Iron Fertilization in Bareroot Nursery Seedbeds

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Abstract

With adequate fertilization, bareroot conifers grow well at pH 4.5 to 5.5. Because some guidelines suggest that seedlings grow best at pH 5.5 to 6.5, lime is sometimes applied when soil drops below pH 5.5. Liming, however, can result in "lime-induced" chlorosis which may be attributed to an iron (Fe) deficiency. Fe deficiency is often associated with "summer chlorosis" or "nitrate-induced" chlorosis. With no treatment, however, seedlings may return to a green color when temperatures cool. At many bareroot nurseries, Fe deficiency has declined because: (1) soil acidity of seedbeds has been lowered to below pH 5.6; (2) nitrate application has decreased by more than 55 percent; and (3) irrigation is used to cool seedbeds in July. Now, about one-third of bareroot nurseries in the southern United States do not fertilize with Fe. This article gives an overview of publications and observations regarding the use of Fe in bareroot nurseries and associated products, challenges, and misconceptions.

Introduction

Iron (Fe) is the most common element in the Earth and the fourth most common element in the Earth's crust. Although various soils may contain more than 6 percent Fe, sometimes soil tests extract less than 10 ppm (Mexal and Fisher 1987, Solan et al. 1979, Van Lear and Smith 1972). When growing in neutral or alkaline soils, bareroot seedlings can exhibit Fe deficiency since the ion occurs mostly in the oxidized form (Fe^{+++}) which some consider biologically inactive. In very acid soils, Fe deficiency is rare since Fe occurs in the ferrous (Fe^{++}) form. Although seedlings deficient in Fe have lower chlorophyll concentrations, chlorotic needles typically have high concentrations of inactive Fe. Details about the role of Fe in plants and the role of soil pH in Fe solubility have been reviewed previously (Abadía 1992, Barker and Stratton 2015, Brown 1961, Chen and Barak 1982, Korcak 1987, Landis 1988, Mortvedt 1991, Wallace 1962). Visual deficiency symptoms include chlorosis of newly formed needles or leaves. For hardwoods, the veins in the leaves often remain green. Photos illustrating Fe deficiency symptoms on various species have been published (table 1).

Fe has been applied to chlorotic bareroot seedlings for more than 100 years (Korstian et al. 1921). Some nursery managers routinely apply Fe to seedlings while others have not applied any Fe to bareroot seedlings this century (figure 1).

Although greenhouse trials demonstrate that Fe is an essential element (Howell 1932, Lyle 1969, Nelson and Selby 1974, Pessin 1937), the information is often of no practical use for bareroot nursery managers. For example, a 0.072 millimolar Fe solution applied to seedlings in a greenhouse does not inform growers if an Fe chelate product will reduce chlorosis in bareroot seedbeds (El-Jendoubi et al. 2011, Whittier 2018). Unfortunately, empirical trials with Fe in bareroot nurseries are rare. Although many questions remain unanswered, the goal of this paper is to provide some practical information and observations.

[Abbreviations: Al = aluminum. AN = ammonium nitrate. AS = ammonium sulfate. ATS = ammonium thiosulfate. Ca = calcium. Cl = chloride. Cu = copper. EDTA = ethylenediaminetetraacetic acid. EDDHA = ethylendiaminedi (o-hydroxyphenylacetic) acid. DTPA = Diethylenetriamine pentaacetic acid. Fe = iron. $FeSO_4$ = ferrous sulfate. HEDTA = N-(2-Hydroxyethyl) ethylenediaminetriacetic acid. K = potassium. LSD_{05} = Least significant difference, α= 0.05. Mg = magnesium. Mn = manganese. N = nitrogen. P = phosphorus. ppm = parts per million. S = sulfur. UAN = urea ammonium nitrate. Soil pH was measured in water.]

Table 1. Scientific and common names of selected species mentioned in this article. References listed provide photographs of Fe deficiencies.

Species	Common name	Photo reference
Acer rubrum L.	Red maple	Starkey 2012
Acer saccharinum L.	Silver maple	Koenig and Kuhnes 2002
Citrus unshiu Marc.	Satsuma tangerine	No photo
Eucalyptus maculate Hook.	Spotted iron gum	Dell and Robinson 1993
Juglans nigra L.	Black Walnut	Hacskaylo et al. 1969
Liquidambar styraciflua L.	Sweetgum	Hacskaylo et al. 1969
Liquidambar styraciflua L.	Sweetgum	Goldberg and French 2017
Pinus banksiana Lamb.	Jack pine	Landis et al. 1989
Pinus contorta Dougl.	Lodgepole pine	Majid 1984
Pinus elliottii Engelm.	Slash pine	No photo
Pinus palustris Mill.	Longleaf pine	www.ipmimages.org/ browse/detail.cfm? imgnum=1611152
Pinus pinea L.	Stone pine	Lamhamedi et al. 2009
Pinus radiata D. Don	Monterey pine	Will 1985
Pinus resinosa Ait.	Red pine	Armson and Sadreika 1979
Pinus sylvestris L.	Scots pine	Goslin 1959 Hacskaylo et al. 1969
Pinus taeda L.	Loblolly pine	Bengtson 1968
Populus tremula × *P. tremuloides*	Hybrid poplar	Masuda et al. 2018
Prunus persica (L.) Batsch	Peach	Fernández et al. 2008
Pseudotsuga menziesii Mirb. Franco	Douglas-fir	van den Driessche 1989
Quercus palustris Münchh.	Pin oak	Harrell and Andrews 1986 Hoch 2015
Quercus suber L.	Cork oak	Gogorcena et al. 2001
Robinia pseudoacacia L.	Black locust	Hacskaylo et al. 1969
Tectona grandis L.f.	Teak	Whittier 2005

20th Century Practices

Chlorotic seedlings are caused by a variety of factors: nematodes, too much organic matter, too much N fertilizer, too much soil alkalinity, not enough S, too much carbonates in irrigation water, too much *Pythium*, too much heat, anaerobic conditions in the rhizosphere, etc. Since foliar tests are not useful for proving an Fe deficiency, it was easier just to apply an Fe product and hope for the best. In some cases, untreated seedlings turned green in August with the onset of cooler weather.

Initially, $FeSO_4$ was the primary fertilizer used to correct an Fe deficiency (Cossitt 1938, Korstian et al. 1921) because it was available and could also be used to lower soil pH. At some nurseries, $FeSO_4$ (4 kg/ha/application) was sprayed on seedlings on a weekly basis to reduce chlorosis. At other nurseries, 700 kg/ha was applied before sowing to lower soil pH. Until 1950, chelates were rarely used in nurseries (Stoeckeler and Slabaugh 1965) because they were more expensive than $FeSO_4$. In some cases, $FeSO_4$ will penetrate leaves better than Fe chelates (Chakraborty et al. 2014).

Fe deficiencies were not common at nurseries in the Pacific Northwest (Anderson 1968, van den Driessche 1984). For 2-0 bareroot Douglas-fir seedlings, foliar Fe values for four nurseries ranged from 67 to 225 ppm (Krueger 1967). Approximately 2 out of 13 nurseries in New Zealand applied $FeSO_4$ to pine seedlings in 1977. At the FRI Nursery at Rotorua, chlorosis occasionally occurred on young needles during the cold, wet periods of spring weather (Knight 1978). This symptom was corrected by foliar applications of $FeSO_4$ (5 percent weight/volume) at about 465 L/ha: "One to two repeat applications made at 7- to 10-day intervals have generally been necessary to restore good colour" (Knight 1978).

At several pine nurseries, a rust fungicide (containing 13 percent Fe) was applied twice weekly at 0.3 kg/ha of Fe/application (Marx et al. 1984, Snow et al. 1979). At this rate, 18 applications would total 5.4 kg/ha of Fe which might explain why several managers did not apply Fe chelates to pine seedbeds (Marx et al. 1984). In addition, Bengtson (1968) tested several Fe products and he "never did get any definite response to the application of iron elements" (Rowan 1969). Likewise, several nursery managers saw no need to apply Fe when pine foliage was green (e.g., figure 1).

Figure 1. These green, bareroot loblolly pine seedlings are growing in an acid soil that has never received an application of Fe. (Photo by Tom Anderson)

Sometimes applying Fe chelate was ineffective because chlorosis was due to a S deficiency. In some cases, S can improve growth as much as Fe (Meena et al. 2013) or more than Fe (Browder et al. 2005, Dale et al. 1955, Lyle and Pierce 1968, van den Driessche 1989).

In the 1970s, fertilizer tests with hardwoods showed improved growth when the N source was switched from AN to AS (Stone 1980, Williams and Phares 1972). Likewise, when grown in containers (pH < 5.5), oak and maple seedlings respond to fertilization with S, but Fe-EDTA did not increase growth (Browder et al. 2005). Nursery managers in Virginia also noticed a lack of summer chlorosis when pine seedlings were fertilized with AS. When growers added ATS to liquid UAN, summer chlorosis did not occur. As a result, Fe fertilizers have not been applied to bareroot pines in state nurseries in Virginia in more than 25 years.

During the last century, many said that Fe was "immobile" in seedlings. Although Fe does not retranslocate easily away from older tissue, Fe is partially mobile (Bukovac and Wittwer 1957). When foliar applied, some Fe will retranslocate from a leaf surface towards the leaf petiole (Fernández et al. 2008, Hüve et al 2003, Zhang et al. 1995).

Fe Fertilization

There are six approaches to fertilizing bareroot seedlings with Fe: (1) keep soil pH below 5.6 and apply no Fe (Bonner and Broadfoot 1964, Landis 1997, Mizell 1980, Young 1938); (2) apply Fe before sowing on alkaline seedbeds (Landis 1988, Martian 1989, Maxwell 1988); (3) wait until foliage starts to show deficiency symptoms and then apply Fe (Shoulders and Czabator 1965); (4) apply Fe chelate soon after the first N topdressing (Carter 1964); (5) apply multiple Fe chelate treatments to green foliage (Jacobs and Landis 2014, Will et al. 2013); or (6) apply a mixture of micronutrients to soil or foliage (Flinn et al. 1980, Iyer and Wilde 1974, Marx et al. 1984). Although seedling growth may be correlated with soil Fe (South et al. 2018b), Fe fertilization is not based on routine soil tests (Davey 2002, Hardy et al. 2013, Hochmuth 2011, Horneck et al. 2011), in part, because soil Fe tests can vary widely. For example, when analyzing the same soil, one laboratory estimated 34 ppm of available Fe while another estimated 120 ppm (South 2019). Similarly, routine foliar Fe tests have little meaning for determining when to apply Fe. Furthermore, foliage Fe tests can fluctuate wildly from month to month due to contamination of epicuticular wax.

Soil pH, bicarbonates, and leaf color are the main factors used to determine when to apply Fe to seedlings. When soil pH and bicarbonates are high enough to lower chlorophyl concentrations, a visual ranking (Messenger 1990, Mexal et al. 2004), a "greenness" meter (Chieppa et al. 2017, Loh et al. 2002), or a simple color chart (figure 2) can be used to determine when to fertilize with Fe. In contrast, some recommend never using visual symptoms as a guide for Fe fertilization (Baer 1984, Jacobs and Landis 2014).

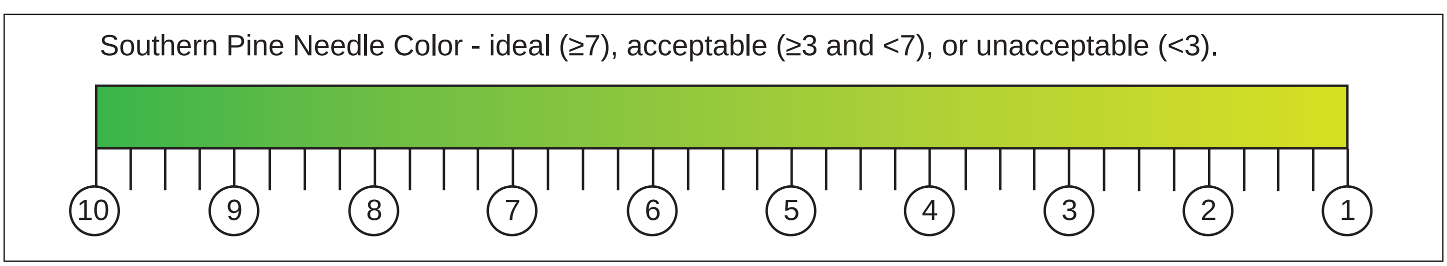

Figure 2. Steve Grossnickle (NurseryToForest Solutions, North Saanich, BC) developed this color chart used by CellFor in a quality control program for loblolly pine clonal stock (Grossnickle 2011). When bicarbonates in irrigation water increased pH levels, needle color decreased. A value of 3 was used to determine when to apply a chelated Fe product.

Examples of commercial products are provided in table 2. Granular products are typically applied before sowing as a prophylactic treatment while liquid products are primarily applied after seedlings have true leaves. Due to uniformity, many growers prefer to apply fertilizers as a liquid spray. Several products include urea which aids in the uptake of Fe (Hochmuth 2011). Frequent use of some wettable powder products can wear out sprayer parts (e.g., roller pumps) and increase application costs. Products applied before sowing include $FeSO_4$ (Landis 1988, Maxwell 1988) and Milorganite® (Landis and Dumroese 2012, Marx et al. 1984) while $FeSO_4$ and chelated products can be topdressed (Chakraborty et al. 2014, Landis 1997). Recommended rates vary. For example, DTPA (10 percent Fe) might be recommended at 3.7 to 10 kg/ha of Fe (Davey 1984, Danielson 1966, Shoulders and Czabator 1965), though nursery managers tend to use lower rates (0.40 to 0.56 kg/ha/application of Fe). Three weekly applications might total 1.7 kg/ha of Fe.

Fe is sometimes applied with every N application using a N/Fe ratio of 220 (Will et al. 2013). When bareroot seedlings receive 200 kg/ha of N, the total amount of Fe applied can vary from zero (Donald 1990, Marx 1984) to 3 kg/ha (Martin 1989). For container-grown pine seedlings, the Fe rate applied per 200 kg N can vary from zero (Dumroese and Wenny 1997), to 0.8 kg (Fu et al. 2017), to 4 (Landis et al. 1989), to 8 kg (Carlson 1979). Some container nurseries apply 8 applications over a 4-month period (June to September).

Bicarbonates in Well Water

Bicarbonates (HCO_3^-) in irrigation water can produce chlorotic seedlings (Nelson and Switzer 1969, Wang et al. 2020). Bicarbonates are typically low in lakes and rivers, and therefore chlorosis is not a problem when nursery managers keep soil pH below 5.6 and irrigate using surface waters with less than 7 ppm Ca. Nursery well water, however, can contain high Ca and high bicarbonates which can cause problems. Well water containing 2 ppm Ca may have 30 ppm of bicarbonates while water with 38 ppm Ca may have 180 ppm of bicarbonates. In Florida, deep wells tend to have alkaline water with more than 100 ppm bicarbonates, while shallow wells have acid water and less than 40 ppm bicarbonates (Morgan and Graham 2019). Water with less than 40 ppm bicarbonates is desired while 60 ppm is considered marginal (Landis et al. 1989). In one survey, water samples from 8 nurseries (Alabama, Florida, Georgia and North Carolina) contained more than 30 ppm Ca (McNabb and Heidbreder-Olson 1998) and therefore several managers applied Fe to reduce summer chlorosis.

Alkaline and Basic Soils

For conifers, Fe deficiencies are common at nurseries with alkaline soils where the soil solution contains mostly the oxidized form (Fe^{+++}). Due to high soil Ca and salinity, several bareroot nurseries on alkaline soils have closed. Some hardwood species also become chlorotic in alkaline soil (McComb and Kapel 1942, Smith and Mitchell 1977) while others grow well without any Fe fertilization (Fisher and Fancher 1984). The preferred chelate used at alkaline nurseries (figure 3) is Fe-EDDHA (Landis 1997) and one bareroot nursery applied this product 9 times (Mexal and Fisher 1987).

Several studies on alkaline soils indicate hardwoods and conifers respond favorably to applications of Fe (figures 3, 4, and 5). At one nursery, shoot mass of pine seedlings increased by 50 percent when soil (pH 7.5) was treated with Fe-EDDHA (Fisher and

Figure 3. The alkaline soil at the Albuquerque Nursery ranged from pH 7.2 to pH 8.4 with a $CaCO_3$ content from 2 to 12 percent (Mexal and Fisher 1987, Hooks et al. 1988). This photo demonstrates the difference between Fe-deficient seedlings (foreground) and those treated with a foliar application of Fe-EDDHA (background). A 1982 study at the Albuquerque Nursery (Fisher and Chan 1985) indicated a single soil application of Fe-EDDHA could increase shoot growth of 1-0 pine seedlings by 50 percent. Other forms of Fe chelate were ineffective at this nursery. (Photo by Tom Landis 1988).

Table 2. A partial list of iron (Fe) fertilizer products which are sold as liquids (L), wettable powders (WP), or granules (G).

Tradename	Common name	Form	% Fe	% N	% S	Formula
Sucra Min®	Iron sucrate	G	50			Fe_2O_3 - organic complex
Brant®	Ferrous sulfate	G	30		18	$FeSO_4 \bullet H_2O$
Nu-iron™	Iron malonate	G	30			$FeC_3H_4O_4$
Ironite®	Ferric oxide	G	20	1	5	FeO
Extreme Green®	Ferrous sulfate	WP	20		12	$FeSO_4 \bullet 7H_2O$
Ferrous sulfate	Ferrous sulfate	G	20		11	$FeSO_4 \bullet 7H_2O$
Hi-Yield®	Ferrous sulfate	G	19		11	$FeSO_4 \bullet 7H_2O$
Micromax®	Ferrous sulfate	G	17		12	$FeSO_4 \bullet 7H_2O$
Osmocote® iron	Ferric sulfate	G	17		15	$F_e2O_{12}S_3$
Frit™ 503 G	Ferric oxide	G	14			FeO - crushed glass
Axilo®	EDTA	WP	13	6		$Fe(C_{10}H_{12}N2O_8Na) \bullet 3H_2O$
13% Iron EDTA	EDTA	WP	13	6		$Fe(C_{10}H_{12}N_2O_8Na) \bullet 3H_2O$
Sequestrene® Na	EDTA	WP	12	6		$Fe(C_{10}H_{12}N_2O_8Na) \bullet 3H_2O$
Sequestrene® 330	DTPA	WP	10	7		$Fe(C_{14}H_{23}O_{10}N_3)$
Sprint® 330	DTPA	WP	10	7		$Fe(C_{14}H_{23}O_{10}N_3)$
Brant® EDTA	EDTA	L	7	3		$Fe(C_{10}H_{12}N_2O_8Na) \bullet 3H_2O$
Ferromec® AC	Ferrous sulfate	L	6	15	3	$FeSO_4 \bullet 7H_2O$
Six Iron™	Ferrous sulfate	L	6	12	3	$FeSO_4 \bullet 7H_2O$
Sequestrene® 138	EDDHA	WP	6	4		$Fe(C_{18}H_{20}O_6N_2)$
Sprint® 138	EDDHA	WP	6	4		$Fe(C_{18}H_{20}O_6N_2)$
Greenol™	EDTA	L	5	2	3	$Fe(C_{10}H_{12}N2O_8Na) \bullet 3H_2O$
Green-T®	Iron glucoheptonate	L	5			$Fe(C_7H_{13}O_8)$
Tracite® iron 5%	Ferrous citrate	L	5		3	$FeC_6H_6O_7$
Nutrite™ Iron Plus	Ferrous citrate	L	5	5	4	$FeC_6H_6O_7$
Versenol™	HEDTA	L	4	2		$Fe(C_{10}H_{18}O_7N_2Na_2)$
MaxiGreen II®	Iron glucoheptonate	L	2		2	$Fe(C_7H_{13}O_8)$
Milorganite®	Biosolid	G	2	6	2	—

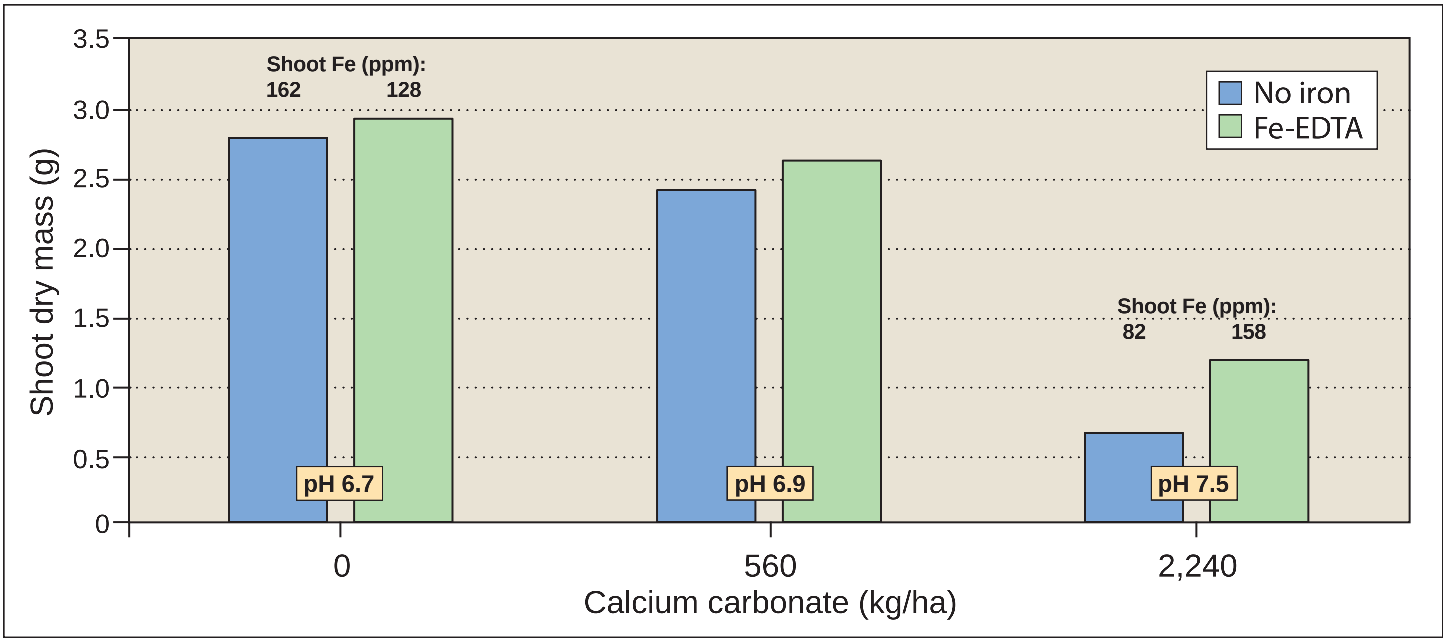

Figure 4. Applying lime increased soil pH, reduced loblolly pine seedling growth (5 months old), and increased seedling response to an application of Fe-EDTA (3.1 kg Fe/ha) (Richards 1961). Fe levels in shoots are provided above bars. Seeds were sown in pots on December 23 and chlorosis was noticed in early February (pH 7.5). An application of Fe-EDTA (0.25 percent solution) was applied on March 13 and the treated seedlings were green by March 28. The LSD_{05} = 0.37 g.

Chan 1985). When soil pH is less than 5.5, however, pines are less likely to respond to Fe fertilization.

In a greenhouse trial with slash pine (pH 7.3), an application of Fe-tartrate reduced chlorosis in July and increased height growth (Steinbeck 1962). In another trial at pH 7.6, applying $FeSO_4$ increased the chlorophyll content of citrus leaves more than Fe citrate (figure 5). In greenhouses, it is relatively easy to produce deficiencies by growing pine seedlings in

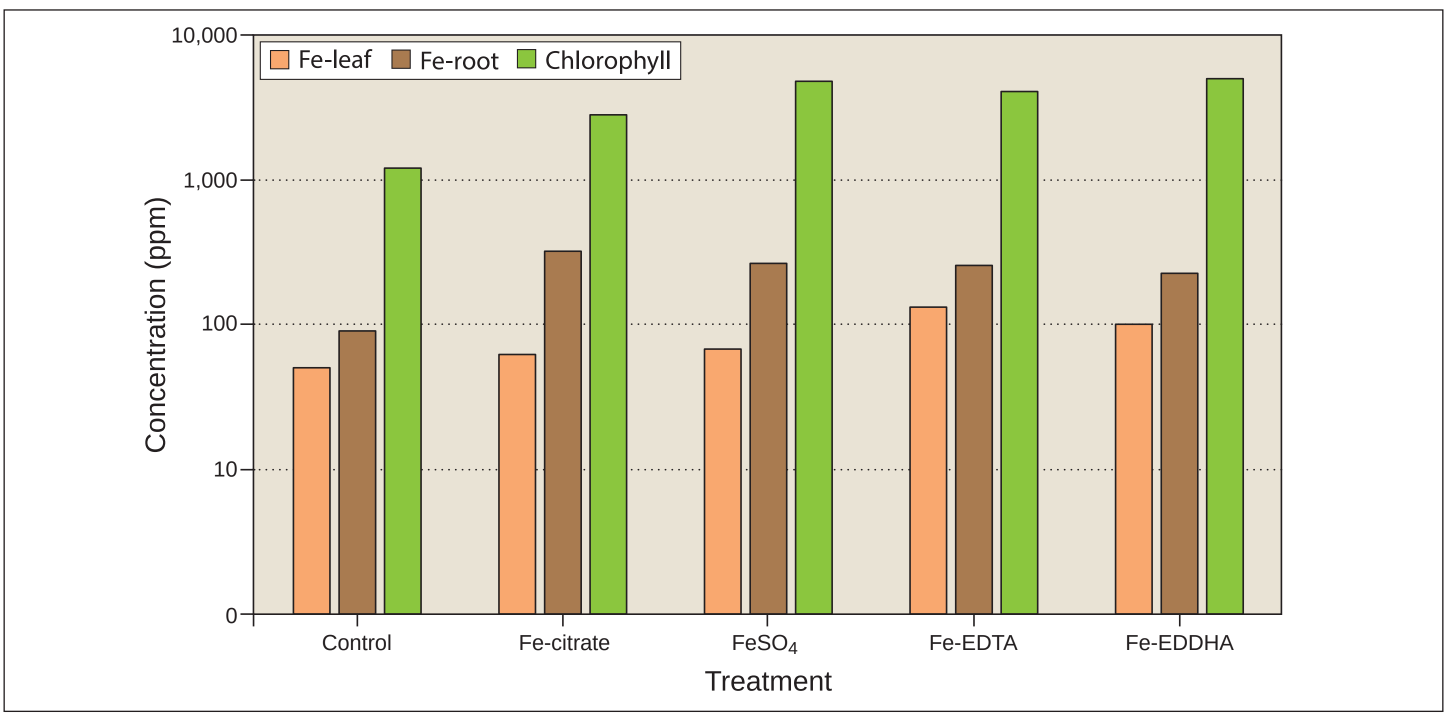

Figure 5. Iron applications (0.6 g of Fe per pot: equivalent to 60 ppm Fe) to Satsuma tangerine plants affected Fe concentrations in leaves and roots and chlorophyll concentration in leaves (Mordogan et al. 2013). The untreated sandy clay soil had a pH of 7.6 with 0.08 ppm Fe, and each pot was treated 5 times during the growing season. The LSD_{01} values are 13 ppm (leaf), 54 ppm (root), and 930 ppm (chlorophyll).

deionized water or sand (Blackmon 1969, Goslin 1959, Steinbeck et al. 1966).

Acid Soils

Low soil pH is critical for keeping Fe^{++} from being oxidized into Fe^{+++}. Therefore, some bareroot nursery managers maintain soil pH below 5.6. At some locations, increasing soil acidity with sulfuric acid will increase growth of pines and eliminate the need to apply Fe (Dale et al. 1955). Fe chlorosis of conifers is rare when soil acidity is pH 3.7 to 5.5, and, so far, studies to demonstrate that Fe application will increase seedling growth on these soils have not been published (Lynch et al. 1943, Maki and Henry 1951). In fact, certain types of Fe fertilizers may even reduce growth (figure 6). Although applying Fe-phosphate increased growth of pines at a nursery in Indiana (pH 6), the phosphate, not the Fe, likely increased the growth of non-mycorrhizal seedlings (Auten 1945).

Fe deficiencies have purportedly occurred on mildly acid soils (Danielson 1966, Shoulders and Czabator 1965) due to applying too much lime (figure 4) or too much nitrate-N (Landis 1976). At these nurseries, seedlings typically turn green with the onset of cooler weather. If irrigation water contains 60 ppm (or more) bicarbonates, however, then applying Fe chelates may reduce the chance of chlorosis. In very strongly acid soils (pH 4.5 to 5.0), chlorotic seedlings might be due to a deficiency in Mg (Voigt et al. 1958) or Ca, or due to antagonism from Mn (South 2017). Some alkaline nursery soils have less than 25 ppm soluble Fe (Mehlich 3) but most acid nursery soils contain enough available Fe so that pine seedlings lifted in November are not Fe deficient (Baer 1984, Boyer and South 1985).

Summer Chlorosis

In some soils (> pH 5.5), high temperatures in summer will temporarily turn conifer needles yellow (Foster 1959, Marks et al. 1985, Ronco 1970). This phenomenon is known as summer chlorosis (Carter 1964). When nursery beds are oriented east-west, chlorosis appears on the southside of the bed. Although

Table 3. Soil (Mehlich 3) and foliage data (July 23) from non-replicated plots that were sown on April 20, 2018 at the Arborgen Nursery at Bullard, Texas. Dolomitic lime (6,776 kg/ha) and gypsum (6,776 kg/ha) were applied prior to sowing. On July 9, loblolly pine needles on lime-treated plots were chlorotic but the chlorosis was gone by August 13. Soil and foliar samples were taken July 22. Highest air temperatures for June, July, and August were 35.5 °C, 41.1 °C, and 37.8 °C, respectively, and the highest seedbed temperatures (7.6 cm depth) were 35.0 °C, 40.6 °C, and 37.3 °C, respectively. Seedlings were not fertilized with Fe or N.

Variable	No lime	Gypsum	Lime	Lime + gypsum
pH	4.6	5.4	7.0	6.7
Soil Ca (ppm)	318	847	881	1251
Soil Fe (ppm)	291	279	262	325
Soil Mg (ppm)	49	69	168	124
Soil P (ppm)	145	136	131	153
Foliar B (ppm)	21	16	17	18
Foliar Fe (ppm)	90	69	68	65
Foliar Ca (ppm)	2,300	3,100	3,500	2,800
Foliar Mg (ppm)	1,100	1,100	1,200	1,100
Foliar Mn (ppm)	788	448	391	616
Fe/Mn ratio	0.11	0.15	0.17	0.11
Height (cm)	27.8	23.8	23.8	25.9
Chlorosis (21 May)	no	no	no	no
Chlorosis (9 July)	no	no	some	yes
Chlorosis (24 Aug)	no	no	no	no

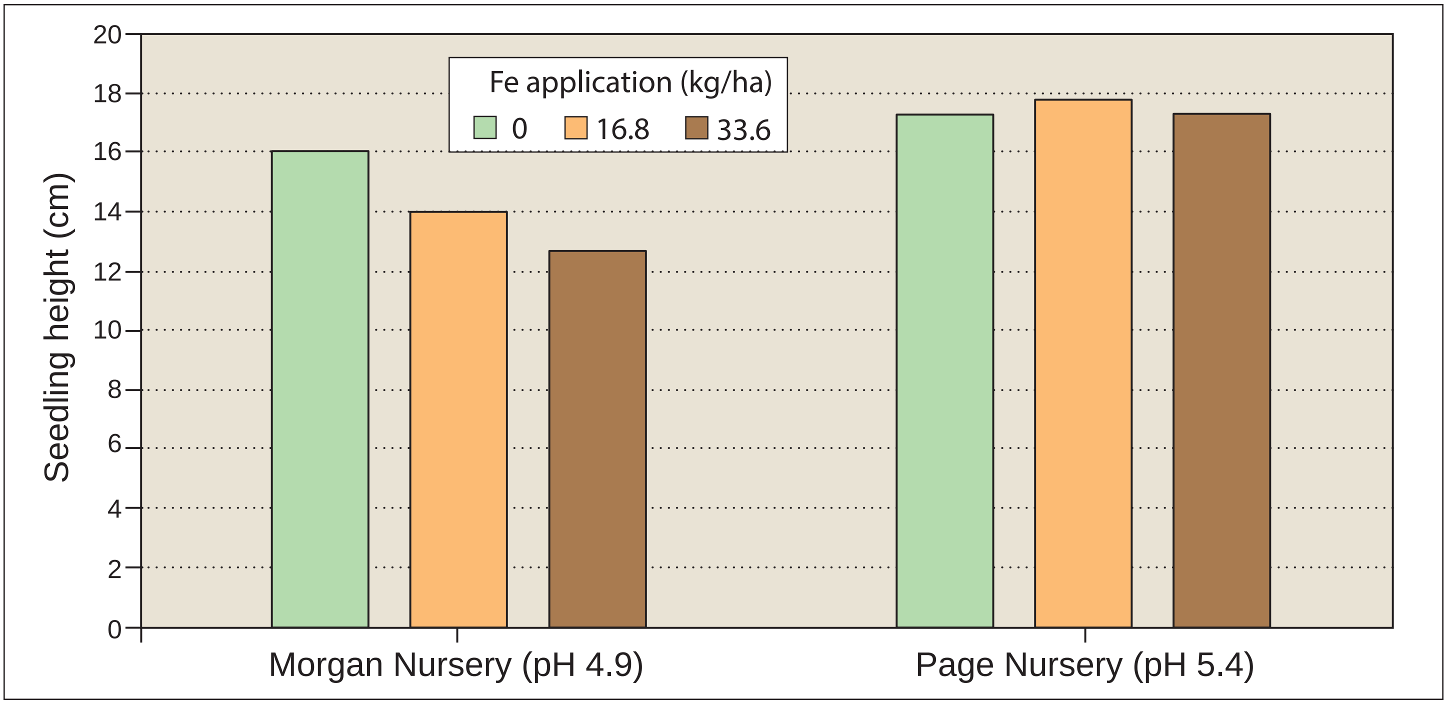

Figure 6. Presow applications of Fe-malonate (Nu-Iron™; Tenn Corp.) affected slash pine seedling height differently at two Georgia nurseries (Steinbeck 1962). Prior to sowing, all plots were treated with 118 kg N/ha, 240 kg P/ha, and 186 kg K/ha. Seed were sown on April 17, 1961 (Morgan Nursery) and April 12 (Page Nursery). Seedlings were treated with 224 kg N/ha in July. Seedlings were measured 149 days after sowing. LSD_{05} = 3.3 cm.

summer chlorosis might have several causes (Hendrix and Campbell 1968, Lewis 1960, Nelson and Switzer 1969), high soil temperatures can reduce Fe^{++} availability and limit both new root growth and soil moisture. Some growers believe they can prevent the occurrence of chlorosis with irrigation (Cloud 1969). In some cases, chlorotic needles occur when soil temperatures exceed 40 °C (table 3).

Summer chlorosis can also result from N fertilization. Several N sources can produce summer chlorosis, but nitrates likely play a key role (Carter 1961, Fisher and Chan 1985, Khalil et al. 1989, Nelson and Selby 1974, van den Driessche 1978). To reduce or prevent summer chlorosis, some managers have decreased

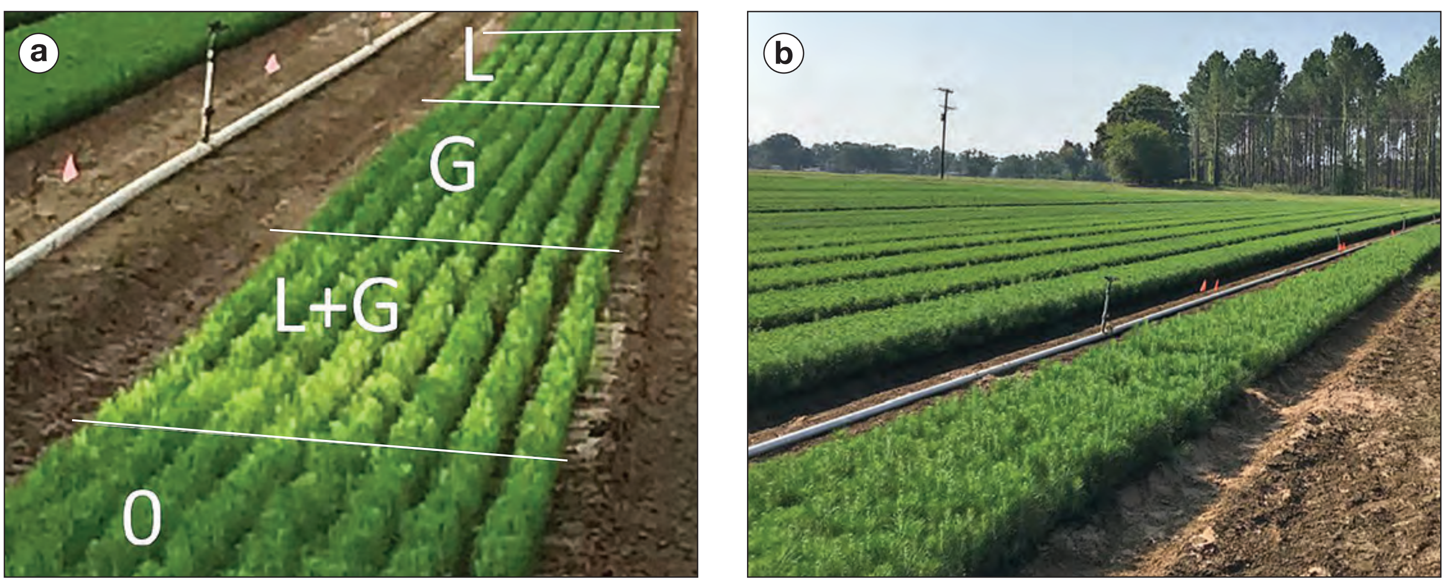

Figure 7. (a) Summer chlorosis (July 9, 2018) was observed for loblolly pine seedlings (L+G; pH 6.7) when growing in soil treated with dolomitic lime and gypsum (see table 3). Slightly chlorotic seedlings (L) were growing in soil treated with only dolomitic lime (pH 7.0). Untreated seedlings (0; pH 4.6) and seedlings growing in soil treated with gypsum (G; pH 5.4) remained green. (b) Without any treatment, all chlorotic seedlings turned green by August 24, 2018. (Photos by Gene Bickerstaff, 2018)

the use of AN (Nelson and Switzer 1969) and have increased application of ATS and UAN.

Although chlorotic needles in summer (figure 7) may initially cause some alarm, many seedlings turn green with cooler weather with no obvious damage (Foster 1959, Steinbeck et al. 1966). For this reason, nursery managers should always leave untreated check plots when they fertilize chlorotic seedlings with Fe. Otherwise, they may never know if the Fe treatment was the true cause of greener needles. Knowing chlorosis lasted about a month, one manager applied a Christmas tree colorant in July to keep loblolly pine seedlings green.

Autumn Chlorosis

After the fall equinox, N concentration in pine needles declines (Irwin et al. 1998, Sung et al. 1997) and can result in some seedlings being yellow at lifting. Growth after transplanting to the field can be positively related to N concentration (Barker 2010, Irwin et al. 1998, Jackson et al. 2012, Larsen et al. 1988) which is related to foliar greenness. When lifted from strongly acid nursery beds, yellow needles in November are typically not deficient in Fe. As a result, field performance of seedlings is positively related to N status but is not positively related to total foliar Fe levels (Boling et al. 2006, Grossnickle and MacDonald 2018, Larsen et al. 1988, van den Driessche 1991). Thus, Fe fertilization is typically unnecessary to address autumn chlorosis.

Soil and Foliage Tests

When using a Mehlich 1 soil test, nursery soils (pH 4.5 to 6.1) can range from 13 to 217 ppm Fe (South and Davey 1983). The Mehlich 3 method extracts more Fe from soils than Mehlich 1 (Sistani et al. 1995) and therefore nursery seedbeds may average 160 ppm Fe (Mehlich 3) instead of 45 ppm Fe (Mehlich 1). Less than 25 ppm Fe (Mehlich 3) is considered very low and 20 ppm Fe is considered a threshold value for deficiency (Davey and McNabb 2019). Likewise, 51 to 100 ppm is considered a medium level. Silt loam soils in Arkansas can average 149 ppm (Mehlich 3) with a range of 67 to 521 ppm (Bhandari and Ficklin 2009).

Foliar analysis can be confusing because total Fe concentration levels (Fe^{++} plus Fe^{+++}) can be higher in stunted seedlings than in healthy foliage (Carter 1980, Landis 1988, Lewis 1960, Mitchell et al. 1990, MacFall et al. 1991, Potvin et al. 2014, South et al. 2018a, Zhang 2015). This effect is referred to as the “chlorosis paradox” (El-Jendoubi et al. 2011, Römheld 2000) and occurs when Fe concentration is increased by a slower growth rate.

Although reports suggest that the standard range for bareroot seedling foliar Fe levels should be different than for container-grown seedlings (Hawkins et al. 2011, Landis 1997), these differences are confounded with stock type and management practices. The cited range for container-grown conifers (40 to 200 ppm) was obtained from a fertilizer company (Landis 1985) while the range for bareroot conifers (50 to 100 ppm) was derived from needles sampled from trees in the forest (Powers 1974). Furthermore, the upper limit of 200 ppm Fe for forest trees is of no practical value for nursery managers who occasionally report values greater than 300 ppm (Baer 1984, Boyer and South 1985, Danielson 1966, Landis 1976). For example, when sampled in July, 45 percent of bareroot loblolly pine samples contained more than 300 ppm Fe, and one sample collected in February had 1,161 ppm Fe (figure 8).

High Soil Phosphorus

In theory, phosphates within the seedling will combine with Fe to make both elements unavailable (Barker and Stratton 2015, Landis 1997). Therefore, it has been suggested that high soil P in nurseries can induce Fe chlorosis (Auten 1945, Foster 1964, Nelson and Switzer 1969, Wallace and Wallace 1986). Research shows, however, that 30 ppm P (Mehlich 3) does not result in Fe chlorosis (Dale et al. 1955, Teng and Timmer 1990, Yawney et al. 1982). In fact, some authors recommend seedbeds have 150 to 300 ppm P (Landis 1988, Solan et al. 1979, Teng and Timmer 1990). Applying 400 ppm P to slash pine growing in sand did not cause an Fe deficiency (van Lear and Smith 1972) and 1,152 kg/ha of P did not cause an Fe deficiency to hybrid poplar cuttings (Teng and Timmer 1990).

Toxicity

Billions of nursery seedlings have been sprayed with Fe with no injury symptoms. Some species were

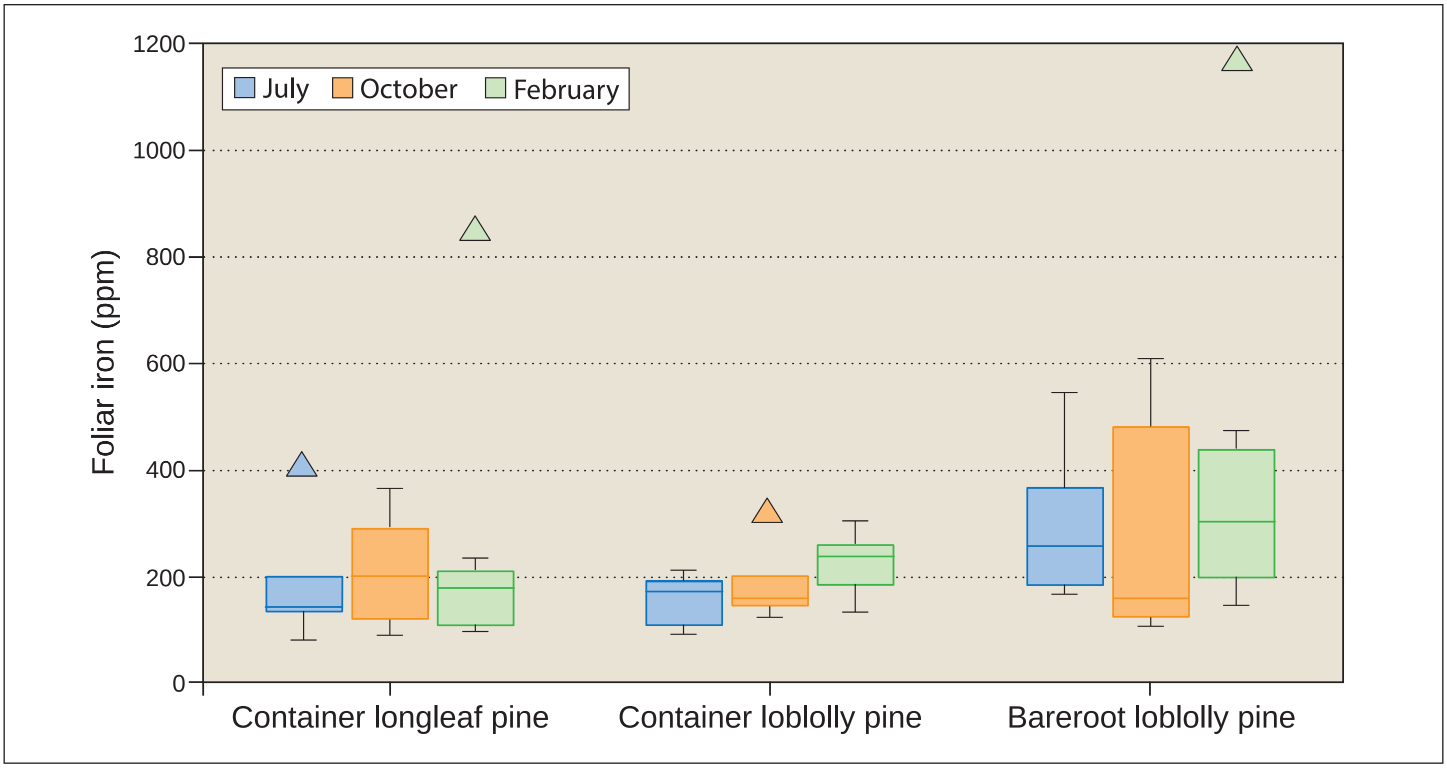

Figure 8. Foliar Fe can vary by sampling month (2010-2011), species, and stock type (Starkey and Enebek 2012). Data are based on 20 bareroot nurseries and 6 to 7 container nurseries with box plots for foliar Fe data (box represents the 25th and 75th percentiles, horizontal line within the box shows the median, and triangles indicate outliers). The lowest Fe values for each month were greater than the 25 to 75 ppm range considered adequate for conifers (Davey 1995). Sampling different species, different nurseries, or in different years will produce different trends.

treated with DTPA containing up to 18 kg/ha of Fe during the growing season (Davey 2002). Under specific circumstances, however, toxicity can occur (Majid 1984). Therefore, some managers lightly irrigate seedlings to reduce the chance of leaf burn (Davey and McNabb 2019). Delaying irrigation for 8 hours after application is likely not important since chelates will wash into the soil where they can be taken up by roots (Landis 1988, Lucena 2006). One HEDTA product is registered for use as an herbicide and applying too much might stunt seedlings (Landis 1997). Likewise, applying a high rate of EDTA can stunt growth of some container-grown conifers (Allen and Hallett 1987, van den Driessche 1989). James (1979) speculated that 614 ppm Fe in pine needles could cause chlorosis, but he was unaware that soil imbedded in epicuticular wax could elevate foliar Fe test results. Likewise, no chlorosis was reported when foliage samples from the Mount Sopris Nursery contained 610 ppm Fe (Landis 1976).

When compared to a foliar application, applying Fe to soil reduces the chance of toxicity. In some soils, high rates of $FeSO_4$ did not reduce pine germination (Cockerill 1957, Davis 1941) but did reduce growth at pH 6.1 (figure 9). Likewise, in a slash pine greenhouse trial, growth reductions may have resulted when soil was treated with 60 kg/ha of $FeSO_4$ (van Lear and Smith 1972).

Soil Fumigation

Methyl bromide fumigation can reduce chlorosis because it reduces nematodes (Hodges 1962), increases the amount of Fe in soil solution (Fraedrich and Dwinell 2003), and sometimes increases Fe concentration in shoots (Danielson 1966). Soil fumigation in the spring may delay ectomycorrhizal formation resulting in P deficient seedlings while Fe in foliage is either increased (Danielson 1966) or unaffected (figure 10).

In non-fumigated soil, nematodes can stunt roots and cause chlorosis in acid nursery soils (Cram and Fraedrich 2012, Hodges 1962, Korstian et al. 1921, Marks et al. 1985). Without close examination, nematode injury may be confused with Fe deficiency. Although it is easy to claim that yellow seedlings in a bareroot nursery are Fe deficient, it is hard to prove by analyzing foliage.

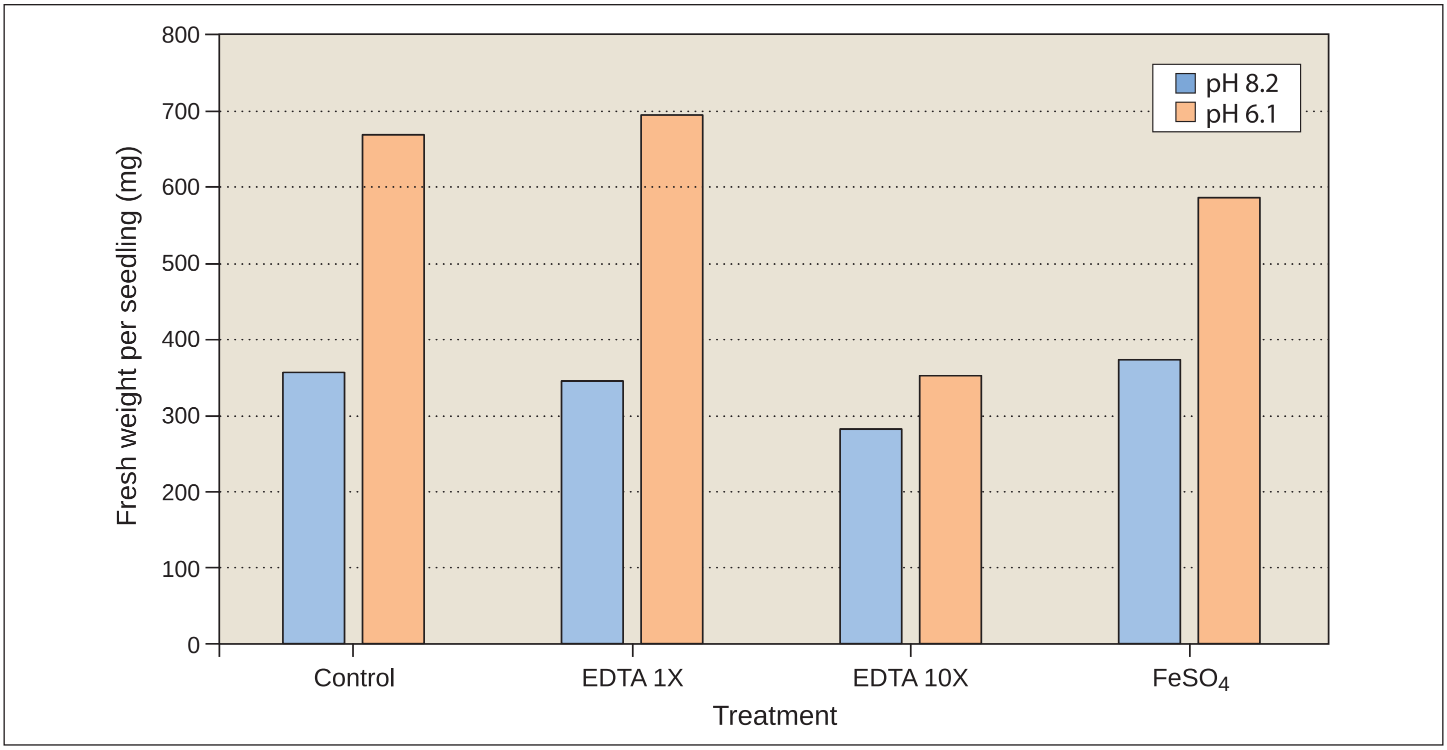

Figure 9. Acidifying an alkaline soil increased growth of small, non-mycorrhizal jack pine (end of first year). A 10X rate of Fe-EDTA (224 kg/ha or 29 kg/ha of Fe) reduced growth (LSD_{05} = 65 mg) (Dale et al. 1955). In the acid soil, an application of $FeSO_4$ (224 kg/ha or 44.8 kg/ha of Fe) also reduced growth. None of the Fe treatments prevented chlorosis in the alkaline soil where non-mycorrhizal seedlings were pale green with purple needle tips and were near death.

Nutrient Removal

The amount of Fe removed when a crop of seedlings is harvested depends on the overall mass of seedlings. Harvesting 1-0 pine seedlings from a nursery can remove 1.0 to 3.5 kg/ha of Fe (Boyer and South 1985, Hopmans and Flinn 1983, Knight 1978, Pritchett and Fisher 1987). Due to soil dynamics, irrigation, atmospheric deposition (Przybysz et al. 2014), and impurities in lime and fertilizers (Dillard et al. 1982, Fan et al. 2012, MikosSzymańska et al. 2019), most nursery managers need not worry about depleting Fe

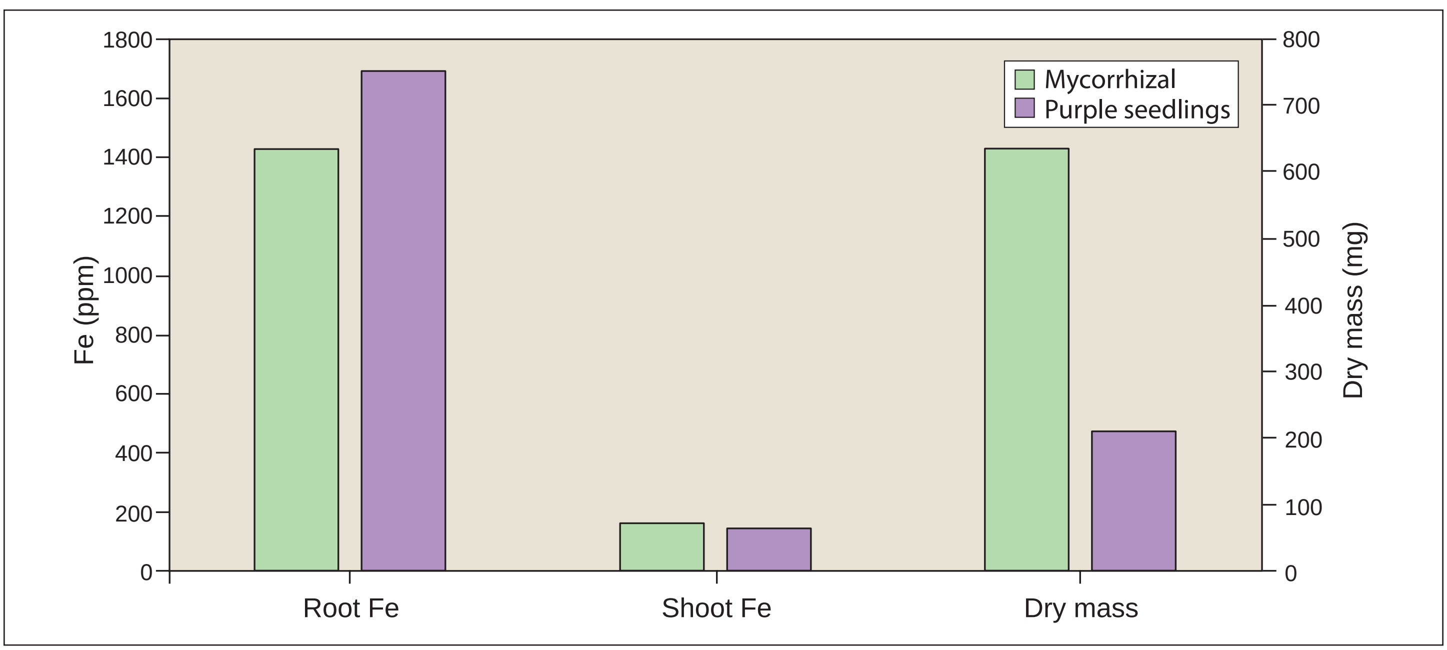

Figure 10. Mycorrhiza increased P uptake and seedling mass ($P<0.003$) but reduced root Fe concentrations ($P=0.029$) at the Union Camp Nursery in Alabama (July 1986). Shoot Fe concentrations were unaffected ($P=0.16$). The LSD_{05} was 29 ppm Fe for shoots and 214 ppm Fe for roots. Prior to sowing, the soil was fumigated with 439 kg/ha of methyl bromide plus 9 kg/ha of chloropicrin (South et al. 1988) and the soil contained 16 ppm Fe (DPTA extraction).

levels. About one-third of bareroot nurseries in the South did not apply Fe fertilizers in 2020. When irrigation water contains 0.2 ppm Fe, 1,000 mm of irrigation will add 2 kg/ha of Fe to the soil.

Although some nursery managers apply organic matter to replace nutrients, this practice is not always effective in increasing soluble Fe levels. Applying 6.7 tonnes/ha of pine bark added 10 kg of Fe at one alkaline nursery but did not increase either soil solution Fe or foliar Fe (Mexal and Fisher 1987). At one nursery in Tennessee, mulch applied after sowing added 18 to 30 kg/ha of Fe (dos Santos 2006).

Hidden Hunger

A hidden hunger exists when there are no visual deficiency symptoms (Landis et al. 2005), but addition of fertilizer increases growth (figure 11). Foliar Fe is adequate in cases where adding more Fe does not increase growth. A hidden hunger does not exist when a treatment increases the chlorophyll concentration but does not increase subsequent growth. The critical point (Landis et al. 2005) is the concentration value that separates the deficient zone from the adequate zone. In one greenhouse trial, 28 ppm Fe in the shoot was deficient and 31 ppm was adequate (van den Driessche 1989). Unfortunately, too few Fe trials exist to accurately identify a critical point. Thus, estimates for bareroot seedlings are quite variable. For example, estimates of adequate Fe in pine needles vary from 15 ppm (Jokela 2004), to 25 ppm (Aldhous and Mason 1994, Davey 1995), to 50 ppm (Ballard and Carter 1986, Garrison-Johnston et al. 2005, Hawkins et al. 2011). As a precaution, some managers apply Fe chelate when foliage Fe tests drop below 100 ppm. It is a misconception that loblolly pine hedges should contain 400 ppm Fe. For example, cuttings taken from hedges ranged from 36 to 57 ppm Fe (Rowe 1996).

Without using check plots, some managers may assume seedlings have a hidden hunger and routinely apply Fe chelates. The only way to prove a hidden hunger exists for Fe is to apply an effective Fe chelate and compare the biomass of treated and non-treated seedlings. Use of $FeSO_4$ is not recommended when testing for hidden hunger for Fe because a growth response could be due to a hidden hunger for S (Browder et al. 2005, Lyle and Pierce 1968).

Soil Imbedded in Epicuticular Wax

Foliar Fe in bareroot pine seedlings has varied from 40 to 2,638 ppm in the USA (Baer 1984, Boyer and South 1985, Iyer and Wilde 1974, Landis 1976, Landis 1988), 104 to 483 ppm in New Zealand (Knight 1978), 36 to 382 ppm in Finland (Jalkanen and Rikala 1995), and 85 to 440 ppm in Australia (Flinn et al 1980, Hopmans and Flinn 1983). Leaves or needles with Fe values above 300 ppm are likely contaminated with soil, dust, or fertilizer residues (Jacobson 1945, Przbysz et al. 2014).

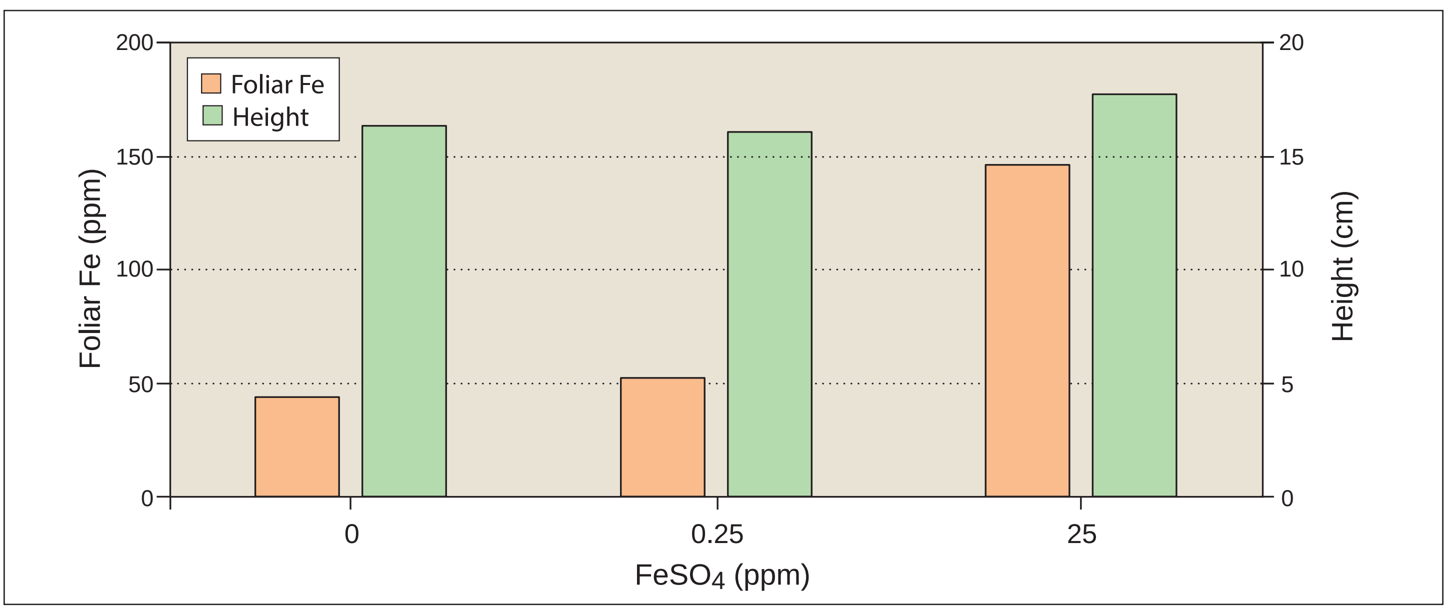

Figure 11. Soil applications of $FeSO_4$ applied every 2 days affected height growth and nutrient concentrations of lodgepole pine foliage in a greenhouse (Majid 1984). Seedlings were grown in sand (pH < 5.6) and were fertilized with 100 ppm N and 69 ppm S. The 25-ppm $FeSO_4$ rate increased height growth and foliar Fe concentrations (α= 0.05) and lowered foliar S concentration.

At one nursery, container-grown loblolly pine foliage averaged 110 ppm Fe (range 95 to 120 ppm) which was similar to bareroot seedlings grown in an adjacent field (average 93 ppm; range 78 to 117 ppm). Values from a more distant bareroot field, however, averaged 2,131 ppm Fe (range 1,461 to 2,638 ppm). Apparently, wind-blown soil and dust can become imbedded in the epicuticular wax (Boyer and South 1985, Oserkowsky 1933, Przybysz et al. 2014, Weyttenbach et al. 1985) and will elevate foliar values for both Fe and Al.

Foliar values for Fe are typically not useful for diagnostic purposes (Landis et al. 2005) unless the wax is removed prior to sample digestion. After washing needles for 30 seconds in chloroform, green needles may contain 24 to 29 ppm Fe and deficient needles may contain 14 ppm (Van Dijk and Bienfait 1993). Values this low are almost never reported for conifer needles with wax. A light washing of samples using a colander and distilled water can be used (Krueger 1967), but this practice is not as effective as washing with a solution of HCl (Jacobson 1945). For North America, it appears the "adequate" Fe ranges for pine were estimated without first removing epicuticular wax with chloroform.

Typically, the concentration of N and K in pine needles declines after fertilization ceases while the concentration of Fe increases (Baer 1984, Baer 1985, Rowe 1996, Starkey and Enebak 2012, Sung et al. 2019). Foliar Fe concentration in loblolly pine needles can increase from October to January (figure 8) which may be due to accumulation of soil in the epicuticular wax. At one nursery, Fe in bareroot loblolly pine needles averaged 55, 199, 66, and 118 ppm in June, July, August, and November, respectively (LSD_{05} = 88 ppm). The 66 percent drop from July to August was likely due to sampling new foliar growth with less soil contamination (Nelson and Selby 1974). At some nurseries, foliar Fe concentration can double after the second growing season (1-0 = 185 ppm; 2-0 = 380 ppm; Landis 1976).

Fe/Mn Ratio in Foliage

Too much Mn can interfere with uptake or translocation of Fe (Lafond and Laflamme 1970, Morrison and Armson 1968). Therefore, some laboratories calculate a foliar Fe/Mn ratio. In laboratory reports, the expected ratio varies from 0.3 to 0.7. The ratios for good-quality seedlings (July) can range from 0.11 to 4.8 for loblolly pine, from 0.28 to 5.8 for ponderosa pine (Baer 1984, Starkey and Enebak 2012), and from 0.18 to 0.36 for loblolly pine cuttings (Rowe 1996). High Fe/Mn ratios are not a problem since they are likely due to soil imbedded in epicuticular wax. Thus, it is a misconception that the desired Fe/Mn ratio for loblolly pine seedlings should range from 1.3 to 1.7. Chlorotic needles and stunted pine seedlings may occur when foliage contains too much Mn relative to Fe (e.g., 86 ppm Fe and 1,895 ppm Mn). For jack pine, the foliar Mn concentration alone is more operationally meaningful than the Fe/Mn ratio (Morrison and Armson 1968).

Cost

Some managers assume a hidden hunger for Fe exists and proactively apply DTPA several times during the growing season. The cost for these applications can exceed $800/ha/crop. At many nurseries, there is no need to apply Fe chelates (Landis 1997), so some managers have not purchased DTPA in more than 2 decades. Because of the expense, Fe chelates should not be used unless there is a clear need (Davey 1984). Since EDTA products can degrade when tank mixed with certain fertilizers, it might be wise to treat seedbeds soon after mixing to improve the cost effectiveness of the treatment (Albano and Miller 2001).

The cost (2020 USD) of 3 kg of Fe can vary from $20 (solid $FeSO_4$), to $115 (liquid $FeSO_4$), to $240 (EDTA), to $885 (DTPA), to $1,760 (EDDHA). When EDDHA products are applied, the cost typically exceeds 10 percent of the total fertilizer cost (Fisher and Chan 1985, Martian 1989, Mexal and Fisher 1987). Even so, for many managers, efficacy is more important than price (Mexal et al. 2004). For example, when an effective treatment increases nursery production by 3,600 seedlings/ha, the increase in revenue can equal $1,800 (when seedlings are sold for 50 cents each). Therefore, at some nurseries with alkaline soils, an increase of 0.3 percent in plantable seedlings could justify applying EDDHA chelates.

In some studies, applying $FeSO_4$ was more cost effective than applying either EDTA (figure 5) or EDDHA (Chakraborty et al. 2014, Ferrarezi et al. 2007, Mexal et al. 2004). Although comparison trials are not available for bareroot nurseries, some managers choose to apply the less expensive liquid $FeSO_4$ products (table 2).

Conclusions

There is no need to apply Fe chelates to bareroot pine seedlings when unlimed soil (pH 4.0 to 5.5) is irrigated with water low in bicarbonates. To improve usefulness of foliar tests, researchers should first remove epicuticular wax from pine needles before analyzing for Fe.

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