Dolomitic Lime Amendment Affects Pine Bark Substrate pH, Nutrient Availability, and Plant Growth: A Review

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James Altland
United States Department of Agriculture

Reviews

Dolomitic Lime Amendment Affects Pine Bark Substrate pH, Nutrient Availability, and Plant Growth: A Review

James E. Altland[1,3,5] and Kay Yeon Jeong[2,4]

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SUMMARY. Dolomitic lime (DL) is one of the most commonly used fertilizer amendments in nursery container substrates. It is used to adjust pH of pine bark substrates from their native pH, 4.1 to 5.1, up to about pH 6. However, additions of DL have been shown to be beneficial, inconsequential, or detrimental depending on the crop to which it is applied and irrigation water quality. Carbonate ions from DL cause a rate-dependent change in pH. Dolomitic lime can adjust pH of pine bark up to ≈6.5, after which there is little change regardless of how much additional DL is added. Changes in pH affect the rate of nitrification in pine bark substrates. The rate of nitrification can impact the quality of some plants that are sensitive to ammonium toxicity, as well as affect nitrogen leaching from containers. Changes in pH also affect micronutrient availability in pine bark substrates. Dolomitic lime provides an abundant source of calcium (Ca) and magnesium (Mg) for plant uptake. However, the additional Ca and Mg might also suppress potassium uptake in plants.

Ground pine bark pH ranges from 4.1 to 5.1 before amendment with other components or fertilizers (Brown and Pokorny, 1975; Gillman et al., 1998; Wright et al., 1999a, 1999b). Limestone is traditionally used to raise the pH of pine bark substrates to between 5 and 6.5, a range that is thought to be most conducive for growth of most plants. The two primary limestone products used in agriculture include calcitic lime [calcium carbonate ($CaCO_3$)] and DL [$CaMg(CO_3)_2$]. Pure dolomite has equal molar ratios of $CaCO_3$ and magnesium carbonate ($MgCO_3$), but is 54.3% $CaCO_3$ and 45.7% $MgCO_3$ since the mass of Ca is larger than Mg (Barber, 1984). Commercial sources of DL vary in their actual Ca and Mg proportions due to the geological properties and impurities in the dolomite at each particular mine site.

Dolomitic lime is used almost exclusively as the neutralizing agent for raising pH in pine bark substrates. Its preference over calcitic lime is presumably due to the balance of Ca and Mg in DL, although there is no literature to support or suggest it results in better plant growth or nutrition than other lime forms. Starr and Wright (1984) irrigated plants with varying concentrations of Ca and Mg, and concluded the Ca:Mg ratio in the substrate solution was not an important factor for plant growth. Mayfield et al. (2007) compared several lime types and formulations for production of 'Nana Purpurea' nandina (*Nandina domestica*) and reported little or no differences in plant growth.

Despite the perceived importance of substrate pH on crop growth and quality, and the near ubiquitous use of DL for increasing pH of pine bark substrates, plant response to substrate pH in pine bark substrates has been established for relatively few crops. A review of the literature provided a list of nursery crops growing in a predominantly pine bark substrate for which a pH response is reported over a range of DL rates (Table 1). Of the ≈400 genera of plants grown in the U.S. nursery industry (Yeager et al., 2007), the 42 entries reviewed represent only 22 unique genera and 31 different species (Table 1). Plant response to substrate pH varied across the diverse species grown in container culture. Some species responded favorably to DL amendment, whereas others responded poorly or did not respond at all (Table 1). Differences in plant response could be related to a specific characteristic of the plant's native habitat. For example, Harvey et al. (2004) reported that 'Aureola' hakonechloa (*Hakonechloa macra*) grew best in a 3 pine bark : 2 sphagnum peat : 1 sand (by volume) substrate

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[1]U.S. Department of Agriculture, Agricultural Research Service, Application Technology Research Unit, 1680 Madison Avenue, Wooster, OH 44691

[2]The Scotts Miracle-Gro Company, 14111 Scottslawn Road, Marysville, OH 43041

[3]Research Horticulturist

[4]Senior Scientist

[5]Corresponding author. E-mail: james.altland@ars.usda.gov.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
0.5933	lb/yard^3	kg·m^{-3}	1.6856
1	meq/L	mmol·L^{-1}	1
1	ppm	mg·L^{-1}	1

Table 1. Nursery crop response to dolomitic lime (DL) rate and substrate pH when growing in a predominantly pine bark substrate.

Common name	Scientific name	Substrate type (ratios by vol)	DL rates applied ($lb/yard^3$)[z]	Results	Citation
Japanese maple	*Acer palmatum*	Pine bark	0 or 6	DL reduced growth	Wright et al. (1999b)
'October Glory' red maple	*Acer rubrum*	3 pine bark : 1 peat	0, 5, or 10	DL reduced foliar color, but not growth	Cooper et al. (1997)
Sugar maple	*Acer saccharum*	pine bark	0 or 6	DL reduced growth	Wright et al. (1999b)
'Pink Delight' butterfly bush	*Buddleja davidii*	4 pine bark : 1 peat	0, 1, 4, 8, 16, or 24	DL rate had no effect on growth	Altland et al.(2015)
'Royal Red' butterfly bush	*Buddleja davidii*	Pine bark	0, 4, 8, or 16	All DL rates improved growth over nonlimed controls; however, 4 $lb/yard^3$ was optimum	Gillman et al. (1998)
Japanese boxwood	*Buxus macrophylla* var. *japonica*	5 pine bark : 1 sand	0, 1.7, 3.4, 6.8 or 13.6	Growth increased with DL rate	Walden and Epelman (1988)
'Suffruticosa' boxwood	*Buxus sempervirens*	3 pine bark : 1 peatmoss	0 or 6	DL increased growth compared with nonlimed control	Leda and Wright (1991)
Redbud	*Cercis canadensis*	Pine bark	0 or 6	DL reduced growth	Wright et al. (1999b)
Flowering dogwood	*Cornus florida*	Pine bark	0 or 6	DL reduced growth	Wright et al. (1999b)
Kousa dogwood	*Cornus kousa*	Pine bark	0 or 6	DL reduced growth	Wright et al. (1999b)
'Yellow jacket' chrysanthemum	*Dendranthemum ×morifolium*	3 pine bark : 1 peat	0, 5, or 10	DL increased growth regardless of micronutrient amendment	Cooper et al. (1997)
Gardenia	*Gardenia radicans*	4 pine bark : 1 sand	0, 8, or 16	Lime reduced growth of gardenia compared with nonlimed controls	Laiche (1982)
Hakonechloa	*Hakonechloa macra* 'Aureola'	3 pine bark : 2 sphagnum peat : 1 sand	0, 2, 6, or 16	DL reduced growth	Harvey et al. (2004)
Lenten rose	*Helleborus* x*hybridus*	Pine bark	0, 3, 6, 9, or 12	Shoot growth was least in nonamended control, but similar with DL rates 3 to 12 $lb/yard^3$	Kraus and Warren (2006)
'Meta Peka' hosta	*Hosta japonica*	3 pine bark : 1 peat	0, 5, or 10	Growth increased with increasing DL rate; however, foliar color decreased with DL rate in the absence of micronutrient amendment	Cooper et al. (1997)
'Burfordii' holly	*Ilex cornuta*	3 pine bark : 1 peat	0, 5, or 10	Growth increased with DL rate	Cooper et al. (1997)
'Greenluster' holly	*Ilex crenata*	3 pine bark : 1 peat	0, 5, or 10	Growth increased with DL rate	Cooper et al. (1997)
'Helleri' holly	*Ilex crenata*	Pine bark	0, 3.4, 6.8, or 13.6	DL rates greater than 6.8 $lb/yard^3$ reduced shoot growth, while all rates reduce root growth	Chrustic and Wright (1983)

(*Continued on next page*)

Table 1. (*Continued*) Nursery crop response to dolomitic lime (DL) rate and substrate pH when growing in a predominantly pine bark substrate.

Common name	Scientific name	Substrate type (ratios by vol)	DL rates applied ($lb/yard^3$)[z]	Results	Citation
'Helleri' holly	*Ilex crenata*	5 pine bark : 3 peatmoss : 2 sand	0, 4, or 8	DL reduced root and shoot growth	Yeager and Ingram (1983)
'San Jose' juniper	*Juniperus chinensis*	100% pine bark	0, 3.4, 6.8, or 13.6	Growth was maximized at 3.4 to 6.8 $lb/yard^3$	Chrustic and Wright (1983)
'Andorra Compacta' juniper	*Juniperus horizontalis*	1 pine bark : 1 peatmoss : 1 sand or 2 pine bark : 1 sand	0, 3.5, or 7	No effect	Ingram and Sartain (1982)
'Plumosa' juniper	*Juniperus horizontalis*	5 pine bark : 3 peatmoss : 2 sand	0, 4, or 8	DL reduced root and shoot growth	Yeager and Ingram (1983)
'Sky Rocket' juniper	*Juniperus virginiana*	5 pine bark : 1 sand	0, 2.5, 5, 7.5, 10, or 15	No growth effect	Cobb and Zarko (1983)
Red cedar	*Juniperus virginiana*	5 pine bark : 1 sand	0, 5, or 10	5 $lb/yard^3$ was optimum	Wright and Hinsley (1991)
Golden raintree	*Koelreuteria paniculata*	Pine bark	0, 2, 4, or 6	No growth effect	Wright et al.,(1999a)
Golden raintree	*Koelreuteria paniculata*	Pine bark	0 or 6	DL reduced growth	Wright et al. (1999b)
Privet	*Ligustrum sinensis*	4 pine bark : 1 sand	0, 8, or 16	DL applications greatly improved growth	Laiche (1982)
'Sizzling Pink' loropetalum	*Loropetalum chinensis*	6 pine bark : 1 sand	4, 6, 8, or 10	Rates above 4 $lb/yard^3$ reduced shoot growth, 8 and 10 $lb/yard^3$ caused stem abnormalities; nonlimed control not included	Midcap (1999b)
'Lennei' magnolia	*Magnolia* x*solangiana* 'Lennei'	Pine bark	0 or 6	DL reduced growth	Wright et al., (1999b)
Heavenly bamboo	*Nandina domestica*	5 pine bark : 1 sand	0 or 6.7	Improved shoot growth and foliar color at 6.7 $lb/yard^3$	Walden and Wright (1995)
Heavenly bamboo	*Nandina domestica*	6 pinebark : 1 sand	0 or 2.5	Low DL rates improved growth and nutrient uptake compared with nonlimed control	Mayfield et al. (2007)
'Wood's Dwarf' heavenly bamboo	*Nandina domestica*	3 pine bark : 1 peat	0, 5, or 10	DL increased foliar color and growth	Cooper et al. (1997)
Black tupelo	*Nyssa sylvatica*	Pine bark	0 or 6	DL reduced growth and height	Wright et al. (1999b)
'Fraseri' photinia	*Photinia*	4 pine bark : 1 sand	0, 7, or 14	Growth increased with DL rate	Nash et al. (1983)
'Variegata' pittosporum	*Pittosporum tobira*	5 pine bark : 1 sand	0, 2.5, 5, 7.5, 10, or 15	No growth response	Cobb and Zarko (1983)
'Mojave' pyracantha	*Pyracantha*	4 pine bark : 1 sand	0, 8, or 16	DL increased growth over nonlimed controls	Laiche (1982)
Pin oak	*Quercus palustrus*	Pine bark	0 or 6	DL reduced growth and height	Wright et al. (1999b)
'Delaware Valley White' azalea	*Rhododendron*	6 pine bark : 1 sand	0, 4, 6, 8, or 10	Rates above 4 $lb/yard^3$ reduced root and shoot growth	Midcap (1999a)

(*Continued on next page*)

Table 1. (*Continued*) Nursery crop response to dolomitic lime (DL) rate and substrate pH when growing in a predominantly pine bark substrate.

Common name	Scientific name	Substrate type (ratios by vol)	DL rates applied (lb/yard³)^z	Results	Citation
'Formosa' azalea	*Rhododendron indicum*	4 pine bark :1 sand	4 or 8	Highest quality with 4 lb/yard³	Wade et al. (1982)
'Formosa' azalea	*Rhododendron indicum*	3 pine bark : 1 peat	0, 5, or 10	Better foliar color with no lime	Cooper et al. (1997)
'Gerbing' azalea	*Rhododendron indicum*	4 pine bark : 1 sand	4 or 8	Highest quality with 4 lb/yard³, nonlimed controls not included	Wade et al. (1982)
'Judge Solomon' azalea	*Rhododendron indicum*	4 pine bark : 1 sand	4 or 8	Highest quality with 4 lb/yard³, nonlimed controls not included	Wade et al. (1982)
'Coral Bells' azalea	*Rhododendron obtusum*	4 pine bark : 1 sand	4 or 8	Highest quality with 4 lb/yard³, nonlimed controls not included	Wade et al. (1982)
'Hino Crimson' azalea	*Rhododendron obtusum*	5 pine bark : 3 peatmoss : 2 sand	0, 4, or 8	DL did not affect root or shoot growth	Yeager and Ingram (1983)
'Rosebud' azalea	*Rhododendron obtusum*	100% pine bark	0, 3.4, 6.8, or 13.6	Growth was maximized at 0 to 3.4 lb/yard³	Chrustic and Wright (1983)
'Red Wing' azalea	*Rhododendron*	1 pine bark : 1 peatmoss : 1 sand or 2 pine bark : 1 sand	0, 3.5, or 7	DL caused chlorosis	Ingram and Sartain (1982)

^{z}1 lb/yard³ = 0.5933 kg·m^{-3}.

with no DL amendment (pH 4.5). They speculated that the reason for this favorable response to low pH was due to the plant's adaptation to low pH soil found in the mesic, forested mountains of its native range in Hakone, Japan. Differing plant response among species could also be caused by one of several chemical changes DL imparts on pine bark. Dolomitic lime has two primary effects on pine bark substrates. The carbonate fraction of DL causes an increase in substrate pH, which can have secondary effects on nitrogen (N) form and N dynamics, as well as micronutrient availability. Dolomitic lime also introduces a source of Ca and Mg into the substrate, which can have secondary effects on potassium (K) uptake in plants. The objectives of this review are to 1) describe the impact of DL rate on substrate pH, 2) discuss the primary and secondary effects of DL on nutrient availability, and 3) summarize the literature on the effects of DL on plant growth in pine bark substrates.

Dolomitic lime rate affects substrate pH

Pine bark substrate pH increases with increasing DL rate, up to a point, after which additional DL has little or no measurable impact on pH. For example, Altland et al. (2015) using a 80 pine bark : 20 peatmoss (by volume) substrate showed a curvilinear response in pH to DL rate over the range of 0 to 4.8 kg·m^{-3}, but doubling or tripling the rate up to 14.3 kg·m^{-3} resulted in little or no additional change. Likewise, Gillman et al. (1998) reported a pH increase in 100% pine bark from 4.4 up to 6.1 with 4.8 kg·m^{-3} DL, but only up to 6.4 when the rate was doubled to 9.5 kg·m^{-3}. Harvey et al. (2004) reported that 3.6 kg·m^{-3} DL raised pH of a 3 pine bark : 2 peatmoss : 1 sand (by volume) substrate from 3.7 to 6.2, whereas more than doubling the rate up to 9.5 kg·m^{-3} only raised the pH an additional 0.9 units up to 7.1.

Altland and Buamscha (2008) suggested exponential functions are ideal for defining pH response in soilless substrates. Exponential curves in the form pH = $c + a(1 - e^{-b\cdot\mathrm{rate}})$ provide a more realistic fit for pH response to DL rate, in that pH increases rapidly but then plateaus at some maximum value. Furthermore, parameter estimates of the exponential equation provide intuitive interpretation. The solved estimate for c equates to the pH of the substrate with 0 $kg \cdot m^{-3}$ (or nonamended pH), whereas the sum $c + a$ is equal to the maximum pH (the level at which the curve plateaus), and b (>0) is a gauge of how rapidly pH increases from its minimum to maximum.

The plateau shape of the curve that describes pine bark pH response to DL is due to the solubility of $CaMg(CO_3)_2$. All carbonates are weak bases, and thus their solubility is a function of pH (Lindsay, 1979). The solubility of dolomite can be derived solely as a function of pH, which explains the inability of DL to raise pH much above levels of 6.5. Consider the following reactions, which occur partially with dolomite in water:

$$CaMg(CO_3)_2 \rightleftharpoons Ca^{2+} + Mg^{2+} + 2CO_3^{2-} \quad [1]$$

$$2CO_3^{2-} + 2H^+ \rightleftharpoons 2HCO_3^- \quad [2]$$

The solubility products and dissociation constants (Michalowski and Asuero, 2012) of importance include

$$K_{sp1} = [Ca^{2+}][Mg^{2+}][CO_3^{2-}]^2 = 3.5 \times 10^{-18} \quad [3]$$

$$K_{sp2} = [Ca^{2+}][CO_3^{2-}] = 3.3 \times 10^{-9} \quad [4]$$

$$K_{sp3} = [Mg^{2+}][CO_3^{2-}] = 3.5 \times 10^{-8} \quad [5]$$

$$K_2 = [H^+][CO_3^{2-}]/[HCO_3^-] = 4.8 \times 10^{-11} \quad [6]$$

Eq. [6] can be rearranged as follows:

$$[HCO_3^-] = \frac{[H^+][CO_3^{2-}]}{K_2} \quad [7]$$

The solubility (S) of dolomite can be calculated as the sum of the concentrations of either $Ca^{2+} + Mg^{2+}$ or $CO_3^{2-} + HCO_3^-$ from [1] and [2]:

$$S = [Ca^{2+}] + [Mg^{2+}] = [CO_3^{2-}] + [HCO_3^-] \quad [8]$$

Substituting [7] into Eq. [8], the following set of equations can be derived and simplified:

$$S = [Ca^{2+}] + [Mg^{2+}] = [CO_3^{2-}] + \frac{[H+][CO_3^{2-}]}{K_2}$$

$$S = [Ca^{2+}] + [Mg^{2+}] = [CO_3^{2-}]\left(1 + \frac{[H^+]}{K_2}\right) \quad [9]$$

Multiplying both sides of Eq. [9] by the sum $[Ca^{2+}] + [Mg^{2+}]$:

$$S = ([Ca^{2+}] + [Mg^{2+}])^2 = ([Ca^{2+}] + [Mg^{2+}]) \cdot [CO_3^{2-}] \times \left(1 + \frac{[H^+]}{K_2}\right)$$

$$S = ([Ca^{2+}] + [Mg^{2+}])^2 = ([Ca^{2+}][CO_3^{2-}] + [Mg^{2+}][CO_3^{2-}]) \times \left(1 + \frac{[H^+]}{K_2}\right) \quad [10]$$

Substituting Eqs. [4] and [5] into Eq. [10], the final equation relating the solubility of dolomite to solution pH can be derived:

$$S = ([Ca^{2+}] + [Mg^{2+}])^2 = (K_{sp2} + K_{sp3})\left(1 + \frac{[H^+]}{K_2}\right)$$

$$S = [Ca^{2+}] + [Mg^{2+}] = \sqrt{(K_{sp2} + K_{sp3})\left(1 + \frac{[H^+]}{K_2}\right)} = \sqrt{(3.83 \times 10^{-8})\left(1 + \frac{[H^+]}{4.8 \times 10^{-11}}\right)} \quad [11]$$

where $[H^+]$ is the hydrogen ion concentration and $pH = -\log[H^+]$. Plotting the $[Ca^{2+}] + [Mg^{2+}]$ solubility as a function of pH reveals the very low solubility of DL as pH increases above 6.5 (Fig. 1). The practical consequence of this empirical relationship is that dolomite will cause a pH change up to ≈6.5, above which pH limits dolomite solubility and thus limits subsequent increases in pH. Once a sufficient amount of DL is added to a container substrate to achieve a pH of ≈6.5, very little change in pH will occur no matter how much additional DL is added. Limestone particle size also affects pH reactivity as reviewed and demonstrated by Huang et al. (2007). Limestone products with larger particle size will react more slowly and cause less pH change. However, the empirical relationship in Eq. 11 is true even if particle size were not limiting to reactivity.

Substrate pH affects nitrogen dynamics

Dolomitic lime amendments increase substrate pH, which in turn affects N form and possibly N retention in substrates. Niemiera and Wright (1986) reported that in a 100% pine bark substrate fertilized with ammonium sulfate [$(NH_4)_2SO_4$], ammonium (NH_4^+) concentration decreased rapidly and nitrate (NO_3^-) concentration increased when amended with 3 or 6 $kg \cdot m^{-3}$ DL. In the same substrate not amended with DL, NH_4^+ decreased more slowly and NO_3^- was not detected. This effect was attributed to the limed containers having more rapid nitrification (biological conversion of NH_4^+ to NO_3^-). Nitrification rates are optimum at pH 7 to 8. Others have shown that DL-induced increases in substrate pH cause more rapid nitrification and subsequently lower NH_4^+ levels and higher NO_3^- levels in container substrates or their leachates (Chrustic and Wright, 1983; Midcap, 1999a, 1999b; Walden and Wright, 1995).

Walden and Epelman (1988) reported increased japanese boxwood (*Buxus microphylla* var. *japonica*) root and shoot growth with increasing DL rate and concomitant increase in pH. The increase in growth and pH was also associated with a decrease in the NH_4^+:NO_3^- ratio. A second experiment by the authors (Walden and Epelman, 1988) showed that DL rate and pH were superfluous as long as the NH_4^+:NO_3^- ratio was less than 20:80. They concluded that japanese boxwood prefer the NO_3^--N form and possibly suffered from NH_4^+ toxicity at lower DL amendment rates, and higher pH substrates resulted in more rapid nitrification of NH_4^+ to NO_3^-. Similarly, Walden and Wright (1995) reported that nandina had better growth and less chlorosis in a limed (4 $kg \cdot m^{-3}$) vs. nonlimed substrate. The nonlimed substrate had an 8-fold increase in NH_4^+:NO_3^- ratio. The authors attributed the improved growth in limed containers to higher nitrification rates compared with nonlimed substrates. Many controlled release fertilizers used by the nursery industry contain urea (which readily hydrolyzes to NH_4^+) and NH_4^+ nitrogen forms. Thus, under standard fertilization regimes, high pH substrates will

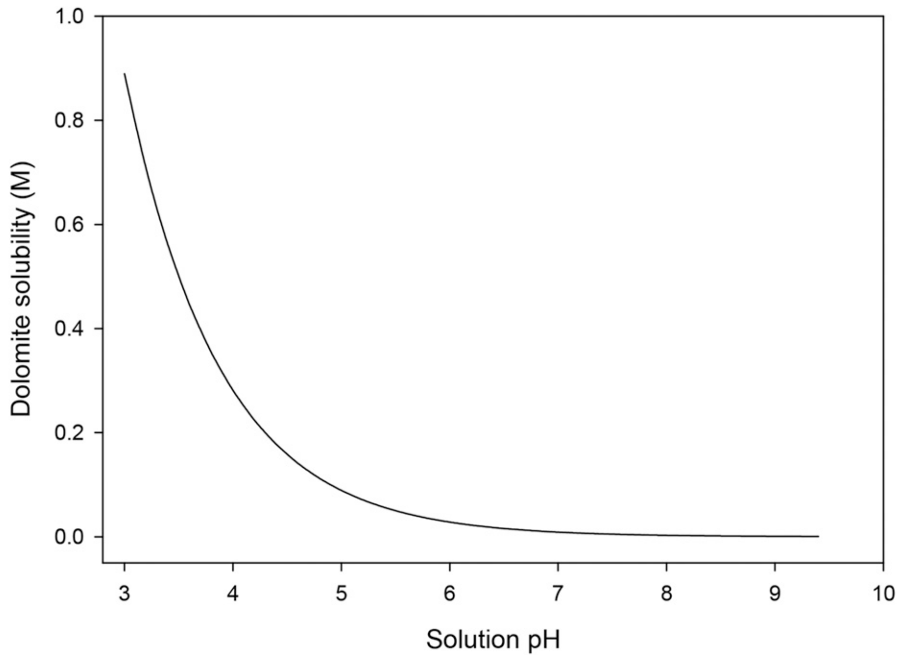

Fig. 1. The solubility (S) of dolomite $[CaMg(CO_3)_2]$ as a function of pH $(-\log[H^+])$ according to the empirical relationship $S = [3.83 \times 10\text{-}8(1 + [H+]/4.8 \times 10\ \text{-}11)]1/2$.

result in more rapid nitrification and better growth for crops with preference for NO_3^--N.

Another consequence of greater nitrification rates with high pH substrates is loss of N via leaching. Pine bark substrates have a cation exchange capacity (CEC) similar to other organic substrates, and generally range from 40 to 75 meq/L (Altland et al., 2015). In contrast, pine bark has no measureable anion exchange capacity (personal observation, data not published). Ammonium cations can be bound by pine bark CEC sites, whereas NO_3^- anions leach readily. Thus, higher pH substrates that promote the conversion of NH_4^+ to NO_3^- via nitrification would presumably leach N more quickly than low-pH substrates, assuming some fraction of the applied N was in the form of urea or NH_4^+. Of the papers cited in Table 1, only four provided data on plant N uptake. Harvey et al. (2004) reported a decrease in foliar N in hakonechloa with increasing DL rate, suggesting that more N was available for plant uptake at lower DL and pH levels. Likewise, Chrustic and Wright (1983) reported that shoot N was higher in 'Helleri' holly (*Ilex crenata*), 'San Jose' juniper (*Juniperus chinensis*), and 'Rosebud' azalea (*Rhododendron obtusum*) at lower DL rates and attributed greater growth of these crops a low lime rates to greater N, phosphorus (P), and K availability. Gillman et al. (1998) reported 'Royal Red' butterfly bush (*Buddleia davidii*) foliar N was highest in nonlimed controls; however, trends in shoot N with increasing DL rates did not follow a clear pattern. In contrast, Nash et al. (1983) reported similar shoot N levels among limed and nonlimed photinia (*Photinia ×fraseri*). Although there is little evidence that higher pH substrates result in greater N leaching, the possibility of reducing N leaching in crops with no favorable response to the addition of DL warrants further research.

Substrate pH affects micronutrient availability

Pine bark may contain sufficient micronutrients to grow woody plants. Niemiera (1992) extracted slightly lower concentrations of copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) from pine bark alone compared with pine bark amended with a micronutrient package (Micromax; Scotts Co., Marysville, OH) or fertilizer amendment (Ironite; Ironite Products Co., Scottsdale, AZ). This led Niemiera (1992) to speculate that such small differences in micronutrient concentrations between fertilized and nonfertilized pine bark would not be physiologically significant in terms of plant growth. Rose and Wang (1999) reported no improvement in 'Girards Scarlet' rhododendron (*Rhododendron*) growth when adding biosolids compost or micronutrient fertilizer to a 3.0 pine bark : 1.0 hardwood bark : 1.0 peat : 0.2 sand (by volume) medium compared with a nonamended control, suggesting that a predominantly pine bark substrate contains sufficient micronutrients to support plant growth.

There are little specific data showing how DL affects micronutrient availability in pine bark substrates. Lucas and Davis (1961) determined the relationship between pH and nutrient availability in organic soils and concluded the ideal pH range (in terms of total nutrient availability) to be between 5.5 and 5.8 for wood-sedge soils, and 5.0 for sphagnum peat soils. They further commented that this pH range was 1 to 1.5 units lower than what was considered ideal for mineral soils. This report formed the basis for future studies as the greenhouse industry switched from mineral soils to those composed primarily of peat or bark. Peterson (1980) documented the effect of substrate pH on macronutrient and micronutrient availability in a well-fertilized commercial greenhouse substrate (peatmoss, perlite, vermiculite, granite sand, and composted pine bark; ratios not given). His study agreed with Lucas and Davis (1961) in that the optimum pH range was 5.2 to 5.5, which he characterized as being a whole pH unit or more below what was considered optimum for mineral soils. Peterson (1980) reported decreasing availability of P, Fe, Mn, boron (B), Zn, and Cu in this particular substrate with increasing pH. In nonfertilized douglas fir (*Pseudotsuga menziesii*) bark (DFB), a substrate component similar to pine bark, Altland and Buamscha (2008) found that diethylenetriaminepentaacetic acid-extractable B, Fe, Cu, and aluminum (Al) decreased with increasing pH. In fertilized DFB, however, B and Fe still decreased with increasing pH but Mn, Zn, and Cu behaved unexpectedly; they increased and then decreased over the range of observed pH (Altland et al., 2008). Argo (1998) reviewed the effects of pH on nutrient availability in soilless substrates citing numerous sources, and generally agreed with the conclusions of Peterson (1980) and Altland and Buamscha (2008).

Although there is some disagreement on whether pine bark alone can provide crops with sufficient micronutrients, many commercial growers still amend pine bark substrates with a micronutrient fertilizer package. This is to minimize the occurrence of high-pH-induced micronutrient deficiencies that often result in limed substrates when DL is added without additional micronutrients. For example, Cooper et al. (1997) reported excellent 'October Glory' red maple (*Acer rubrum*) foliar color in a 3 pine bark : 1 peat (by volume) substrate receiving neither DL nor micronutrients. However, when DL was added, micronutrient amendment was necessary to prevent adverse effects on foliar color. Likewise, nandina and 'Meta Peka' hosta (*H. plantaginea* var. *japonica*) foliar color decreased with increasing DL rate in the absence of amended micronutrients, whereas DL rate had no effect on foliar color when micronutrients were added. In an evaluation of DL and micronutrient application to nine tree species, Wright et al. (1999b) found that plants in the lime-only treatments were particularly chlorotic and had lower foliar micronutrient levels than those that received neither micronutrients nor DL. They further showed that when micronutrients were added, DL did not affect plant growth. There are two practical conclusions that could be drawn from these results. First, micronutrient packages could be eliminated from pine bark substrates if DL were also eliminated. This would only be applicable to crops that show no benefit from the addition of DL to the substrate (to alleviate ammonium toxicity in boxwood, for example). Second, and in contrast, micronutrients should always be recommended in pine bark substrates due to the prevalence of DL usage in the nursery industry. Although not addressed specifically by any of the experiments cited herein (Table 1), irrigation water with sufficiently high alkalinity (>4 meq/L $CaCO_3$) could have a liming effect on substrates over time (Farnham et al., 1985). Thus even nonlimed substrates may benefit from micronutrient amendments.

Dolomitic lime rate affects Ca and Mg in substrates

As the $CaMg(CO_3)_2$ in DL dissociates in the substrate solution, Ca^{2+} and Mg^{2+} are released and potentially available for plant uptake. Nash et al. (1983) suggested that increased growth of photinia with increasing DL rates was due to the greater quantity of Mg^{2+} available for uptake, and was not related to pH. Gillman et al. (1998) reported that butterfly bush root and shoot growth, as well as flower number, increased with DL compared with nonlimed controls. They attributed the increased growth to increased amounts of Ca^{2+} and Mg^{2+} from the DL available for plant uptake.

Calcium and Mg^{2+} can also be provided by irrigation water and substrate components. Argo et al. (1997) reported that the mean Ca^{2+} concentration in U.S. greenhouse irrigation water was 52 $mg \cdot L^{-1}$ (4306 samples), although this varied by state, with state means ranging from 14 to 78 $mg \cdot L^{-1}$. Average irrigation water Mg concentration of these samples was 19 $mg \cdot L^{-1}$ and ranged from 6 to 34 $mg \cdot L^{-1}$. Starr and Wright (1984) demonstrated that 'Helleri' holly required 5 to 10 $mg \cdot L^{-1}$ for both Ca^{2+} and Mg^{2+} in the substrate solution, a value far less than that supplied by most irrigation water throughout the United States. It has also been shown that 2 $mg \cdot L^{-1}$ Ca^{2+} was sufficient for growth of three species of holly (*Ilex crenata* 'Convexa', *I. opaca* 'Silica King', and *I. cornuta* 'Burford'), although 20 $mg \cdot L^{-1}$ Ca^{2+} was optimum (Dunham and Tatnall, 1961). Edwards and Horton (1979) reported that 'Elberta' peach (*Prunus persica*) seedlings grown with 0.9 $mg \cdot L^{-1}$ Ca^{2+} or greater in sand culture displayed no deficiency symptoms in roots or shoots. Edwards and Horton (1981) further showed that 1 $mg \cdot L^{-1}$ Mg^{2+} in sand culture was also sufficient for peach seedling growth.

The quantity of Ca^{2+} and Mg^{2+} provided by irrigation water over the course of a growing season in many cases is equivalent to the amount of Ca^{2+} and Mg^{2+} provided by DL amendment. For simplicity, consider the mass of Ca^{2+} provided by irrigation relative to the mass provided by DL. The mass of Ca^{2+} provided by irrigation can be calculated as a function of Ca^{2+} concentration in irrigation water and volume passing through the container. This mass can be compared with the equivalent amount of Ca^{2+} provided by DL with the following equation:

$$\text{Equivalent DL rate} = C \times r^2 \times \pi \times i \times D \times \left(4.4 \times 10^{-5}\right)/V \times L \qquad [12]$$

where C is the concentration of Ca^{2+} in milligrams per liter from an irrigation water analysis, r is the radius of the container in centimeters, i is the depth of irrigation in centimeters, D is the number of days the container is irrigated, V is the volume of the container in gallons, and L is the percent Ca^{2+} in a DL source (21% is typical). For example, an irrigation water source with 50 $mg \cdot L^{-1}$ Ca^{2+}, applied at a depth of 1 cm per day to a #3 (3 gal) container with 15 cm radius, and irrigated for 120 d, would provide the equivalent mass of Ca^{2+} as 3 lb/yard³ DL.

As previously mentioned, Gillman et al. (1998) reported that butterfly bush growth increased with DL amendment compared with nonlimed controls due to supplemental Ca^{2+} and Mg^{2+} provided by DL. In contrast, Altland et al. (2015) reported that DL rates similar to that used by Gillman et al. (1998) had no effect on butterfly bush root or shoot growth. The differing results between these two experiments can probably be attributed to Ca^{2+} and Mg^{2+} concentration in the irrigation water and/or substrate. Gillman et al. (1998) reported that Ca^{2+} and Mg^{2+} concentrations in leachates from their pine bark media at the beginning of the experiment were 0.52 and 0.01 $mg \cdot L^{-1}$, respectively, in nonlimed controls, while those reported by Altland et al. (2015) were 60.8 and 34.5 $mg \cdot L^{-1}$ Ca^{2+} and Mg^{2+}, respectively.

Calcium and Mg^{2+} are also provided by pine bark and available for plant uptake. On a dry weight basis, pine bark contains ≈0.6% Ca^{2+} and 0.1% Mg^{2+} (personal observation, data not published). The concentration of Ca^{2+} and Mg^{2+} released into solution from pine bark over time is more difficult to ascertain from the literature, as most experiments are irrigated with water containing dissolved Ca^{2+} and Mg^{2+}. Chrustic and Wright (1983) reported that nonlimed controls irrigated with water containing 13 and 5 $mg \cdot L^{-1}$ Ca^{2+} and Mg^{2+}, respectively, had leachates containing 34 and 15 $mg \cdot L^{-1}$ Ca^{2+} and Mg^{2+}, respectively. The additional Ca^{2+} and Mg^{2+} in the leachates compared with that provided by the irrigation presumably was provided by the substrate. In a similar experiment, Starr and Wright (1984) used irrigation water containing 15 and 5 $mg \cdot L^{-1}$ Ca^{2+} and Mg^{2+}, and found leachate Ca^{2+} and Mg^{2+} concentrations 29 weeks after potting to be 39 and 13 $mg \cdot L^{-1}$, respectively, in nonlimed controls. Although DL provides a source of Ca^{2+} and Mg^{2+} for plant uptake, it is probably not necessary for Ca and Mg nutrition, considering the concentration already present in most irrigation water and pine bark substrates.

The relatively high levels of Ca^{2+} and Mg^{2+} in irrigation water and substrates highlights an important consideration in interpreting research on plant response to lime rates. Irrigation water parameters, such as Ca^{2+} and Mg^{2+} concentration, as well as alkalinity and irrigation pH, are necessary for comparing results of one experiment to another. Unfortunately, much of the research on plant response to DL or substrate pH originates from abstracts and proceedings with limited details on methods.

Dolomitic lime affects K in substrates and plants

The Ca and Mg component of DL generally reduces K uptake in plants. There has been no research directly addressing the impact of DL on K in pine bark substrates. Lucas and Davis (1961) suggest that pH has little or no effect on K in organic soils. However, they explain that the high CEC of organic soils allows for absorption of large quantities of Ca, which due to mass-action effect, depresses uptake of K. Increasing lime rates caused a depression in foliar tissue K concentration for butterfly bush (Altland et al., 2015), holly, azalea, juniper (Chrustic and Wright, 1983; Cobb and Zarko, 1983), hakonechloa (Harvey et al., 2004), and photinia (Nash et al., 1983). Foliar K was depressed, albeit slightly, with increasing DL rate consistently across all papers in which foliar K data are presented (Table 1).

Conclusions

Dolomitic lime is one of the most commonly used substrate amendments in container nursery production. Its persistent and near-ubiquitous use could be considered more "traditional" than necessary in light of the scarcity of scientific literature supporting its use. Although liming of soil can be traced back to the first century BCE, experimentation with lime in the United States did not begin until the 1880s (Barber, 1984). Use of lime in the United States expanded greatly in the 1930s as part of a federal soil-conservation program that assisted farmers in the purchase of lime (Barber, 1984). Use of lime in mineral soils today is done to alleviate Al toxicity and increase crop yields. Ogden (1982) showed that pine bark ash contains high concentrations of Al, although no symptoms of Al toxicity were apparent in a series of experiments with tomato (*Solanum lycopersicum*). Wright (1989) reviewed Al interactions with soils and crops, and described Al speciation as complex, dependent on soil pH and other mineralogical factors, and difficult to predict. Wright (1989) also explained that Al forms complexing ligands with sulfate and soluble organic compounds, which alleviates Al toxicity. In an analysis of DFB response to lime rate, Altland and Buamscha (2008) speculated that Al was present in relatively high levels (pH dependent) in DFB, but in nontoxic forms due to a consistent supply of sulfate from bark and fertilizer amendments, as well as the presence of soluble organic compounds in DFB. Problems associated with Al toxicity in mineral soils also are not evident in the literature as problems in pine bark substrates. Of the research reviewed, plant response to increasing DL rate was positive in only 15 entries (Table 1). Of these 15 entries, 5 were either boxwood or nandina, which were susceptible to NH_4^+ toxicity at low pH, and thus responded favorably to increased DL rates. Others that responded favorably seemed to respond to a lack of Ca or Mg in the growing media, which was surprising considering the concentration of Ca and Mg in irrigation water throughout the United States. Nonetheless, it can be deduced that not only is DL not necessary for many crops, it can be inhibitory to growth for some (Table 1).

When making a decision to use DL, or providing a recommendation for DL rates, consider the main points discussed below:

1. Dolomitic lime rate affects substrate pH, but to a limit. Due to solubility of weak bases, DL solubility and further pH reactions are limited as substrate pH rises above 6.5. Adding more lime beyond this point will have little effect on substrate pH.
2. Substrate pH affects N form in the container. Higher pH supports the growth and activity of nitrifying bacteria, and the conversion of NH_4^+ to NO_3^-. This is ideal for crops such as boxwood and nandina that suffer from NH_4^+ toxicity. However, it could have negative environmental consequences as NO_3^- is more readily leached from container substrates than NH_4^+.
3. Substrate pH affects micronutrient availability. Pine bark may contain sufficient micronutrients to support crop growth. However, in the presence of DL these micronutrients will not likely be available for uptake in sufficient quantity. If DL is used, a supplemental micronutrient package is recommended to overcome this pH-induced effect.
4. Dolomitic lime provides an abundant supply of Ca and Mg. Although this source of Ca and Mg may not be necessary depending on the concentration of the two elements in irrigation water, its addition from a DL source will not inhibit plant growth.
5. High Ca and Mg from DL can suppress K uptake in plants, although this effect is slight and its mechanism is not fully understood.

One of the challenges in writing this review was reconciling the methods and growing conditions used in each experiment to understand why the plants responded the way they did. This was made difficult by the fact that many of the papers were abstracts and lacked the details in methods to fully understand the growing conditions and how they may have affected plant response. It is recommended for all future research on plant response to lime or pH, that irrigation water quality analyses be included. Parameters, such as concentration of Ca, Mg, and micronutrients in irrigation water, as well as irrigation water pH and alkalinity, are needed to fully understand plant response. Initial and final substrate nutrient concentrations are also useful.

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