Manganese Fertilization in Bareroot Pine Nurseries

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Abstract

Manganese (Mn) deficiencies in bareroot pine seedlings are rare when nursery soil is below pH 6.5, but they can occur when soil pH is above 6.5 and calcium (Ca) is above 6,000 ppm. Growth can be reduced when needles contain less than 20 ppm Mn. A simple way to avoid a Mn deficiency is to not sow pine on calcareous soils. When avoiding calcareous soils is not possible, treating seedlings with $MnSO_4$ (manganese sulfate) might prevent development of visual symptoms. Use of Mn fertilization in bareroot pine nurseries is currently infrequent because soils typically provide sufficient Mn to seedlings, and several nurseries located on calcareous soils have ceased operation. Mn toxicity does not occur at nurseries with low cation exchange capacity, but when soil Mn is greater than 300 ppm, low soil oxygen (especially after extended rainfall) may increase soil Mn to toxic levels. To avoid Mn toxicity, managers can sow seed on sandy soils with Mn levels below 200 ppm and apply lime to keep soil above pH 5.0. This article gives an overview of publications and observations regarding the use of Mn in bareroot pine nurseries and associated products, challenges, and misconceptions.

Introduction

Manganese (Mn) is a commonly applied micronutrient in the United States, and its use on agronomic crops can exceed 15,000 tonnes annually (Mortvedt 1991). In Australia, about 32 tonnes of Mn were applied to *Eucalyptus* plantations in 2003 (May et al. 2009). In comparison, reforestation nurseries in the United States likely purchased less than 300 kg total of Mn in 2020. Although fertilizers are generally not applied to seedlings at many container nurseries in developing countries (Hubbel et al. 2018), Mn fertilizer is typically added to potting media in developed countries (Donald 1991, Landis et al. 1989). Assuming 0.15 mg/container, the total amount of Mn used to grow 320 million container seedlings (Haase et al. 2021) might be 50 kg. For bareroot pines, less than 250 kg of Mn might be applied to grow 893 million seedlings.

At many bareroot nurseries, $MnSO_4$ is not applied (Donald 1991, van den Driessche 1984) because the soil contains enough Mn to keep foliage above 40 ppm (table 1). For example, a sandy soil with 4 ppm Mn can grow pine seedlings with 500 to 700 ppm Mn in foliage (van Lear and Smith 1972) (figure 1). When soil Mn drops below 5 ppm, $MnSO_4$ may be applied before sowing (Davey 1991, South and Davey 1983), or it may be applied to hardwood seedlings after leaves become chlorotic (Altland 2006). Although Mn deficiency symptoms can be relatively easy to identify for some angiosperms, symptoms might be overlooked on pine seedlings growing in calcareous soils since iron (Fe) and Mn deficiencies appear similar (Alejandro et al. 2020, Stone 1968).

Details about the role of Mn in plants and the role of soil pH in Mn solubility have been reviewed previously (Alejandro et al. 2020, Broadley et al. 2012, Eaton 2015, Landis 1998, Mortvedt 1991). Mn moves to the top of trees in the xylem, but movement in the phloem is limited (Ducic and Polle 2005, Kluthcouski and Nelson 1979, Loneragan 1988). Despite the importance of Mn for photosynthesis (Safford 1975), there are only a few published trials where Mn was tested in bareroot pine nurseries. Due to a lack of research, several misconceptions regarding Mn have emerged. For this reason, a literature review was undertaken for this article to establish what is known about Mn fertilization practices in bareroot pine nurseries. Although many questions remain unanswered, a summary of some practical information and observations are provided.

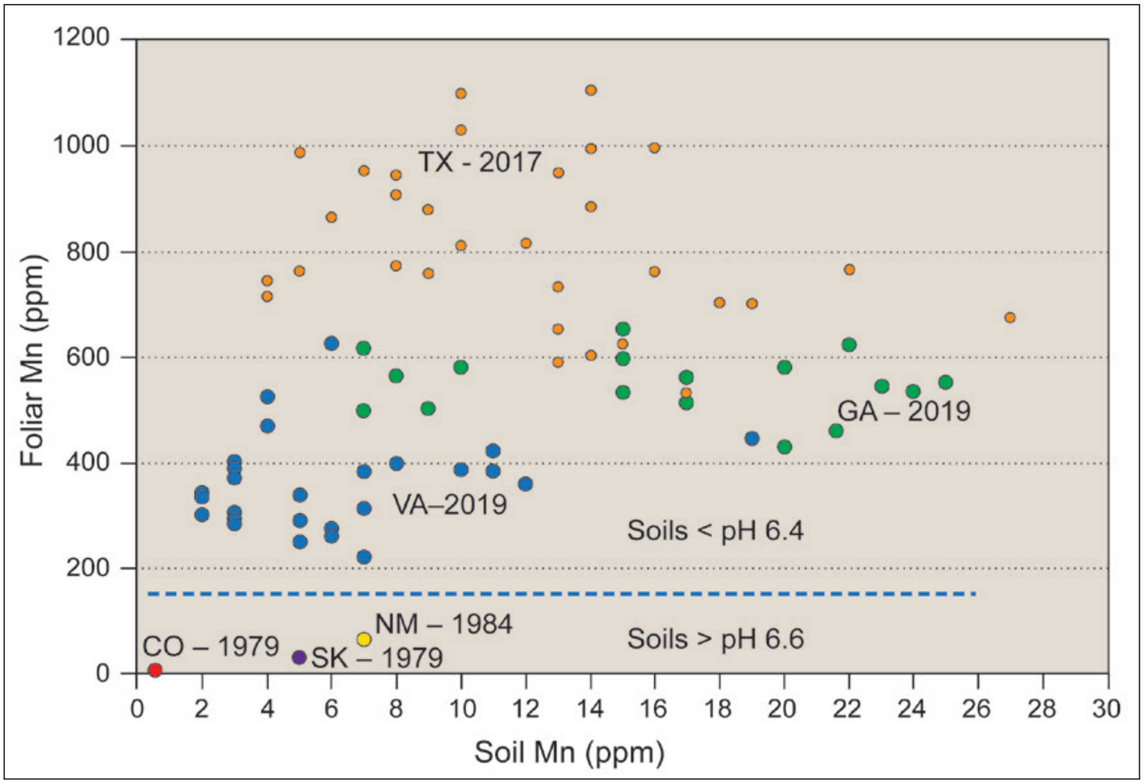


Figure 1. Foliar Mn values varied for bareroot pine seedlings sampled from nurseries in Colorado (CO), Georgia (GA), New Mexico (NM), Texas (TX), Saskatchewan (SK), and Virginia (VA). Soils sampled after 2016 were extracted using the Mehlich 3 procedure. Nursery soils with pH > 6.6 (CO, NM, SK) had foliar values less than 70 ppm Mn, while more acid soils had foliar concentrations greater than 200 ppm Mn (GA, TX, VA). Data points obtained from personal files and from publications by Carter (1980), Landis (1988), Mexal and Fisher (1987), Solan et al. (1979), and South et al. (2017).

[Abbreviations: AN = ammonium nitrate. B = boron. Ca = calcium. CEC = cation exchange capacity. Cl = chlorine. Cu = copper. EDTA = ethylenediaminetetraacetic acid. DTPA = Diethylenetriamine pentaacetic acid. Fe = iron. HCL = hydrogen chloride. K = potassium. LSD_{05} = Least significant difference. Mg = magnesium. Mn = manganese. $MnCl_2$ = manganese chloride. MnO = manganese oxide. $MnSO_4$ = manganese sulfate +1 H_2O. N = nitrogen. Na_2HPO_4 = sodium phosphate. P = phosphorus. ppm = parts per million. Pt = *Pisolithus tinctorius*. r = Pearson's correlation coefficient. S = sulfur. TSP = triple superphosphate. Tt = *Thelephora terrestris*. Zn = zinc. Except where noted, soil pH was measured in water. See table 1 for species scientific names.]

Manganese in Soils

Mn availability in bareroot nurseries is determined mainly by soil pH. In general, Mn deficiencies occur in basic soils while a few very acid soils (pH<5) may produce toxic levels during periods of low soil oxygen. When growing in calcareous soils, stunted pine seedlings may have low foliar Mn (< 10 ppm) which is a diagnostic deficiency symptom (Horak 2008, Landis 1988, Ruiter 1983, Will 1990). Although Mn is plentiful in basic soils (unavailable plus extractable), the oxidized forms are biologically inactive (Altland 2006). In acid soils, however, Mn typically occurs as Mn^{++} and, therefore, foliar values below 100 ppm Mn are rare when soil pH is below 6.5 (figure 1). Even so, some acid soils (pH 3.9) may contain 0.1 ppm Mn (Mehlich 3) (Vogel and Jokela 2011).

Various soil factors influence the amount of extractable Mn. In low CEC soils, rainfall can lower extractable Mn, but in fine textured soil, saturated conditions can increase Mn levels. Since available Mn is positively related to the proportion of silt and clay in nursery soils (South and Davey 1983), a deficiency is unlikely in acid soils with less than 85 percent sand. Even in soils with less than 0.5 ppm Mn (Mehlich 3), foliar levels in needles can be >130 ppm Mn (Vogel and Jokela 2011). Mahler (2004) stated that Mn deficiencies do not occur in acid soils. Although organic matter can reduce leaching of cations, soil organic matter may be negatively correlated with soil Mn (r = -0.35; r = -0.40; r = -0.16; NCSFNC 1991, Smiley et al. 1986, South et al. 2018, respectively). Adding 67,000 kg/ha of peat to a nursery soil might temporarily increase soil Mn by 3 to 5 ppm (McGrath et al. 1988, Mexal and Fisher 1987, Munson 1982). When sandy soils with low CEC are limed, the uptake of Mn by pine seedlings declines (Marx 1990) (figure 2).

Table 1. Scientific and common names of selected species and the reported range of foliar manganese (Mn). Seedlings were grown in soil except for one hydroponic study included as a comparison (Goslin 1959).

Species	Common Name	Mean (ppm)	Min (ppm)	Max (ppm)	Reference
Bareroot nurseries					
Acer rubrum L.	Red maple	--	70	285	Altland 2006
Picea abies (L.) Karst.	Norway spruce	50	28	1,986	Benzian and Smith 1973
Pinus banksiana Lamb.	Jack pine	414	350	495	Iyer et al. 1971
P. contorta Douglas ex Loudon	Lodgepole pine	284	80	703	Landis 1976
P. echinate Mill.	Shortleaf pine	412	60	560	Bryson 1980
P. elliottii Engelm.	Slash pine	224	95	486	Munson 1982
P. nigra Melville	Corsican pine	56	--	--	Benzian and Smith 1973
P. ponderosa Lawson & C. Lawson	Ponderosa pine	110	50	600	Baer 1984
P. ponderosa Lawson & C. Lawson	Ponderosa pine	13	6	20	Landis 1988
P. radiata D. Don	Monterey pine	188	70	350	Flinn et al. 1980
P. radiata D. Don	Monterey pine	176	32	487	Knight 1978
P. radiata D. Don	Monterey pine	437	100	1,500	Hopmans and Flinn 1983
P. radiata D. Don	Monterey pine	100	38	216	Richardson and Perkins 1985
P. resinosa Aiton	Red pine	182	102	268	Iyer et al. 1971
P. resinosa Aiton	Red pine	339	295	371	Iyer and Wilde 1974
P. strobus L.	Eastern white pine	157	92	255	Iyer et al. 2002
P. sylvestris L.	Scots pine	558	322	901	Raitio 1983
P. sylvestris L.	Scots pine	369	45	735	Januszek et al. 2014
P. taeda L.	Loblolly pine	308	196	404	Danielson 1966
P. taeda L.	Loblolly pine	518	85	1,350	Boyer and South 1985
P. taeda L.	Loblolly pine	486	135	1,677	Starkey and Enebak 2012
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir	523	250	860	Krueger 1967
Greenhouse nurseries					
Pinus caribaea Morelet	Caribbean pine	480	350	703	Hart and Widdowson 1981
P. elliottii Engelm.	Slash pine	595	184	2,950	Van Lear and Smith 1972
P. occidentalis Swartz	Hispaniola pine	347	54	1,138	Hubbel 2015
P. ponderosa Lawson & C. Lawson	Ponderosa pine	192	66	374	Majid 1984
P. sylvestris L.	Scots pine	667	88	1,604	Goslin 1959
Field sites					
Pinus elliottii Engelm.	Slash pine	296	251	315	Vogel and Jokela 2011
P. elliottii Engelm.	Slash pine	76	21	284	Grey 1988
P. patula Schiede ex Schltdl. & Cham.	Mexican weeping pine	1,308	276	2,790	Schutz 1990
P. pinaster Aiton	Maritime pine	55	18	90	Trichet et al. 2018
P. radiata D. Don	Monterey pine	109	1	593	Grey 1988
P. radiata D. Don	Monterey pine	258	139	431	Hans 2013
P. rigida Mill.	Pitch pine	1,268	649	1,911	Berry 1982
P. sylvestris L.	Scots pine	727	209	1,202	Steinbeck 1965
P. sylvestris L.	Scots pine	476	120	1,740	Innes 1995
P. taeda L.	Loblolly pine	222	51	409	Sypert 2006

Most nursery soils contain less than 200 ppm Mn (South and Davey 1983, Tanaka et al. 1967), and about half contain less than 35 ppm Mn (figure 3). One field (pH 6.7) contained 0.56 ppm extractable Mn (Solan et al. 1979). A tentative maximum value of 200 ppm Mn has been proposed for bareroot seedbeds (Davey 1991). Increasing soil pH may decrease soil solution Mn (figure 4), which can decrease foliar Mn concentration (Marx 1990, Plass 1969, Wright et al. 1999, Xu et al. 2020). In contrast, available Mn increases when soil becomes saturated for an extended period (Levan et al. 1986, Slaton and Iyer 1974, Stone 1968). When the soil (pH 4.5) at nursery 19 (figure 3) remained saturated, the Mn level exceeded 800 ppm in one field (data not shown). The combination of low soil pH, low soil oxygen, and high soil Mn can result in stunted and chlorotic pine seedlings.

Soil Testing

To estimate the amount of soil Mn available to plants, soil laboratories use different extraction methods. Tests that extract all Mn (available plus unavailable) are not useful for making fertilizer recommendations. A Mehlich 3 test might extract only 12 percent of the total Mn (Michopoulos et al. 2021) and a Mehlich 1 test would extract even less of the total (Mylavarapu et al. 2002, Sistani 1995). Nursery soils (pH 4.5 to 6.1) can range from 1 to 278 ppm Mn with Mehlich 1 or 2 to 500 ppm with Mehlich 3 (figure 2). When testing the same soil, reports may indicate 8 ppm (Mehlich 1) or 15 ppm (Mehlich 3). Therefore, when using a 5 ppm Mn value to trigger fertilization, nursery managers relying on Mehlich 3 tests will fertilize less frequently than those relying on Mehlich 1 tests. When using Mehlich 1, 4 ppm Mn is considered adequate for growing pines and other species (Horneck et al. 2011, Roberds et al. 1976, Tanaka et al. 1967).

Laboratories using Mehlich 3 may produce similar results (Tucker and Hight 1990), but occasionally there are large differences among laboratories (table 2). As a result, managers who use laboratory Z would spend more money on Mn fertilization than mangers who receive reports from laboratory Y (table 2).

Manganese in Foliage

Some nursery managers apply Mn to soil and then monitor foliar nutrients as part of a quality-control program. Typically, nursery managers compare foliar Mn values with ranges deemed adequate in published nursery manuals. Unfortunately, many of these ranges are not based on research trials in bareroot pine nurseries (table 3). When an upper value of 250 ppm Mn is used for all tree species (Landis 1997, Römheld 2012), then many pine samples listed in table 1 would be considered above adequate.

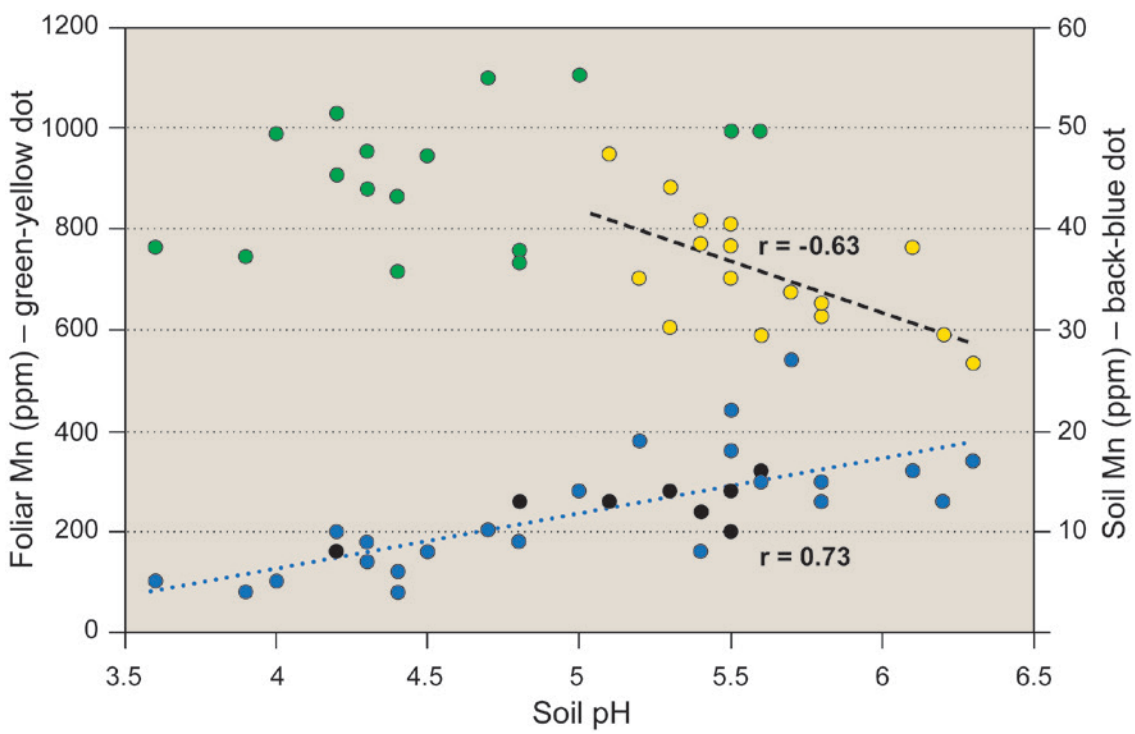
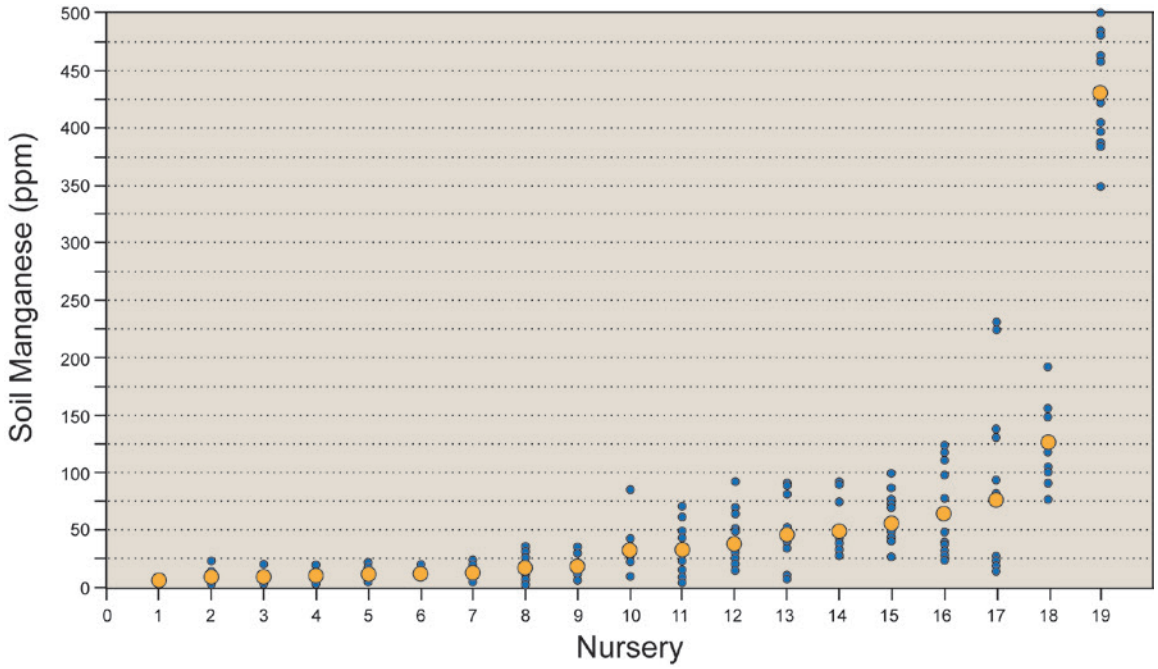


Figure 2. At a sandy nursery soil in Texas with less than 30 ppm Mn (Mehlich 3), Mn concentrations in loblolly pine (*Pinus taeda* L.) foliage declined after dolomitic lime was applied before sowing (South et al. 2017). As a result, there was a negative relationship (black line) between soil pH and foliar Mn for 16 lime plots (yellow dots). Green dots represent foliage from seedlings growing in plots not treated with lime. There was a positive relationship (blue line) between soil pH and soil Mn (blue dots). Sulfur was applied to 12 plots below pH 5.1 and black dots represent control plots that were not treated with lime or sulfur.

Figure 3. Soil Mn (Mehlich 3) from 19 southern nurseries in the United States varies from 2 to 500 ppm (excluding nursery 19 outlier, mean for the other 18 nurseries was 35 ppm). Each nursery is represented by a mean (orange dot) of about 15 soil samples. After receiving soil tests, Mn fertilizer was applied in March to 11 fields at 5 nurseries (i.e., 11 out of 282).



Although laboratories may list a normal range for Mn based on survey data, that range is not synonymous with an adequate range and may not reflect foliar values determined from a fertilizer response curve. As a result, normal ranges vary by country, region, and species. One laboratory might list a normal range of 100 to 250 ppm Mn for pine based on greenhouse tests with soybean [*Glycine max* (L.) Merr.] (Ohki 1976), while another may list a range of 75 to 500 ppm.

Although Powers (1974) reported an adequate Mn range of 100 to 5,000 ppm for all tree species, this range is not valid for pine. The upper limit of 5,000 ppm likely originated from mature stands of Norway spruce in Germany with 5,210 ppm Mn in foliage (Stone 1968). Even an upper limit of 3,000 ppm Mn is too high for some pine species (Schutz 1990, van Lear and Smith 1972). A more appropriate upper limit might be 1,700 ppm Mn, since visual toxicity symptoms have been observed when loblolly pine foliage reached 1,895 ppm Mn. Although some suggest Mn is toxic when foliage exceeds 700 ppm (Adams and Walker 1975, de Lanuza 1966, Lafond and Laflamme 1970), millions of pine seedlings have been produced with greater concentrations in foliage. At three nurseries (table 2) and in one greenhouse trial (Kavvadias and Miller 1999), Mn in pine foliage exceeded 1,300 ppm. In a greenhouse, growth of slash pine was greater at 795 ppm foliar Mn than at 642 ppm foliar Mn (figure 5).

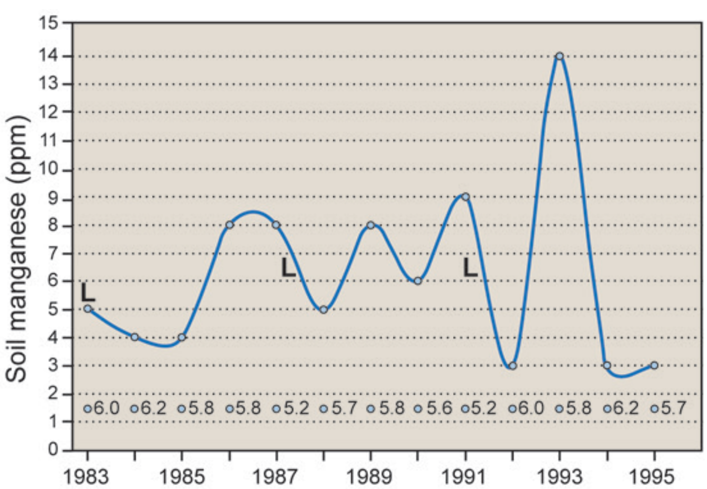


Figure 4. Soil Mn and pH varies by year for Field I-2 at the Westvaco Nursery in South Carolina. This field produced cover crops from 1983 to early 1995, and soil Mn (Mehlich 1, in November) varied from 3 to 14 ppm. Dolomitic limestone (indicated by the black L in the figure) was applied in the spring of 1983 (2,240 kg/ha), 1988 (2,240 kg/ha), and 1992 (1,456 kg/ha). Liming increased soil pH and temporarily decreased soil Mn. An application of FRIT 287 (28 kg/ha on March 23, 1995), provided 7.8 kg/ha of Mn.

The lower number in the adequate Mn range could be as low as 30 ppm (Carter et al. 2021) or 20 ppm (Albaugh et al. 2010, Horak 2008, Jokela 2004, Will 1978). For example, Hubbel (2015) suggested that pine seedling growth may have been inhibited because foliar Mn (54 to 85 ppm) was below the adequate range published for conifer needles (Landis 1997, Timmer 1991). Hubbel's container-grown seedlings with 54 ppm Mn were, however, taller than seedlings in the same trial with 384 ppm Mn in foliage. Thus, it will likely be a waste of Mn and money to fertilize pine nursery stock when foliar Mn levels drop to 50 ppm. At lower levels, however, Mn fertilization may be beneficial. Calcareous nurseries in Colorado and New Mexico (Landis

Table 2. Examples of Mn soil test results (ppm - Mehlich 3) using actual soil laboratories. Laboratories X and Z indicate a low level for soil A, while laboratory Y indicated Mn was at a very high level. Laboratory X ranks 38 ppm Mn as a medium level, while 160 ppm Mn was considered to be within the optimum range.

Sample	Laboratory X	Laboratory Y	Laboratory Z
	Mn ppm	Mn ppm	Mn ppm
Soil A	11	32	3.5
Soil B	13	15	7.9
Soil C	38	43	8.0

Low (Soil A: X, Z; Soil B: X, Z) · Medium (Soil B: Y; Soil C: X, Z) · Very High (Soil A: Y; Soil C: Y)

1988) may have benefitted from a 20-ppm trigger for applying foliar Mn.

Manganese Deficiency

"In plants, Mn deficiency often occurs as a latent disorder, without clear visual symptoms. Thus, the magnitude to which Mn deficiency affects crop yield is difficult to quantify" (Alejandro et al. 2020). The Mn deficiency range for pine needles is 1 to 22 ppm (de Lanuza 1966, Landis 1988, Lange 1969, Ruiter 1983, Trichet et al. 2018). In hydroponics, stunting is observed before obvious symptoms appear (Ingestad 1958, Stone 1968). When visual deficiency symptoms occur on stunted pines, the needles have a pale green color (Brown 1955, de Lanuza 1966, Kavvadias and Miller 1999, Lyle 1969, Majid 1984). When stunted Scots pine were grown in hydroponics without Mn, however, there were no diagnostic visual characteristics (Goslin 1959). Since Mn deficiency symptoms on pines are elusive (i.e., few or no photos), most descriptions found in nursery manuals describe symptoms found on hardwoods.

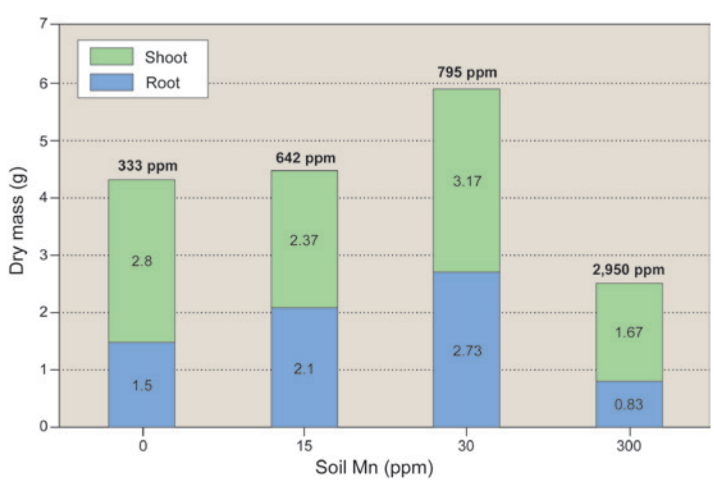


Figure 5. The effect of manganese sulfate concentrations (0, 15, 30 and 300 ppm Mn) on root and shoot dry mass of slash pine (*Pinus elliottii* Engelm.) seedlings in a greenhouse (van Lear and Smith 1972). The Lakeland sand initially contained 0.4 ppm Mn and each pot was treated twice with 100 ml of Mn solution over a 3-month growing period. Foliar Mn concentrations (age 6 months) are listed above each bar.

Sometimes stunted seedlings occur in alkaline soils, and the reason for poor growth is unknown. The best way to test for Mn deficiency is to establish fertilizer rate trials using $MnCl_2$ and $MnSO_4$ (Ingestad 1958). If both sources increase growth, then the deficiency was not due to low sulfur. Tests of $MnSO_4$ did not improve growth of conifers in U.K. nurseries (Benzian 1965), and only a few Mn trials have been installed at nurseries in North America (table 3). In several plantation trials, deficiencies were alleviated after applying 30 to 40 kg/ha of $MnSO_4$.

Although pictures are available of Mn-deficient pines in plantations (Davis et al. 2015, Lange 1969, Trichet et al. 2018, Will 1985) and greenhouses (de Lanuza 1966, Hernández-Gil 1989, Goslin 1959) (figure 6), photographs from bareroot nurseries (pH > 6.5) might not exist. When Mn was applied at high rates, seedling yield increased by more than 13 percent at two nurseries

Figure 6. Stunted growth is a symptom of Mn deficiency. The container on the right contains loblolly pine (*Pinus taeda* L.) seedlings (normal color Munsell 7.5 GY 5/6) growing in a nutrient solution containing $MnCl_2$ (Lyle 1969). The seedlings on the left were grown in a nutrient solution that did not contain Mn (foliage color 7.5 GY 7/8 or 6/6). In some cases, deficient seedlings produced no secondary needles. (Photo by Jack May, 1965)

Table 3. Pine response to manganese sulfate ($MnSO_4$; MS) varied in nursery, greenhouse, and field trials where seedlings were grown in soil. Using rates applied in tests before 1966, the cost (2022 USD) to apply nursery treatments would exceed $1,980/ha, while the cost to apply field rates would be less than $400/ha. See table 1 for species' scientific names.

Treatment	Pine common name	Response variable	% response	Reference
Bareroot nursery trials				
381 kg MS/ha	Ponderosa	Number of seedlings	+ 100	Stoeckeler and Slabaugh 1965
268 kg MS/ha	Ponderosa	Number of seedlings	+ 14	Wahlenberg 1930
224 kg MS/ha	Slash	Height	+ 10	Steinbeck 1962
224 kg MS/ha	Loblolly	Chlorosis	0	Shoulders and Czabator 1965
224 kg MS/ha	Slash	Height	- 6	Steinbeck 1962
292 kg MS/ha	Shortleaf	Dry mass	- 7	Auten 1945
Greenhouse nursery trials				
30 mg Mn/L	Slash	Dry mass	+ 37	Van Lear and Smith 1972
55 mg Mn/L	White	Dry mass	0	St.Clair and Lynch 2005
5 mg Mn/L	Slash	Dry mass	- 13	Van Lear and Smith 1972
5 g MS/pot	Mexican weeping	Dry mass	- 22	Buchler 2002
448 kg MS/ha	Red	Dry mass	- 47	Slaton and Iyer 1974
Field trials				
40 kg MS/ha	Monterey	Volume	+ 465	Donald et al. 1987
40 kg MS/ha	Monterey	Height	+ 123	Grey and de Ronde 1988
40 kg MS/ha	Monterey	Volume	+ 106	de Ronde et al. 1988
18 kg MS/ha	Monterey	Height	+ 63	Lange 1969
30 kg MS/ha	Slash	Volume	+ 22	Jokela et al. 1991
45 kg MS/ha	Slash	Height	+ 6	Pritchett 1960
23 kg Mn/ha	Loblolly	Height	0	Sypert 2006
6.6 kg Mn/ha	Loblolly	Volume	0	Vogel and Jokela 2011

(table 3). Since Mn is an active ingredient in some fungicides, high rates of $MnSO_4$ may have reduced the activity of damping-off fungi. No significant height increase occurred after Mn fertilization at nurseries in Indiana and Georgia (Auten 1945, Steinbeck 1965).

Manganese Toxicity

Toxicity of an element can be estimated by establishing a rate study and measuring germination or seedling biomass over time (Juárez-Mirón 2021, Morrison and Armson 1968, Radwan et al. 1979, van Lear and Smith 1972). Toxicity occurs when seedling dry mass is reduced by 10 percent (Ohki 1985) or when a 5- to 9-percent reduction is statistically significant ($\alpha = 0.1$). For example, in a greenhouse trial using saturated soil with low soil oxygen (Slaton and Iyer 1974), two applications of $MnSO_4$ (224 kg/ha/application) reduced shoot mass of red pine by 13 to 45 percent. In another trial, a rate equivalent to 1,866 kg/ha of $MnSO_4$ reduced dry mass by 58 percent (figure 5). Since pines are more tolerant of Mn than other species (Ingestad 1958, Schöne 1992, St. Clair and Lynch 2005), however, it may be difficult to demonstrate a growth reduction when applying less than 200 kg/ha of $MnSO_4$ to well-aerated soils (table 3). In one trial, toxicity occurred when soil was treated with 300 ppm Mn (figure 5).

In other research, toxicity might be declared when Pearson's correlation between Mn and seedling height is negative. For example, negative correlations have been reported between pine heights and foliar Mn (Adams and Walker 1975, Espinoza 2009, Madgwick 1964, South et al. 2018, Steinbeck 1965). Since faster growth reduces foliar Mn concentrations due to carbohydrate dilution, however, these correlations may have little or nothing to do with Mn toxicity.

Although 30 ppm of B or Cu is more toxic to pine seedlings than 30 ppm of Mn (van Lear and Smith 1972), nursery soils typically contain less than 5 ppm of B or Cu. In contrast, some nursery soils contain more than 200 ppm Mn (figure 3), and extended rainfall events can increase exchangeable Mn to toxic levels (Nelson 1977, Siman et al. 1974, Stone 1968). In fact, it may take only 3 days of saturated soil to increase Mn by more than 100 ppm (Graven et al. 1965).

Low soil oxygen has resulted in Mn toxicity at several bareroot nurseries where soil pH was below 5.0. For example, in December 1972, rainfall totaled more than 60 cm at the Wind River Nursery in Washington (Johnson 1975) and Mn toxicity was observed on 2-0 Douglas-fir (Youngberg 1980, 1984). Mn toxicity also occurred on loblolly pine at the Stuart Nursery in Louisiana where rainfall from July through October 1959 was the fifth wettest for the county (Shoulders and Czabater 1965). Similarly, the Camden (figure 7) and Lucky Peak Nurseries in Idaho experienced the fourth wettest October in 2009 and 1975, respectively. Toxicity symptoms also occurred on spruce (Landis 1990). Saturated soil and inadequate aeration stunted 2-0 ponderosa pine seedlings growing in pH 5.5 soil at the Lucky Peak Nursery (Morby et al. 1978), but since micronutrient analysis of pine needles did not include Mn, a Mn toxicity could not be confirmed.

In general, pines with less than 1,500 ppm foliar Mn are not injured, but levels above 1,800 ppm may be toxic. When a pine plantation in South Africa was established on a high Mn soil with low soil pH, toxicity occurred when foliage reached 2,790 ppm Mn (Schutz 1990). In Germany, a diseased Douglas-fir

Figure 7. Chlorotic loblolly pine (*Pinus taeda* L.) seedlings resulted from high soil Mn in a Lenoir soil series. Total rainfall for Wilcox County, AL, in December 2009 was 28.9 cm and, by January 2010, soil Mn ranged from 348 to 414 ppm (pH 4.8 to 5.1). By mid-summer, seedlings in this field were chlorotic, but seedlings in an adjacent field (pH 5.1) were green. Chlorotic needles analyzed in August contained foliar levels of Mn (1,895 ppm), Ca (2,200 ppm), Fe (86 ppm), B (79 ppm), Cu (8 ppm) and Zn (62 ppm). Three foliar applications of Fe did not reduce chlorosis but an application of 1,120 kg of dolomitic lime (before sowing on an adjacent block) produced green seedlings. In some places, chlorotic pine seedlings had dead terminals with resin exudation which are symptoms of a Ca deficiency (Lyle 1969). A Ca deficiency can be induced by high soil Mn (El-Jaoual and Cox 1998, Langheinrich et al. 1992). (Photo by David South, August 8, 2010)

plantation (47 years old) with chlorotic needles had foliar Mn levels that exceeded 7,000 ppm, which likely interfered with Fe metabolism (Kaus and Wild 1998). When growing in perlite, pine seedlings can be injured when foliage contains 3,100 to 4,335 ppm Mn (Kavvadias and Miller 1999, Morrison and Armson 1968). In a study with Mn- and Zn-contaminated soil, pine growth was reduced by 50 percent when foliage contained 3,000 ppm Mn (Beyer et al. 2013).

If needed, managers can apply dolomitic lime to reduce the risk of Mn toxicity (Hopmans and Flinn 1983, Lasota et al. 2021, Phares 1964, Shoulders and Czabator 1965). At one nursery, adding 2,240 kg of dolomite temporarily reduced soil Mn levels by about 1 to 3 ppm (figure 4).

Excessive application of Mn could be toxic if it interferes with Fe uptake (Kaus and Wild 1998, Lafond and Laflamme 1970, Morrison and Armson 1968). Therefore, some laboratories calculate a foliar Fe/Mn ratio and provide expected ratios from 0.3 to 1.0. Actual ratios for bareroot loblolly pine ranged from 0.11 to 4.8 (median = 0.8) when foliage was sampled in July (Starkey and Enebak 2012). In one greenhouse trial (van Lear and Smith 1972), the best growth of slash pine seedlings occurred when the Fe/Mn ratio was 0.04 (i.e., 33/795). Thus, suggestions that the desired Fe/Mn ratio for pine seedlings should range from 1.3 to 1.7 are not true (Barrick and Nobel 1993, Boyer and South 1985, South 2021). For bareroot jack pine (Morrison and Armson 1968) and loblolly pine (Sypert 2006), the foliar Mn concentration is more operationally meaningful than the foliar Fe/Mn ratio.

Although high concentrations of $MnCl_2$ reduce germination of red maple and Norway spruce (Mai and Williams 2019. Rîşca et al. 2011), limited data exist regarding the effect of $MnSO_4$ on germination of pine seed. A trial at the Vallonia Nursery in Indiana (pH 6) found no significant effect on shortleaf pine when soil was treated with 67 kg/ha of Mn (Auten 1945). Similar results were reported for other pines (Morrison and Armson 1968, Stoeckeler and Slabaugh 1965, Wahlenberg 1930).

Manganese Loss in Soils

Depending on species, soil type, cultural practices, and seedling size, a million bareroot pine seedlings may contain 0.6 to 1.5 kg of Mn (Boyer and South 1985, Donald and Young 1982, Flinn et al. 1980, Knight 1978). As a result, harvesting 1.5 million seedlings might lower soil Mn by about 1 ppm, and irrigation might lower it by another 0.5 ppm (Trichet et al. 2018). Over time, leaching, weeding, and harvesting soybean crops might lower extractable Mn by about 3.7 ppm/year (Hickman 2002).

Due to soil pH dynamics, excessive rainfall, irrigation, differences in laboratory procedures, and removal of nutrients at harvest, soil Mn levels can vary from month to month (Danielson 1966, Kazda and Zvacek 1989, Munson 1982, Sparrow and Uren 1987, Trichet et al. 2018) and year to year (figure 4). For example, when irrigation water contains 0.02 ppm Mn, 1,000 mm of irrigation will add 0.2 kg/ha of Mn to the soil. Likewise, when pines are treated with 13.4 kg/ha of the fungicide mancozeb (Marx et al. 1984), about 2.3 kg/ha of Mn is applied over the top of seedlings. Small amounts of Mn in fertilizers and dolomite (Dillard et al. 1982, Fan et al. 2012, Lasota et al. 2021, Weber 1964) also contribute to increasing soil Mn levels. These factors might explain why the average Mn level (35 ppm Mehlich 3) for 18 nursery soils was 8 ppm higher than the average for soil in 39 nonfertilized pine plantations (NCSFNC 1991).

Ectomycorrhiza Effects on Manganese

Nonmycorrhizal pine roots can take up a sufficient amount of Mn so seedlings do not become deficient (Hobbie et al. 2009, Shoulders 1972). For example, stunted, nonmycorrhizal loblolly pine seedlings exhibited P deficiency symptoms (South et al. 1988) and yet had more than 600 ppm Mn in shoots. In fact, even higher foliar Mn concentrations were observed for nonmycorrhizal pine seedlings in North Carolina (South et al. 2018).

In greenhouse trials, pine seedlings inoculated with Pt had more growth and higher foliar Mn concentrations compared with noninoculated seedlings (Miller and Rudolph 1986, Mitchell et al. 1990). On a coal spoil in Alabama (pH 3.4), young pines with Pt had 1,290 ppm foliar Mn compared with 1,808 ppm Mn for seedlings with naturally inoculated Tt (Berry 1982). The Pt inoculated seedlings grew faster than seedlings with natural Tt, however, suggesting that the lower foliar Mn concentrations were likely due to carbohydrate dilution.

Fumigation Effects on Manganese

According to Foy (1984), Mn toxicity is "frequently induced or intensified by N fertilization, which lowers soil pH, fumigation with steam or methyl bromide, air drying, or flooding (Nelson 1977, Kluthcouski and Nelson 1979)." Although fumigation of seedbeds will increase foliar Mn of pine, Mn toxicity induced by either methyl bromide or chloropicrin fumigation has not been recorded in southern pine nurseries. For example, Mn toxicity did not occur after treating nursery soil with methyl bromide followed by fertilization with more than 100 kg/ha of N (Fraedrich and Dwinell 2003, Marx et al. 1984, Marx 1990, Munson 1982, South et al. 2018). Although fumigation with methyl bromide increased foliar Mn in loblolly pine needles to more than 800 ppm (Fraedrich and Dwinell 2003), shoot mass increased by more than 90 percent. When compared with soil fumigation, too much irrigation (producing anaerobic soil) is more likely to induce chlorotic seedlings (Grasmanis and Leeper 1966, Korstian et al. 1921).

Fertilizer Effects on Manganese in Pine Seedlings

Manganese Fertilization

Only a few fertilizer tests with Mn were conducted in bareroot nurseries before 1966 (table 3). Prior to 1980, Mn fertilization was rarely conducted in operational bareroot pine nurseries. As a precautionary measure, 2 kg/ha of Mn (33.6 kg/ha of Frit 503) was applied before sowing pines at a few southern pine nurseries (Marx et al. 1984). In some cases, a blend of micronutrients was applied to pine seedlings during the summer (Hopmans and Flinn 1983, Landis 1979, Maxwell 1988, Munson 1982). In general, however, Mn fertilizers were not applied before 1980 because most routine soil tests at that time did not include Mn, and most nursery soils were acid and not deficient in Mn. Since then, opinions vary as to when seedbeds need to be fertilized with Mn (figure 8).

Since $MnSO_4$ forms a variety of hydrates (monohydrate, tetrahydrate, pentahydrate, and heptahydrate), the amount of Mn applied in experiments is not always certain. In theory, anhydrous $MnSO_4$ contains 36 percent Mn, the monohydrate contains 32 percent Mn, and the tetrahydrate contains 24 percent Mn (van den Driessche 1984). Therefore, the exact amount of Mn applied during previous research (table 3) is unknown since the hydrate tested was not specified.

Currently, less than 5 percent of pine seedbeds in the United States are fertilized with Mn before sowing. Managers who do apply $MnSO_4$ before sowing do so at a rate of 2 to 11 kg/ha of Mn based on soil tests (Aldhous and Mason 1994, Davey 2002, Maxwell 1988). Due to economics, $MnSO_4$ is the preferred source and can be applied before and after sowing. Applying 35 kg/ha of $MnSO_4$ (table 4) might cost $100/ha (2022 USD). If a foliar test indicates less than 20 ppm Mn, then a liquid product, containing either $MnSO_4$ or $MnCl_2$, might be applied over the top of pine seedlings. Application of more expensive chelated products to pine seedlings appears to have no added benefit. Deficient pines respond well after a foliar application of $MnSO_4$ (Lange 1969), but pines have not responded well to fritted Mn sources (Jokela et al. 1991).

Phosphorus Fertilization

At some nurseries, high rates of P + Ca fertilization resulted in chlorosis and stunting of pine seedlings (Shoulders and Czabator 1965, Steinbeck et al. 1966). At that time, some believed increasing P levels in plants would reduce uptake of Mn and Fe (Neilsen et al. 1992, Shoulders and Czabator 1965). Although a high rate of TSP (1,152 kg/ha of P) induced Cu and Zn deficiencies and caused chlorosis on young *Populus* cuttings (Teng and Timmer 1990), the treatment did not result in a Mn deficiency. In fact, the treatment slightly increased soil solution Mn. Likewise, when greenhouse-grown loblolly pine seedlings were fertilized with Na_2HPO_4, foliar P concentration increased but foliar Mn was not affected (Rowan and Steinbeck 1977). Evidence is lacking to support the assumption that a high rate of TSP will produce a Mn deficiency in bareroot conifer seedlings.

Calcium Fertilization

Foliar Mn reached deficient levels (1 to 19 ppm) when soils contained more than 10,000 ppm Ca (Landis 1988, Nakos 1979). Likewise, applying 10,000 ppm Ca to container-grown media reduced foliar Mn to an undetectable level and resulted in chlorosis of Douglas-fir needles (van den Driessche 1984). In some soils, applying lime to increase soil

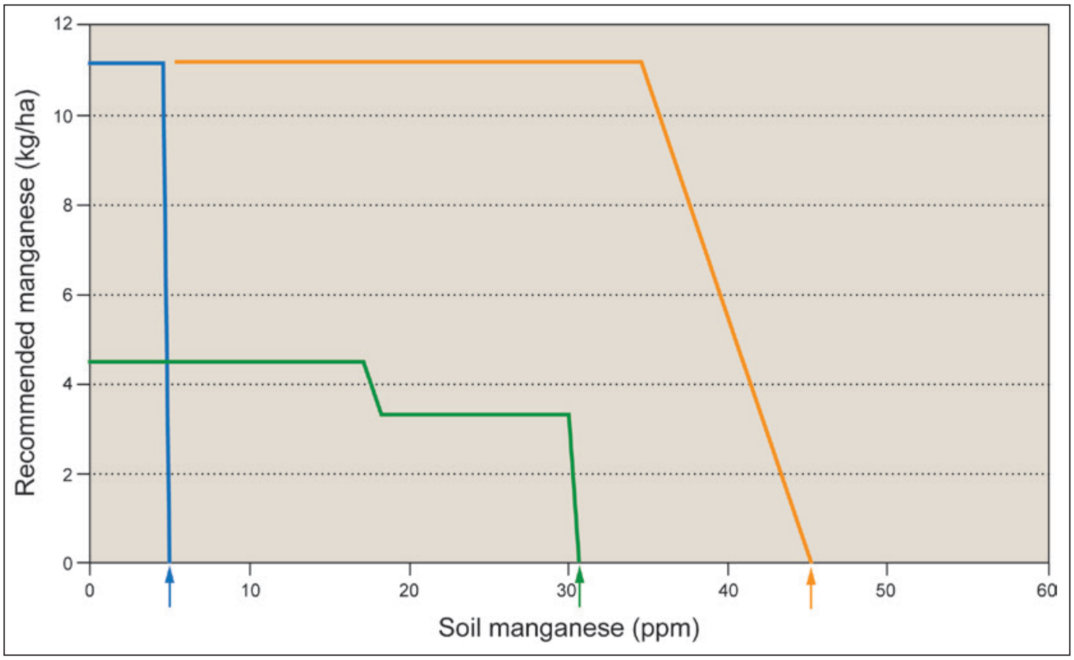


Figure 8. This graph demonstrates three opinions regarding the trigger value for fertilizing pine seedbeds with Mn. Some agronomists set 45 ppm soil Mn (Mehlich 3) as a satisfactory level (orange arrow – line) while others use a 30-ppm (green arrow – line) or 5-ppm trigger value (blue arrow – line).

Table 4. A partial list of Mn fertilizers sold as liquids (L), granules (G), wettable powders (WP), or water-soluble powders (WS). Manganese oxide is not water soluble.

Trade name	Common Name	Type	%	% N	% S	Formula
Wolf Trax™	Mn oxide + Mn sulfate	WP	33			$MnSO_4 \bullet 1H_2O + MnO$
Brant®	Manganese sulfate	WP	31		18	$MnSO_4 \bullet 1H_2O$
Southern Ag	Manganese sulfate	WP	29		17	$MnSO_4 \bullet 1H_2O$
Frit™ 287 G	Mn oxide + Mn sulfate	G	28		6	Mn in crushed glass
Lebosol® Mangan	Manganese carbonate	L	28			$MnCO_3$
Ele-Max®	Manganese carbonate	L	27	3		$MnCO_3$
Nutriseed™ ZnMn	Manganese carbonate	L	16			$MnCO_3$
NitraMar™	Manganese nitrate	L	15	7		$Mn(NO_3)_2$
Tiger-sul	Manganese oxide	G	15		65	MnO
Brant® EDTA	EDTA	L	13			$Mn(C_{10}H_{16}N_2O_8Na_2)$
Mineral Research	Manganese chloride	L	7			$MnCl_2 \bullet 4H_2O$
Britz	Manganese sulfate	L	7		4	$MnSO_4$ in kraft lignin
Ultra-Che®	EDTA	L	6	3		$Mn(C_{10}H_{16}N2O_8Na_2)$
Biomin®	Manganese sulfate	L	5	1	3	$MnSO_4$ in glycine and citric acid
13-13-13	Manganese oxide	G	0.4	13	9	MnO
20-20-20	EDTA	WS	0.025	20		$Mn(C_{10}H_{16}N2O_8Na_2)$

pH to near neutrality will produce a Mn deficiency in some row crops (Foy 1992, Siebielec and Chaney 2006). In a bareroot nursery, applying 2,240 kg/ha of dolomite will increase soil Ca and might lower extractable Mn slightly (figure 4). At one loblolly pine nursery, applying a total of 2,984 kg/ha of Ca (lime plus gypsum) caused summer chlorosis (pH 6.7) without producing a Mn deficiency (South 2021). Although applying Ca before sowing pine (pH < 7.0) may cause Mg and Fe deficiencies, it is unlikely to induce a Mn deficiency. Mn and Ca in pine foliage are closely correlated (Hill and Lambert 1981).

Nitrogen Fertilization

Since several N fertilizers can lower soil pH, it has been suggested that N fertilization might induce in Mn toxicity (Bengtson 1970, Foy 1984, Lingle and Wight

1961). Although improper use of N can certainly injure pine seedlings, billions of bareroot pine seedlings have been fertilized with N without symptoms of Mn toxicity. For example, 450 kg/ha of N produced more growth on loblolly pine (at pH 4.8 soil) than 150 kg/ha (Marx 1990). Although foliar Mn concentration increased to 1,400 ppm, there was no sign of stunting. Other conifer trials have also shown that extra N fertilization did not induce Mn toxicity (Birchler et al. 2001, Rowan and Steinbeck 1977, Woods 1983, Yongliang et al. 2002). At some nurseries, soil Mn is actually lower after seedbeds are fertilized with N and then irrigated (Radwan et al. 1979) (figure 9).

Iron Fertilization

When chlorotic seedlings are related to high pH soil, a foliar application of Fe can reduce chlorosis (Korstian et al. 1921, South 2021). In contrast, if chlorosis appears after acid soil (< pH 5.0) becomes saturated, then the problem is most likely Mn toxicity. Too much Mn in the soil or water can induce an Fe deficiency (Lafond and Laflamme 1970, Morrison and Armson 1968, Olson and Carlson 1950). One way to reduce an Fe deficiency induced by Mn toxicity, is to apply Fe (Bryson and Mills 2014, Lafond and Laflamme 1970). For example, one nursery (pH 4.1 to 4.5) applied three applications of Fe (1.0 kg/ha/application) and successfully reduced chlorosis and restored growth of pines (Shoulders and Czabator 1965).

Manganese after Outplanting Pine Seedlings

Sometimes bareroot pine seedlings are lifted and shipped with less than 100 ppm foliar Mn (table 1). Does the foliar Mn affect plantation growth? Only a few studies have examined the effect of foliar Mn on seedling performance. On a site in Alabama, there was no relationship between foliar Mn in the nursery (118 to 861 ppm Mn) and height growth of loblolly pine after 3 years (Larsen et al. 1988). Likewise, on five sites in Texas, there was no relationship (P =0.65) between foliar Mn and height of shortleaf pine 8 months after planting. Shortleaf pine height averaged 169 and 186 mm (LSD_{05} = 30 mm) for two treatments that averaged 234 and 502 ppm Mn at planting, respectively (Bryson 1980). When needles contain more than 100 ppm Mn, then outplanted pines might not benefit from fertilization with Mn (Jokela et al. 1991, Larsen et al. 1988, Sypert 2006, Vogel and Jokela 2011).

On Mn-deficient sites, nutrient loading with Mn and S in the nursery might increase height growth of pines after planting. At a nursery in South Africa, container seedlings were fertilized five times with $MnSO_4$, and growth after outplanting in the field increased significantly (P = 0.0001) (de Ronde et al. 1988). Assuming 40 mm of irrigation with 3,100 ppm Mn, the total rate applied in the nursery would equal 1,240 kg/ha of Mn.

Conclusion

Additional nursery research using the scientific method is needed to investigate several questions: (1) What is the adequate Mn range for pine needles? (2) Will an ineffective foliar application (280 g/ha of Mn) of a row-crop chelate (Last and Bean 1991) also be ineffective when applied to pine seedlings? (3) In a high pH soil, will pine seedlings develop a Zn deficiency before a Mn deficiency? (4) Will an application of MnO persist longer in a nursery soil than an application of $MnSO_4$? (5) At what rate does weathering convert unavailable Mn to available Mn? (6) Will foliar Fe applications to ponderosa pine seedlings reduce Fe chlorosis caused by low soil pH and high soil Mn? Exploration of these and other nutrient questions will benefit the science of growing quality seedlings.

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Acknowledgments

I thank the nursery managers who shared their experiences with Mn fertilization. I thank J.B. Jett, Eric Jokela, John Mexal, Barbara Hawkins, Tom Starkey, Nelson Thiffault, and Diane Haase for reviews of earlier drafts of this manuscript.

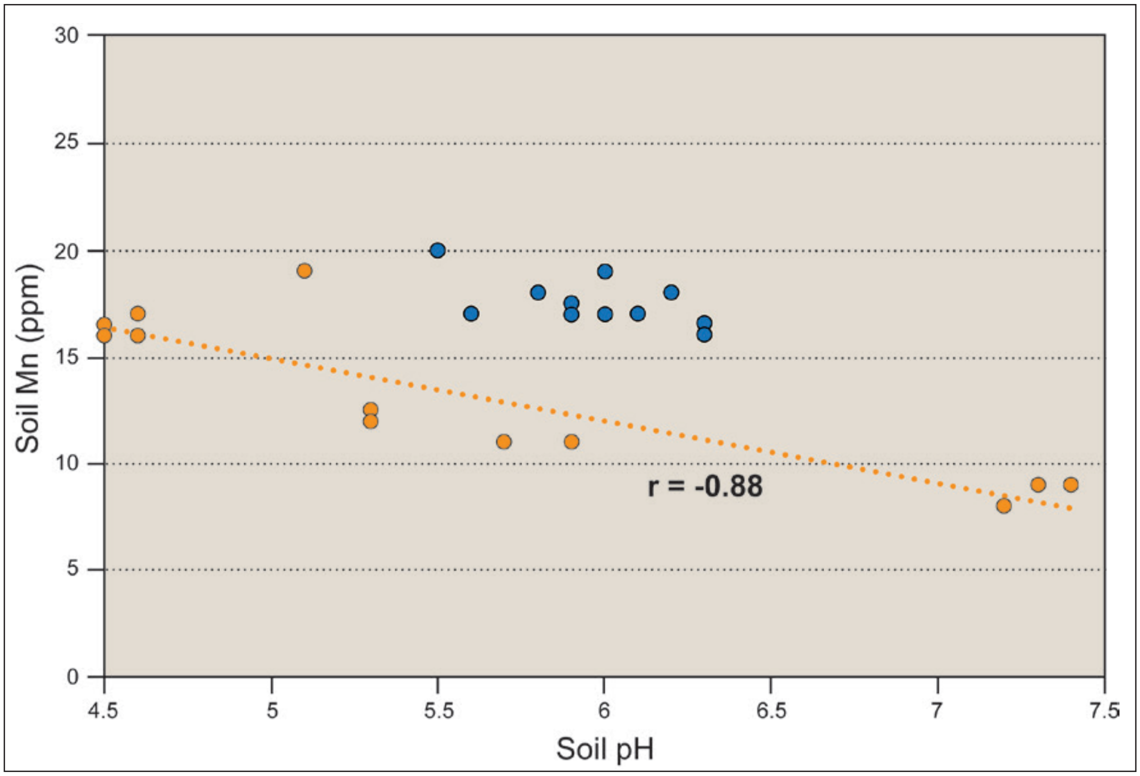

Figure 9. A nitrogen (N) fertilization trial installed at the Union Camp Nursery (Capron, VA) included four sources of N applied at 224, 336, and 448 kg/ha during the growing season (Villarrubia 1980). On June 30, 1978, untreated plots (blue dots) ranged from pH 5.5 to 6.3 and averaged 17 ppm Mn (Mehlich 1). On September 12, 1978, soil treated with N (orange dots) averaged 13 ppm Mn. Irrigation and rainfall leached some Mn and some Mn 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.

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