chelate glycine	3-12	Biomin®	So	12		5.5
dolomitic limestone	8-20	Pro-Select	G	11.3	0.3	
kieserite $MgSO_4{\cdot}H_2O$	17	Amgrow-kieserite	G	15	16	
potassium magnesium sulfate	12	K-Mag® 0-0-22	G	10-11	21-22	
magnesium nitrate hexahydrate	10	Magnisal™	So	9.6		11
magnesium sulfate $MgSO_4{\cdot}7H_2O$	10	Hi-yield®	So	9.5	12.5	
magnesium sulfate $MgSO_4{\cdot}7H_2O$	10	Brant®	So	9.5	12.9	
magnesium – EDTA chelate	3-12	Axilo™	So	6		
magnesium chloride	25	NutriMag™	L	5.5		5
magnesium nitrate	10	Manni-Plex™ Mg	L	5		7
magnesium thiosulfate	24	MagThio®	L	4	10	
magnesium sulfate	10	Biomin®	L	3	3.9	1
magnesium acetate + KMg thiosulfate	3	Nutra -Boost®	L	3	6	
kainit $KMgSO_4Cl{\cdot}3H_2O$	13	Magnesia-Kainit®	G	2	3	
K, S, Mg, Fe, B, Mn, Zn, Ca, P	1-3	Wood ash	-	2	0.4	
K, S, Mg, Fe, B, Mn, Zn	1	MaxiGreenII®	L	1	2	

SPM has been be applied at 300 kg ha^{-1} before sowing or four months after sowing. Assuming other nutrients in SPM have no value, the cost kg^{-1} for Mg might be \$4.50 for SPM and \$6.00 for MS. The total amount of Mg applied to a 1-0 crop of pine seedlings can vary from 10 to 40 kg ha^{-1} (Table 8). For pine plantations, some managers might apply 28 kg ha of Mg when foliar Mg drops below 600 to 800 µg g^{-1}(Jokela et al. 2004).

When seedlings are green, many managers do not apply MS fertilizers (van den Driessche 1984; Donald 1991). If yellow-tip symptoms occur in the summer, treatments like MS or Mg nitrate may be been applied over the top of pine seedlings. In some cases, the color improves within 10 days of treatment.

10 Conclusions

Due to faulty logic and a lack of Mg research, several myths have spread throughout the nursery literature. Likewise, several of the conclusions listed below should be tested using trials in bareroot seedbeds.

(1) When irrigation provides more than 18 kg ha^{-1} of Mg, there is no need to fertilize 1-0 bareroot pine seedlings with extra Mg. [Note: When irrigation water

contains 3 µg g^{-1} Mg, then 600 mm of irrigation will supply 18 kg ha^{-1} of Mg].

(2) When there is less than 3 µg g^{-1} Mg in irrigation water, applying too much N or too much gypsum can induce a Mg deficiency in pine seedlings.

(3) At most bareroot nurseries, there is no need to apply MSbefore sowing pines since soluble Mg will leach with rainfall and irrigation. When needed, longer-lasting Mg sources can be applied before sowing seed.

(4) The belief that 51 µg g^{-1} Mg in irrigation water will harm pine seedlings growing in sandy soil is not based on science. However, 177 µg g^{-1} of $MgCO_3$ in irrigation water can increase soil pH, which will likely reduce growth of pines.

(5) Use of foliar tests (e.g. in August) might reduce routine use of MS at some bareroot nurseries and might increase use at other nurseries. Without foliar tests, some bareroot pine seedlings have been planted with foliage that contained less than 7 µg g^{-1} Mg.

(6) There are no data to suggest that 1-0 bareroot pine seedlings need to be fertilized with more than 20 kg ha^{-1} of Mg.

(7) If the soil Ca/Mg ratio is greater than 10 and irrigation water contains less than 2 µg g^{-1} Mg, then pine seedlings might develop yellow-tip symptoms in the summer. These symptoms may disappear when N fertilization ceases and root growth increases (after the autumnal equinox).

(8) The belief that 1,600 µg g^{-1} Mg in pine needles is outside the "adequate range" (and is harmful to bareroot pine seedlings) is an opinion that is based on faulty logic.

(9) When a foliar spray of magnesium chloride turns "yellow-tip" seedlings green, the seedlings were Mg deficient. Likewise, when deficient seedlings turn green after treatment with sulfate (H_2SO_4), the seedlings were S deficient. When a foliar spray of MS turns seedlings green, then a foliar analysis would help determine which nutrient (Mg or S) was deficient.

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