Optimum pH for Growing Pine Seedlings

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Abstract

Two schools of thought address the optimum soil pH (measured in water) for growing pine seedlings (*Pinus* spp.) in bareroot nurseries. One school uses nutrient availability charts to determine the best pH range for growing conifers. Students of this school believe pine seedlings grow best at pH 5.5 to 6.5. In contrast, another school uses research from nursery trials to conclude that pines grow best in "very strong acid" soils (pH 4.5 to 5.0). This article compiles some of the findings from seedbed and greenhouse trials and attempts to use data to dispel a few myths about growing pine seedlings in soils with pH less than 5.0. This paper was presented at the Joint Meeting of the Northeast Forest and Conservation Nursery Association and Southern Forest Nursery Association (Lake Charles, LA, July 18–21, 2016).

Introduction

It may be surprising, but there is no consensus on the pH (measured in water) range for growing pine seedlings (table 1). In some cases, the "optimum" ranges do not even overlap. Recommendations from the United States typically involve a minimum of pH 5.0 to 5.5. In contrast, some recommendations from other countries set pH 5.0 as the maximum value (table 1). I agree with Bryan et al. (1989: p. 64) that "some of the pH ranges suggested for conifers result in slow growth and unhealthy seedlings..." Not only is the pH 5.5 to 6.5 range too high for Fraser fir (*Abies fraseri* [Pursh] Poir.) (Bryan et al. 1989), but this range is also too high for loblolly pine (*Pinus taeda* L.) (Marx 1990). Indeed, sowing loblolly pine seed at pH greater than 5.5 resulted in smaller seedlings (requiring extra nitrogen [N] fertilization), and in some cases, chlorotic seedlings (figure 1). One might ask why some recommend a pH range of 4.5 to 5.0 (Aldhous 1972, Brix and van den Driessche 1974, Januszek and Barczyk 2003) or 4.2 to 4.5 (Bryan et al. 1989), while others recommend a range of 5.5 to 6.5 (table 1).

Table 1. The recommended pH range for bareroot pine seedbeds varies considerably. Most U.S. authors suggest a minimum pH of 5.0 or greater.

Recommended pH range	Country	Reference
5.5–6.5	USA	Steinbeck et al. (1966)
5.5–6.5	USA	Solan et al. (1979)
5.5–6.5	USA	Youngberg (1984)
5.5–6.5	USA	Landis (1988)
5.5–6.5	USA	Bueno et al. (2012)
5.5–6.0	USA	Leaf et al. (1978)
5.5–6.0	USA	May (1966)
5.3–5.6	USA	Stoeckeler (1949)
5.2–6.2	USA	Davey (1984)
5.2–5.8	USA	Stoeckeler and Jones (1957)
5.2–5.8	USA	Stone (1965)
5.0–6.0	USA	Wilde (1934)
5.0–6.0	USA	Wakeley (1954)
5.0–6.0	USA	Switzer and Nelson (1967)
5.0–6.0	Canada	Armson and Sadrika (1979)
5.0–6.0	USA	Tinus (1980)
5.0–5.5	USA	Wilde (1958)
5.0–5.5	USA	Barnett (1974)
5.0–5.5	Canada	Carlson (1979)
5.0–5.5	USA	South and Davey (1983)
4.5–6.5	USA	Wakeley (1935)
4.5–6.0	Canada	Van den Driessche (1980)
4.5–5.5	Latvia	Mangalis (in Donald 1991)
4.5–5.5	USA	South (this article)
4.5–5.0	UK	Aldhous (1972)
4.5–5.0	Canada	Brix and van den Driessche (1974)
4.4–4.6	Poland	Januszek and Barczyk (2003)
4.0–5.0	Germany	Rehfuess in Donald (1991)

After reviewing the literature, it became apparent that the lower pH recommendations were based on empirical nursery trials (Benzian 1965, Januszek and Barczyk 2003, van den Driessche 1971) while the higher pH recommendations were based primarily

Figure 1. Applying too much lime 2 weeks prior to sowing slash pine (*Pinus elliottii*) seed can result in chlorosis. (Photo by Jack May, University of Georgia, 1961)

on nutrient availability charts that suggest pH 5.5 to 6.5 is optimal for the growth of agronomic species; these species include ryegrass (*Lolium* spp.) and velvet beans (*Mucuna pruriens* (L.) DC.) (Ankerman and Large 2001). In one survey, the average pH for 43 loblolly pine plantations was about 4.8, and the researchers reported a positive correlation (r = 0.4) between soil exchangeable acidity (meq per 100 g of soil) and volume growth (NCSFNC 1991). Likewise, when compared to pH 5.8, loblolly pine sown in soil at pH 4.8 required less N fertilization to reach the target shoot mass (Marx 1990). The purpose of this paper is to review pH research in conifer nurseries and to dispel a few myths about growing pine seedlings on "very strong acid" soils.

Bareroot Nurseries

Liming trials in the United Kingdom determined the optimum pH range for several pines to be 4.5 to 5.0 (Benzian 1965). In contrast, only a few liming trials in bareroot nurseries have been published in the United States. A few trials were conducted at nurseries where soil calcium (Ca) and/or magnesium (Mg) were likely deficient, and as a result, liming reduced needle chlorosis (Stoeckeler and Jones 1957, Voigt et al. 1958, Will 1961). At nurseries where Ca and/or Mg are not deficient, however, applying lime can induce chlorosis and reduce growth. For example, applying 2,240 kg/ha of dolomitic lime 2 weeks before sowing pine seed increased chlorosis at two nurseries in Georgia (Steinbeck et al. 1966). In Louisiana, applying lime (4,480 kg/ha) and fertilizer in April caused seedling chlorosis in May (Shoulders and Czabator 1965).

Studies have demonstrated a correlation between nursery soil pH and seedling growth. In Poland, a sulfur trial with Scots pine (*Pinus sylvestris* L.) showed optimal growth at pH 4.4 to 4.6 (Januszek and Barczyk 2003). Results from a liming trial at a nursery at the University of Georgia (Marx 1990) showed that five genotypes of loblolly pine seedlings grew best at pH 4.8 (figure 2). Armson and Sadreika (1979) examined seedling mass for four nurseries in Ontario and found that red pine (*Pinus resinosus* Aiton.) mass increased about 50 percent (0.6 g) when pH was 5.4 (vs. pH 6.4). Marx et al. (1984) measured soil pH at the time of sowing over a 4-year period, 1977 to 1980, at 30 operational pine nurseries in the United States. These data indicate that pH 4.5 might increase the fresh weight of seedlings by about 33 percent compared with seedlings grown in soils at pH 5.5 (figure 3).

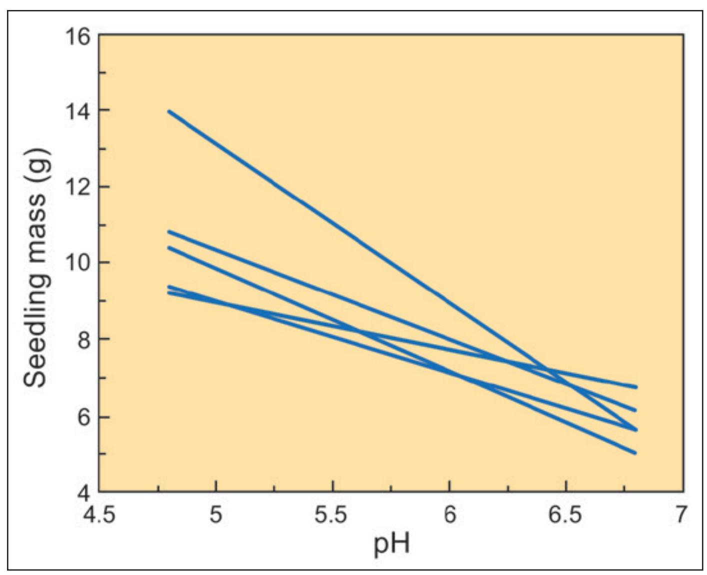

Figure 2. Relationship between seedling mass and soil pH (at time of sowing) for five genotypes of bareroot loblolly pine (*Pinus taeda*) seedlings (adapted from Marx 1990). Prior to adding lime, the soil pH averaged 4.8. After adding 2,850 or 5,700 kg/ha of slacked lime, the soil pH (at sowing) averaged 5.8 and 6.8, respectively. For one genotype (top line), seedling mass was 77 and 130 percent greater on plots with no lime (pH 4.8) versus plots that averaged pH of 5.8 and 6.8, respectively.

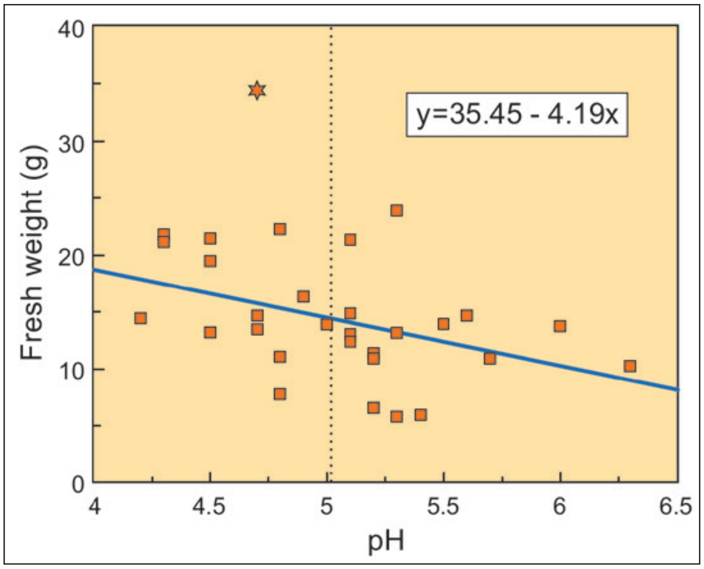

Figure 3. Operational data (control plots) from seedlings grown in 31 different nursery soils indicate a general relationship between soil pH at sowing and fresh weight of pine seedlings at lifting (adapted from Marx et al. 1984). Data include loblolly pine (*Pinus taeda*; n=20), slash pine (*Pinus elliottii*; n=4), Virginia pine (*Pinus virginiana*; n=4), and shortleaf pine (*Pinus echinata*; n=3). The statistical equation (n = 30) does not include the star data point (Westvaco Nursery) since the large seedlings (34.4 g) were grown at a low seedbed density of 150 seedlings per m2. The average fresh weight of seedlings to the left of the dashed line (below 5.05 pH) was 16.1 g (n=14), and the average fresh weight of seedling to the right of the line (above 5.0 pH) was 12.7 g (n = 16). The linear regression indicates lowering pH from 5.5 to 4.5 might increase seedling fresh weight by about 33 percent.

Greenhouse Trials

A number of greenhouse studies indicate pine seedling mass increases as soil acidity increases (i.e. pH decreases) (table 2, Ivanov et al. 2013). Results from these trials can be used to reject the hypothesis that pines grow best at pH 5.2 to pH 6.6. In most of these trials, supplemental fertilization (with N, potassium [K], and phosphorus [P]) was held constant, regardless of pH treatment indicating that increasing acidity to below pH 5.0 can increase nutrient use efficiency (e.g. uptake of N mass in foliage) (Kakei and Clifford 2000). In many cases (table 2), the overall uptake of biomass (and associated nutrients) is increased by 20 percent or more.

Concerns over harmful effects of acid rain helped fund studies (table 3) that examined the effects of acidification of irrigation water with nitric acid and/or sulfuric acid. Typically, the acidified water gradually decreased soil pH as the number of irrigations increased. In most studies with pine, the growth response was positive when small amounts of nitric acid (and other acids) were added to irrigation water (table 3).

Some caution is recommended, however, when making conclusions based on acid rain trials. Natural rainfall (greater than pH 4.0) typically does not injure pine needles. Acid irrigation trials in which pH is lowered by adding nitric acid or sulfuric acid to distilled water to create a high acid treatment (i.e., pH 3.3), however, can result in a negative growth effect (McLaughlin et al. 1994). One should not simply assume irrigation with water at pH 3.3 would produce similar results to growing seedlings in a soil at pH 3.3 (where foliar injury from acids does not occur). Likewise, one should also not assume that applying sulfuric acid just prior to transplanting pines will not injure roots (Shan et al. 1997, van den Driessche 1972).

When To Add Lime

Stoeckeler and Jones (1957) reported that finely ground limestone should not be applied before sowing conifer seed; Steinbeck et al. (1966) said limestone normally should be applied preceding a cover crop; and Wakeley (1954) said that application of lime to increase soil pH should be avoided unless definite evidence of a need exists. The fear of liming prior to sowing pines may have originated from concern over seedling losses, as the rate of damping-off increases with the rate of liming (Chapman 1941, Stoeckeler 1949, Voigt et al. 1958). This concern, however, decreased after soil fumigation with methyl bromide became a common practice. Therefore, some now say pine seed may be sown about 3 weeks after liming. Without methyl bromide, damping-off can increase when alkaline water is used to irrigate pine seedbeds (Januszek et al. 2014).

Because of the high genetic value of pine seedlings today, most nursery managers do not wait until evidence of a low pH problem appears. Therefore, most managers add lime prophylactically according to general guidelines found in nursery manuals (Stoeckeler and Jones 1957; van den Driessche 1969, 1984). In the past, some growers applied lime when soil acidity reached pH 5.4 (Solan et al. 1979: figures 4, 5), while others limed at pH 4.0 to 4.2 (Stoeckeler 1949, Stoeckeler and Arneman 1960). In British Columbia, several bareroot nurseries produced conifers at pH 4.4 (Maxwell 1988). In contrast, when one loblolly pine seedbed (which has a cation exchange capacity [CEC] of 3.4) reached pH 6.1 in 2016, one agronomist suggested applying 1,120 kg/ha of lime to raise the pH to 6.5.

Table 2. Examples of greenhouse trials demonstrating the change (%) in seedling mass (mg) when seedlings are grown at different pH levels. In most cases, mass increased with decreasing pH.

Species	pH #1	pH #2	Mass #1 (mg)	Mass #2 (mg)	Change in mass with decreased pH (%)	Reference
Pinus. radiata D. Don	6.2	4.5	1,610	1,160	– 28	Theodorou and Bowen (1969)
P. sylvestris L.	6.2	4.0	~150	~125	– 17	Erland and Söderström (1990)
P. elliottii Engelm.	6.8	5.8	1,900	1,610*	– 15	van den Driessche (1972)
P. elliottii Engelm.	5.6	4.0	217	242	11	Marx and Zak (1965)
*P. elliotti*i Engelm.	6.8	5.5	580	660	14	van den Driessche (1972)
P. resinosa Aiton	6.0	5.0	7,630	8,980	18	Mullin (1964)
P. radiata D. Don	6.1	4.2	2,170	2,660	22	Theodorou and Bowen (1969)
P. contorta Douglas ex Loudon	6.1	4.2	131	161	23	Griffin (1958)
P. rigida Mill.	5.6	4.6	590	730	24	Helm and Kuser (1991)
P. strobus L.	5.6.	4.3	330	410	24	Sundling et al. (1932)
P. banksiana Lamb.	5.6	4.3	310	390	25	Sundling et al. (1932)
P. resinosa Aiton.	5.6	4.3	310	400	29	Sundling et al. (1932)
P. taeda L.	6.5	4.5	1,060	1,411	33	Harbin (1985)
P. elliottii Engelm.	7.0	5.8	1,140	1,610	41	van den Driessche (1972)
P. ponderosa Law.	6.0	4.0	2,950	4,350	47	Howell (1932)
P. sylvestris L.	5.8	4.4	72	107	49	Wallander et al. (1997)
P. radiata D. Don	6.1	4.5	205	310	51	de Vires (1963)
P. sylvestris L.	6.0	4.5	380	600	58	Rikala and Jozefek (1990)
P. sylvestris L.	6.2	5.5	63	100	59	Carter (1987)
P. elliottii Engelm.	6.9	5.8	4,680	8,090	73	Richards and Wilson (1963)
P. banksiana Lamb.	8.2	6.1	357	669	87	Dale et al. (1955)
P.contorta Douglas ex Loudon	4.9	4.0	80	165	106	Danielson and Visser (1989)
P. radiata D. Don	7.5	6.7	670	2,810	319	Richards (1965)
Larix kaempferi (Lamb.) Carr.	4.9	4.5	~217	~272	25	Choi et al. (2008)
Pseudotsuga menziesii (Mirb.) Franco	5.4	4.0	4,220	5,390	28	van den Driessche (1971)
Abies fraseri (Pursh) Poir.	5.0	4.5	1,896	2,438	29	Bryan et al. (1989)
Taxodium distichum (L.) Rich.	6.0**	4.5	4,100	7,200	75	Hinesley et al. (2001)

~ = approximately. mg = milligrams.

* Sand-vermiculite media treated with 28,062 L/ha of 1N sulfuric acid.

** Estimated from Wright et al. 1999.

Several managers prefer dolomitic lime because it contains Mg (Altland and Jeong 2016, Davey 2002). The rate applied varies with initial soil pH, soil texture, organic matter, and desired pH. From a survey of 11 nurseries (Marx et al. 1984), one manager applied lime at 560 kg/ha, seven applied lime at 1,120 kg/ha, and three applied lime at 1,680 to 2,240 kg/ha. Examples of increasing soil pH with dolomitic lime are provided in figure 4.

When soil is at pH 5.2, less lime will be required to raise pH to 5.5 than to raise the pH to 6.5. For example, at one nursery, two applications of dolomitic lime raised the pH to 6.5 (figure 5). At the time of sowing the pine seed (spring of 1995), the soil was at pH 6.3. Pines growing in soils with pH greater than 6.0 often exhibit "summer chlorosis" in June and July soon after the first N application. Over time, several nursery managers realized that iron (Fe) chlorosis seldom occurs at pH 5.5 (Mizell 1980). Adding lime at pH 5.2 can reduce pine seedling growth (Coultas et al. 1991, Marx 1990), increase the risk of damping-off (Bickelhaupt 1989, Griffin 1958, Helm and Kuser 1991, Pawuk 1981, Voigt et al. 1958) (figure 6), reduce uptake of N (Carter

Table 3. The effect of acidifying irrigation water on pine seedling mass (mg). Mass #1 and mass #2 correspond to the dry mass of seedlings irrigated with water pH #1 or water pH #2, respectively.

Genus/species	Water pH #1	Water pH #2	Mass #1 (mg)	Mass #2 (mg)	Change in mass with decreased pH (%)	Reference
Pinus taeda L.	4.5	3.0	750	680	– 9	Seiler and Paganelli (1987)
P. elliottii Engelm.	5.5	3.5	2,390	2,170	– 9	Hart et al. (1986)
P. ponderosa Law.	5.6	2.0	1,780	1,770	– 1	McColl and Johnson (1983)
P. strobus L.	5.6	3.0	436	435	0	Reich et al. (1987)
P. taeda L.	4.8	3.6	503	501	0	Walker and McLaughlin (1993)
P. strobus L.	5.7	3.0	68	69	+1	Lee and Weber (1979)
P. rigida Mill.	5.6	4.0	49	51	+4	Schier (1986)
P. taeda L.	5.6	2.4	930	970	+4	Shafer et al. (1985)
P. strobus L.	5.6	3.0	631	693	+10	Reich et al. (1987)
P. banksiana Lamb.	4.7	2.5	83	93	+12	MacDonald et al. (1986)
P. echinata Mill.	5.6	4.0	48	54	+12	Schier (1987)
P. strobus L.	6.0	4.0	490	600	+22	Wood and Bormann (1977)
P. strobus L.	5.6	3.0	424	644	+52	Reich et al. (1987)

mg = milligrams.

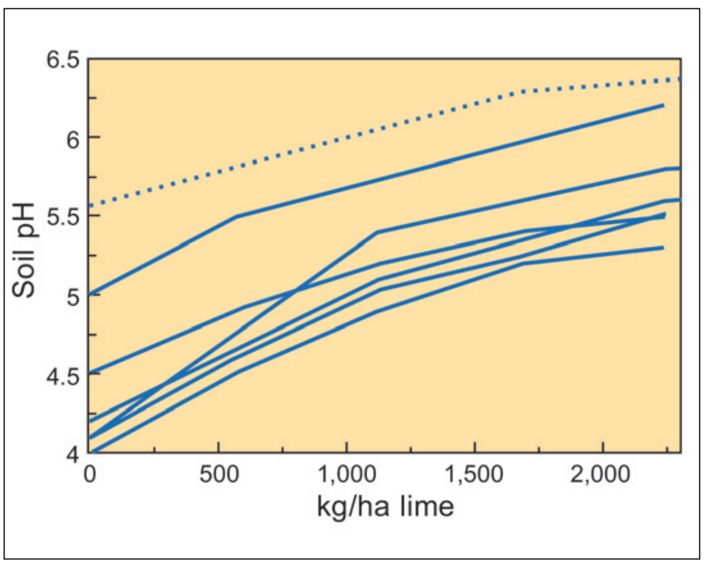

Figure 4. Examples from research trials illustrate the effect of slacked lime (dashed line) or dolomitic lime (solid lines) on soil pH in nurseries. Data are from trials in Wisconsin (Stoeckeler and Jones 1957, Voigt et al. 1958), Louisiana (Shoulders and Czabator 1965), and British Columbia (van den Driessche 1969).

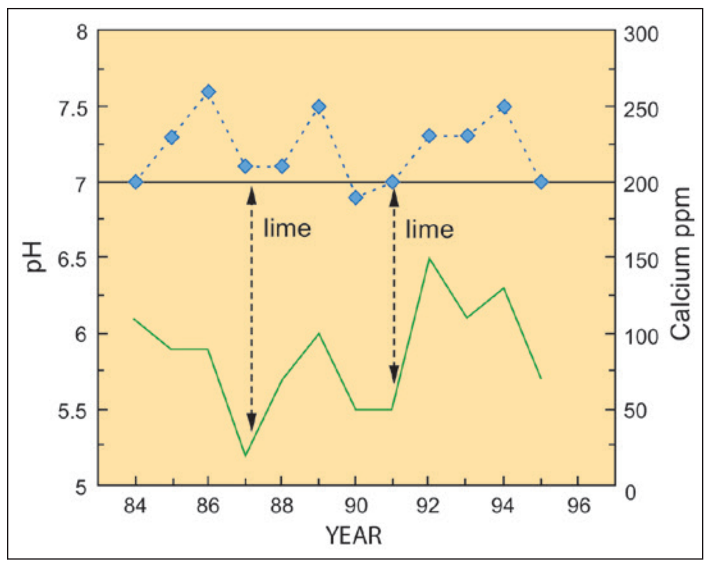

Figure 5. Operational data are from field i3 at the Westvaco Nursery in South Carolina. Dolomitic lime was added to the soil in the spring of 1987 (2,240 kg/ha) and again in the spring of 1991 (1,450 kg/ha). Both applications increased the availability of calcium (dotted line), and the second application increased soil pH to 6.5 (solid line). For each year, soil samples were collected in November.

1987, Kakei and Clifford 2000), and increase chlorosis (Richards 1965, Shoulders and Czabator 1965) (figure 1).

Gypsum, not lime, is recommended when soil pH is in the desirable range but Ca levels are low. In sandy nurseries, chlorosis and resin exudation may occur when available soil Ca is less than 100 ppm. When this happens, adding Ca will produce green needles and may increase foliar Ca levels to greater than 29 ppm (Voigt et al. 1958). Since the median level of Ca in sandy nurseries is 200 ppm (South and Davey

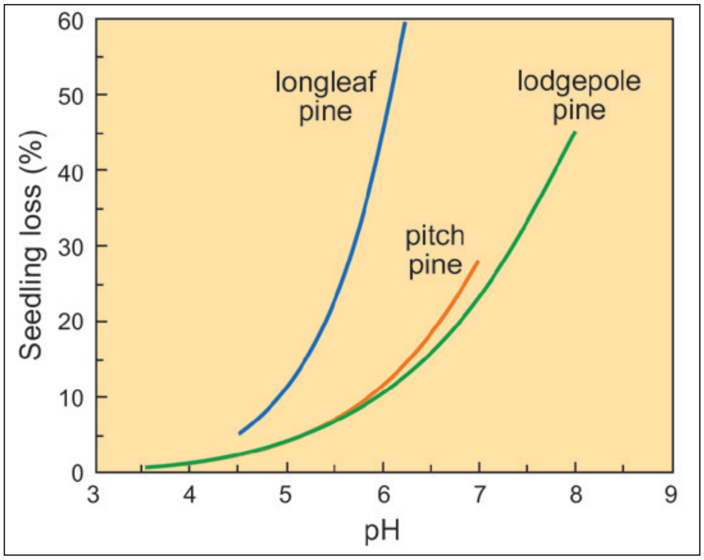

Figure 6. The relationship between pH and damping-off of pine seedlings in greenhouses. Data are for longleaf pine (*Pinus palustris*) (Pawuk 1981), pitch pine (*Pinus rigida*) (Helm and Kuser 1991), and lodgepole pine *(Pinus contorta*) (Griffin 1958).

1983), most managers add Ca when soil tests show levels below 200 ppm (e.g. figure 5).

When should lime be applied to bareroot pine beds to increase pH? Operational data show good growth of pine seedlings when soil pH is less than 4.5. In 2016, fertilized loblolly pine seedlings (in one experimental plot) grew well at pH 3.5 at a nursery in Texas (figure 7). In 1977–78, pine seedlings performed well at pH 4.2 (Griffith Nursery, NC and Nepco Lake Nursery, WI) and pH 4.3 (Ashe Nursery, MS and Vallonia Nursery, IN) (Marx et al. 1984). Other studies have shown that some pines grow well at pH 3.6 to 3.8 in the field (Marx et al. 1995, NCSFNC 1991, Woodwell 1958). On the other hand, stunted pines have been observed at pH 3.6 (Carey et al. 2002) and pH 2.9 (Sundling et al. 1932), and stunted Larix seedlings have been observed at pH 3.8 (Choi et al. 2008). Since poor soil sampling can yield variable results, a tentative trigger point for liming nursery soil might be pH 4.4. This is 0.3 units lower than the current trigger value for southern pines and 0.7 units lower than the value used in the past. In contrast, where manganese (Mn) toxicity is possible, it would be wise to lime when soil pH reaches 4.9. Lowering the trigger value for lime to pH 4.4 might save money. First, the frequency of liming would likely be reduced, since it will take longer for soil to reach this level of acidity. Second, the cost per kg of lime applied would be lower, since the biggest cost of liming is the application. Thirdly, for some soils, the nutrient use efficiency may increase when pine seedlings are grown in soil at pH 4.5 to 5.0. As a result, less N would be required (versus pH 6.0 to 6.5) to produce the desired "target seedling" (Marx 1990).

Figure 7. This photo shows loblolly pine (*Pinus taeda*) seedlings (average 32 cm height and 8.2 mm root-collar diameter; measured in February) in pH 3.5 to 3.6 soil. Soil in this plot was treated with 2,440 kg/ha of elemental sulfur on April 9, and seed were sown on April 16, 2016. Rainfall during the 2 weeks following sowing was above average (330 mm total). The topsoil in this plot contained 96 ppm of sulfur in July. If rainfall had been low, however, gypsum crystals (figure 8) might have formed and stunted the seedlings. (Photo by Gene Bickerstaff, Arborgen, 2017).

When To Add Sulfur

Sulfur has been beneficial at several nurseries. At a nursery in New York (80 to 90 percent sand; CEC 8 to 11), adding 2,000 kg/ha of sulfur (as sulfuric acid) increased soil acidity, from pH 6.5 to 6.2, and doubled seedling production (Bickelhaupt 1987). At a pine nursery in North Dakota (silt loam, organic matter 4.6 percent, pH 7.9), applying 1,525 kg/ha of sulfur at the time of sowing increased acidity (to pH 6.8) and doubled seedling mass (Stoeckler and Arneman 1960). At a nursery in Ontario (83 percent sand; CEC 4 to 8), 840 kg/ha of elemental sulfur lowered soil pH, from 6.5 to 6.0, and increased seedling production by 8 percent (Mullin 1964). In Poland, adding 1,200 kg/ha of sulfur increased root-collar diameter of Scots pine (Januszek and Barczyk 2003).

Operational timing of sulfur applications to lower soil pH varies widely. Some nursery managers apply ammonium sulfate or elemental sulfur when the soil pH is at 6.6, while others apply sulfur at pH 6.0 (Mizell 1980). In the Southern United States, 900 kg/ha of elemental sulfur is a common rate applied at sandy nurseries (Davey 2002). Of course, when a sulfur deficiency exists, it is wise to apply a lower rate of sulfur (e.g. gypsum; ammonium sulfate) even to strongly acidic soils (Bolton and Benzian 1970, Lyle and Pearce 1968).

Armson and Sadreika (1979) suggest sowing seed at least 2 months after soil incorporation of sulfur, and van den Driessche (1969) said this interval should be as long as possible. When rainfall is limited, however, applying sulfur a few months prior to sowing can result in gypsum crystals forming on roots (figure 8). Although chlorosis and stunted growth were observed after a sulfur application at two nurseries (Carey et al. 2002), stunting was attributed to the formation of gypsum crystals on roots. In years with normal rainfall, no stunting has been noted after applying 900 kg/ha of sulfur. To reduce the risk of gypsum crystals forming on pine roots, sulfur application should be applied before sowing a cover crop. This will allow a year for sufficient rainfall to convert the sulfur to sulfuric acid.

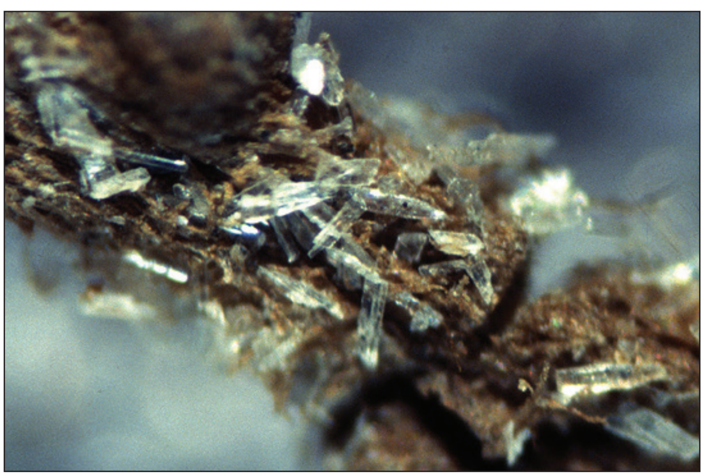

Figure 8. Applying too much sulfur prior to sowing can cause gypsum crystals to form on roots of pine seedlings when rainfall is low. These loblolly pine (*Pinus taeda*) roots were growing in pH 3.6 soil at the Verbena Nursery in Alabama. To reduce the chance of crystals forming on conifer roots, sulfur can be applied prior to sowing cover crops. (Photo by Bill Carey, Auburn University, 1998)

Figure 9. Loblolly pine (*Pinus taeda*) seedlings were grown in a sandy soil where an accidental overdose of elemental sulfur resulted in stunted root development. Soil acidity in July (same time as the photo) was pH 3.3, and the topsoil contained 94 ppm sulfur. Foliar nutrients were: 2.0 percent nitrogen, 0.24 percent phosphorus, 1.04 percent potassium, 0.08 percent magnesium, 0.19 percent sulfur, 0.2 percent calcium, and 77 ppm boron, 8 ppm copper, 949 ppm manganese, and 236 ppm aluminum. (Photo by Chase Weatherly, Arborgen, 2014)

It is important for managers to sample soil in cover crop fields to avoid applying sulfur only a few months before sowing pines. Toxic oxidation products are produced soon after sulfur applications (van den Driessche 1969), which may explain why phototoxic symptoms on roots occurred when too much sulfur was applied a few weeks prior to sowing pine (Mullin 1964). Sundling (1932) applied an unknown amount of sulfur to a Morrison sand, and roots in the most acid pots (pH 1.5) were dark brown with black root tips. An accidental overdose of sulfur at one nursery resulted in a pH 3.3, and by July, stunted roots had the appearance of nematode injury (figure 9). To reduce the risk to young pine germinates, Mizell (1980) applied sulfur at 450 kg/ha before sowing a cover crop and then checked soil pH in the following winter. If the pH had still been above pH 5.9 in March, he would apply another 450 kg/ha before sowing pine seed.

Problems With Low pH on High Manganese Soils

Mn toxicity can occur on fine-textured soils (less than 75 percent sand) with low soil pH (Adams and Wear 1957), and this can be exacerbated by flooding. High levels of Mn may have induced a Ca deficiency at a nursery in Alabama and an Fe deficiency at a nursery in Louisiana (Shoulders and Czabator 1965). When combined with high soil moisture (resulting in low soil oxygen), high levels of Mn can injure pine seedlings (Slaton and Iyer 1974). In a greenhouse study, adding 45 kg/ha of Mn (as Epsom salt) killed red pine seedlings when the water table was 15 cm below the surface. In contrast, when soils were not flooded, applying manganese sulfate did not affect white pine (*Pinus strobus* L.) or loblolly pine seedlings (Shoulders and Czabator 1965, St. Clair and Lynch 2005).

Lowering pH tends to increase the availability of Mn (figure 10). At one nursery in Alabama, in 2008, loblolly pine seedlings were chlorotic when foliage contained 990 ppm Mn, but those with 688 ppm Mn were green. The median level of Mn for loblolly pine seedlings at harvest is about 485 to 520 ppm (Boyer and South 1985, Starkey and Enebak 2012), and the maximum reported level of Mn for loblolly pine foliage in plantations was 916 ppm (Albaugh et al. 2010). In greenhouse trials with pines, growth was reduced when foliar levels exceeded 855 ppm of Mn (Kavvadias and Miller 1999, Morrison and Armson 1968). Some nursery managers apply a mixture of micronutrients to loblolly pine seedlings during the summer, which may explain why one foliage sample in January contained 1,677 ppm of Mn (Starkey and Enebak 2012). Sandy soils have a low reserve of Mn, and therefore are less likely to experience toxic levels of Mn. If the nursery soil has a high reserve of Mn, it may be wise to maintain the pH above 5.0.

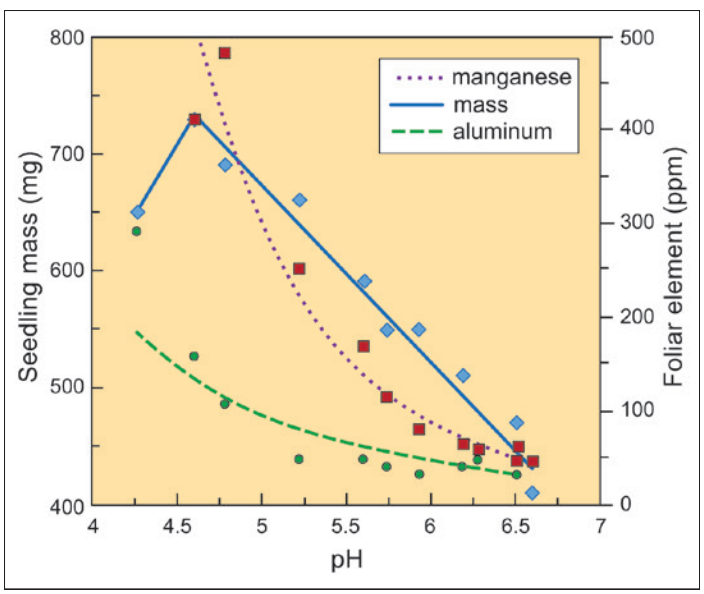

Figure 10. The effect of media pH on seedling mass and foliar aluminum and magnesium on container-grown pitch pine (*Pinus rigida*) seedlings (Helm and Kuser 1991). Seedlings grown with no dolomitic lime (pH 4.3) contained 58 percent more mass than seedlings grown with 40 g of lime per kg of medium (pH 6.6). In this trial, decreasing foliar aluminum concentrations by applying dolomitic lime was not beneficial to seedling growth.

Advantages of Low pH in Conifer Seedbeds

In the past, lowering soil pH with sulfuric acid was an effective pest management practice (Bickelhaupt 1987, Hartley 1921, Jackson 1933, Wilde 1954). Beneficial fungi (*Trichoderma* and *Penicillium*) may increase as acidity increases (Huang and Kuhlman 1991). Populations of damping-off fungi, nematodes, and certain weeds (Aldhous 1972, Buchanan et al. 1975, Huang and Kuhlman 1991, Stoeckeler and Slabaugh 1965) may all be lower when nonfumigated seedbeds have pH values less than 5.0. It has been suspected for some time that nematode populations are lower in acid soils (Wilde 1934), and numbers of some species of nematodes decrease as soil acidity increases to pH 4.0 (Burns 1971, Korthals et al. 1996, Willis 1972).

Seed efficiency may be greater when the soil pH is less than 5.0. In some trials, more than 40 percent of longleaf pine seedlings (*Pinus palustrius* Mill.) died when container media exhibited pH greater than 6.0 (Pawuk 1981). Helm and Kuser (1991) found that pitch pine damping-off mostly occurred at pH greater than 6.0 (figure 6). When pH was 3.5, mortality of lodgepole pine (*Pinus contorta* Douglas ex Loudon) did not exist, but at pH 6.1, about 20 percent of seedlings died due to damping-off (Griffin 1958). In a simulated acid rain study with white pine, seedling emergence was 17 percent greater at pH 4.0 when compared to pH 5.7 (Lee and Weber 1979). Typically, damping-off of pines in containers is lower when pH values are less than 5.0 (figure 6).

Several researchers report that the percent N concentration in conifer needles increases as soil pH decreases (Coultas et al. 1991, Helm and Kuser 1991, Kraus et al. 2004, Marx 1990, Schiler 1986, van den Driessche 1971). When both seedling mass and N concentration increase, it follows that nutrient use efficiency increases. Possible reasons for greater uptake of N on more acidic soils include (1) lower consumption of N by soil microorganisms, (2) reduced leaching of nitrate (NO_3^-), and (3) less activity by nematodes. The belief that N use efficiency is low when pines are grown on "very strong acid" soils appears to be poorly supported.

Warnings About Low Soil pH

Wilde (1954: p. 89) said concerns about the toxicity of hydrogen ions to roots have been "grossly exaggerated." The exaggerated claims originated from "artificially prepared cultures," not soil studies (Wilde 1954). Although some experts claim growing pine seedlings in soil that is below pH 5.2 is not optimum, most provide no data to show their warnings have merit. Some admit they do not know what problems might result when adequate fertilizers are applied to low pH soils (Stone 1965). In contrast, Davey (1991) said that poor growth of pines might occur on low pH soils (with low CEC) due to deficiencies of K, Ca, Mg, and possibly due to toxicity from Mn, Fe, copper (Cu), and zinc. Some (Davey 1991, Landis 1989) warn against high levels of available aluminum (Al), although pines seem to be very tolerant of Al (Cronan et al. 1989), and most sandy soils contain low levels of Al. Al toxicity was not observed in a greenhouse when pines were grown in soil at pH 3.0 (Coultas et al. 1991), or when 740 kg/ha of aluminum sulfate was applied to bareroot seedbeds (Januszek et al. 2014). Naturally high levels of Al are not known to have undesirable effects on conifers (Stone 1965). In fact, seedling growth may increase, up to a point, when both soil acidity and foliar Al increase (Marx 1990, figure 10).

Some authors warn about Ca, Mg, and K deficiencies when seedlings are grown on soils with a pH less than 5.0 (Bueno et al. 2012, Davey 1991, Krause 1965, Voigt et al. 1958). Decreasing soil pH by adding sulfur will increase leaching of Ca, Mg, and K from the soil (figure 11). Increasing soil pH by adding dolomitic lime will increase Ca and Mg levels, and this explains why the correlation between soil pH and the amount of these elements in nursery soils is positive (South and Davey 1983). Increasing soil pH, however, does not prevent Ca leaching in sandy soils (figure 5), and the pH of forest soils is not significantly related to the level of these three elements (NCSFNC 1991, Wytienbach et al. 1991). When soil levels of these cations are low, many nursery managers add fertilizers. For example, when a Ca deficiency occurred in Georgia, an application of gypsum greened up pine seedlings within a month (Haugabook 2017). Cu deficiencies have occurred in pH 3.9 soils in pine plantations (South et al. 2004) and at a peat nursery with pH 4.2 soil in New Zealand (Knight 1975). Cu deficiency for pines, however, has not occurred in nurseries in the 13 Southern States that have sandy soil comprised of low amounts of organic matter with low pH. Several nursery managers apply Cu prior to sowing, when levels in the topsoil fall below 0.7 ppm. Even in low pH soils, the Cu level in loblolly pine foliage was above average (Albaugh et al. 2010, Boyer and South 1985) (figure 9).

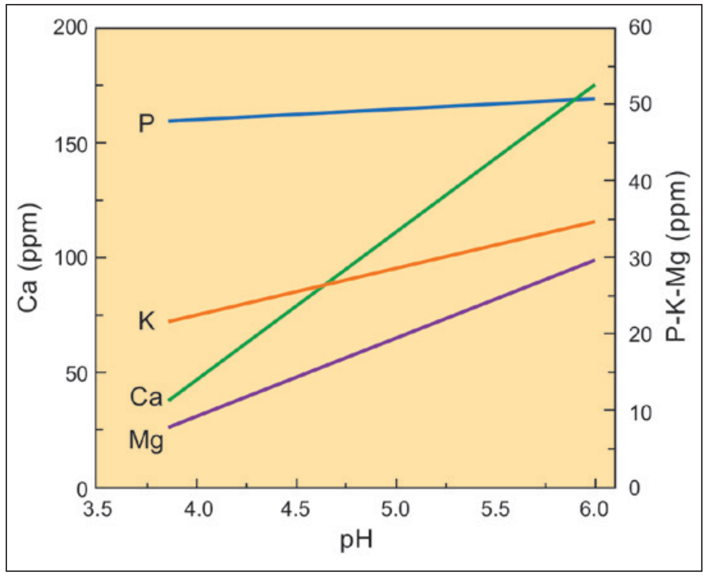

Figure 11. Adding sulfur to a sandy loblolly pine (*Pinus taeda*) nursery (pH 5.0 to 5.3) lowered pH to 4.6 to 3.9, and this lowered available calcium, magnesium, and potassium (soil nutrients measured in the following winter). In contrast, adding dolomitic lime increased soil pH to 5.4 to 6.0 and, as expected, it increased the levels of soil calcium and magnesium.

Future Research

"Assessment of a desirable pH range of a given species is quicker and easier than many growth factors often investigated for improving plant growth and should be one of the first factors investigated" (Bryan et al. 1989: p. 64). For a given pine species and environment, researchers can determine a peak pH value where seedling growth is maximized (e.g. Howell 1932). Future research might determine (1) the shape of the pH-growth curve and (2), exactly why growth increases as hydrogen ion concentrations increase.

There appears to be an interaction between soil texture and optimal pH range. For some fine-textured soils, low soil pH may result in Mn toxicity, but no toxicity occurs when the CEC is low (e.g., sandy soils with less than 2 percent organic matter). Future research is needed to better understand the relationship among soil pH, soil CEC, and Mn toxicity.

An interaction also exists between rainfall and formation of gypsum crystals on pine roots (after applying sulfur to pine seedbeds) (figure 8). For example, applying 1,500 to 2,000 kg/ha of elemental sulfur a few months prior to sowing pines may increase seedling production for years with normal rainfall (Bickelhaupt 1987, Mullin 1964). In a dry year, however, even 900 kg/ha of sulfur might cause problems (Bueno et al. 2012, Carey et al. 2002). Future research could provide more information about this interaction.

One trait common to almost all pH trials is the confounding of certain elements with pH treatments. Most researchers will either start with a high pH soil and lower it with sulfur or an acid treatment, or will start with a low pH soil and then add some type of lime. A classic example of confounding involved overcoming a foliar deficiency of Ca and Mg (Voigt et al. 1958) by applying dolomitic lime over the top of Jack pine seedlings (*Pinus banksiana* Lamb.). Not surprisingly, chlorosis was reduced by one-half, but this could lead to the erroneous conclusion that growth of pine is optimum at pH 5.0 to 6.0 (instead of pH 4.5 to 5.0).

An alternative approach to a single amendment trial would be to conduct a paired trial in which one trial evaluates acidifying an alkaline soil and another evaluates liming an acid soil. Establishing paired trials might result in fewer confounding risks and stronger conclusions about the direct effects of soil pH on seedling growth.

Conclusions

Field observations and greenhouse trials confirm that a range of pH 5.5 to 6.5 is not optimum for growing most pines in nurseries. When based on data, the desired range for growing pine seedlings at sandy bareroot nurseries (more than 75 percent sand) is likely pH 4.5 to 5.0 (Aldhous 1972, Benzian 1965, Brix and van den Driessche 1974, Januszek and Barczyk 2003, Marx 1990). A range of pH 5.0 to 5.5 would be appropriate for fine-textured soils containing high levels of Mn.

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