Effect of Dolomitic Lime Rate and Application Method on Substrate pH and Creeping Woodsorrel Establishment[1]

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Abstract

Experiments were conducted to evaluate the effect of dolomitic lime rate and application method on substrate pH, creeping woodsorrel (*Oxalis corniculata*) establishment in containers, and growth of azalea (*Rhododendron* 'Rosebud') and pieris (*Pieris japonica* 'Claventine'). In Experiments 1 and 2, pulverized dolomitic limestone was incorporated at 0, 6, 12, 24, or 47 kg/m^3 (0, 10, 20, 40, or 80 lbs/yd^3). Containers were overseeded with twenty seeds of creeping woodsorrel. Substrate pH was measured with a pour-through technique. Substrate pH increased linearly and quadratically with increasing lime rate. Creeping woodsorrel shoot fresh weight was negatively correlated to substrate pH ($r = -0.67$, $p = 0.0001$). Creeping woodsorrel germinated and established poorly in substrates with pH higher than 6.7, with commercially acceptable control (>90%) occurring in containers with pH higher than 8.4 and 7.5 in Experiments 1 and 2, respectively. In Experiments 3 and 4, containers were topdressed with a uniform layer of pulverized or pelletized dolomitic limestone at 0, 5, 10, 20, or 40 g (0, 0.18, 0.35, 0.71 or 1.14 oz) per container. Substrate pH was measured in 2.5 cm (1 in) layers from the top to the bottom of the container using a modified saturated media extraction procedure. At each lime rate, pH was higher on the substrate surface than lower layers when topdressed with pulverized compared to pelletized lime. Across all lime types and rates, pH was lower in the 2.5 to 5.1 cm (1 to 2 in) layer compared to the surface layer which indicates that the most significant pH effect occurs on the surface. Topdressing containers with 40 g (1.41 oz.) of pulverized lime provided acceptable creeping woodsorrel control (>90%). In Experiment 5, incorporating the same lime rates used in Experiments 3 and 4 caused chlorosis and in some cases growth reduction in azalea and pieris while topdressed lime caused no change in growth or foliar color by 125 days after potting.

Index words: weed control, Douglas fir bark, lime type.

Species used in this study: creeping woodsorrel (*Oxalis corniculata* L.), pieris (*Pieris japonica* (Thunb.) D. Don ex G. Don 'Claventine'), and rhododendron (*Rhododendron* 'Rosebud').

Significance to the Nursery Industry

Data herein provide nursery producers with important information on how creeping woodsorrel (*Oxalis corniculata* L.) responds to substrate pH. Creeping woodsorrel establishment and growth was reduced as substrate pH exceeded 7.5; however, creeping woodsorrel grew well in the same pH range in which most nursery container crops are produced (4 to 6.5). Surface-applied lime affects substrate pH primarily on the surface, with little or no important pH effect 2.5 cm (1 in) below the surface. As a consequence, lime can be topdressed on the container surface to impede creeping woodsorrel establishment and growth without affecting growth and development of the container crop. Data show that topdressed lime rates of 40 g (1.41 oz) will provide commercially acceptable creeping woodsorrel control without affecting growth of acid-loving plants such as azaleas (*Rhododendron* 'Rosebud') and pieris (*Pieris japonica* 'Claventine'). Unfortunately, this rate is too high to be practically utilized in a commercial nursery setting. Nonetheless, examination of the data provide useful information on how surface applied lime moves through the container substrate. It suggests that efforts to elevate container pH with surface applications of lime will be unsuccessful at changing bulk container pH.

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Introduction

Weed control is important for producing quality container crops. Weeds in container systems are commonly controlled with preemergence herbicides; however, herbicides are not practical in every situation. Some crops such as hydrangea (*Hydrangea macrophylla*) and azalea (*Rhododendron obtusum*) are sensitive to preemergence herbicides (8), and no preemergence herbicide is labeled for use inside enclosed structures such as greenhouses. Understanding weed biology and environmental factors that influence weed growth may provide alternatives to herbicidal control.

Substrate pH has a major influence on plant growth. Changes in pH can increase or decrease mineral nutrients to toxic or deficient levels (10). Only a few species grow equally well in both alkaline and acidic soils (9, 11). Substrate pH in the range of 5.5 to 6 is often considered desirable; however, some crops favor more acidic substrates with pH as low as 4.5 (2). The optimum range for substrate pH is that which allows micronutrients to be soluble enough to satisfy plant needs without becoming so soluble they are toxic (4).

Organic container components such as bark and peat moss typically have lower pH than mineral soil and can sometimes cause problems with iron (Fe), manganese (Mn) and zinc (Zn) toxicity (5). Substrate pH is commonly raised using a liming material such as dolomitic lime ($CaCO_3 + MgCO_3$). There are two types of dolomitic lime, pulverized and pelletized, commonly used in the Oregon nursery industry. Pelletized dolomitic lime uses the same lime source, but is prilled for ease of handling. Pulverized lime raises pH more quickly than pelletized lime due to its smaller particle size (1).

Soil pH has been shown to influence the severity of weed infestations. Research in field soils demonstrated that broadleaf weed densities decreased as pH increased above 5.5 (12).

Also in a field soil, pink woodsorrel (*Oxalis martiana*) leaf number, plant height, and dry weight decreased with increasing soil pH (6).

Creeping woodsorrel (*Oxalis corniculata*) is a troublesome weed throughout the United States. It is most problematic in greenhouse and container production, but is also a weed of turf. Creeping woodsorrel reduces growth of container and greenhouse crops by out-competing plants for water and nutrients, and in some cases by outgrowing and shading smaller ornamental plants (3). Landscape professionals also note its persistence in the landscape. Most landscape infestations likely arise from contaminated nursery stock. Its competitive effects in production and its nuisance in the landscape make control of this weed imperative.

Leda and Wright (7) demonstrated that surface applications of lime are not effective in raising substrate pH throughout the bulk solution of the container profile. Surface application of lime likely only affects the substrate surface. Creeping woodsorrel seed is small and must germinate near the substrate surface, thus surface application of lime could inhibit creeping woodsorrel establishment. Once an optimal or detrimental pH range is established, cultural practices that modify pH at the container surface might be developed to inhibit creeping woodsorrel establishment and growth.

The objective of this research was to determine the influence of substrate pH on creeping woodsorrel establishment, growth, and reproduction. Following this, a secondary objective was to determine the effects of surface applications of lime on container pH and if surface applications of lime could be used to inhibit creeping woodsorrel growth on the container surface without adversely affecting ornamental crop growth.

Materials and Methods

The first experiment was conducted in a heated hoophouse at the North Willamette Research and Extension Center (NWREC) in Aurora, OR. Containers 14 cm (5.5 in) tall and wide were filled with 100% Douglas fir (*Pseudotsuga menziesii*) bark amended with 0.9 kg/m^3 (1.5 lb/yd^3) Micromax micronutrients (The Scott's Co., Marysville, OH) and 7.1 kg/m^3 (12 lb/yd^3) Osmocote 14N–6P–12K (14–14–14, The Scott's Co.). Pulverized dolomitic limestone (99% passed through 10 mesh, calcium carbonate equivalency (CCE) of 102%) (Woodburn Fertilizer Inc., Woodburn, OR), was incorporated into the substrate at 0, 6, 12, 24, or 47 kg/m^3 (0, 10, 20, 40, or 80 lb/yd^3). Twenty seeds of creeping woodsorrel were applied to the surface of each container on December 19, 2003. Containers were overhead irrigated with 0.6 cm (0.25 in) water per day. Substrate pH was measured with the following pour-through technique. Containers were irrigated till runoff and then allowed to drain for 15 minutes. After draining, 150 ml (5.1 oz) of deionized water was poured over the substrate surface and the resulting leachate was collected and measured for pH with a Thermo Orion pH meter (Thermo Electron Corp. Milford, MA). The experimental design was completely randomized with 10 single container replications. Data collected included measurement of substrate pH 40, 70, and 81 days after potting (DAP), weed germination numbers 40 DAP, flower number 70 DAP, estimation of percent coverage of the container surface by creeping woodsorrel 70 and 81 DAP, and shoot fresh weight (SFW) 81 DAP.

Experiment 2. The second experiment was conducted similarly to Experiment 1 with the following exceptions. It was conducted in a greenhouse at Oregon State University (OSU), Corvallis. Containers were filled with Douglas fir bark and peat moss (9:1 by vol) amended with the same nutrients used in Experiment 1. Pulverized dolomitic limestone was incorporated at 0, 6, 12, 24, or 47 kg/m^3 (0, 10, 20, 40, or 80 lb/yd^3). Fourteen seeds of creeping woodsorrel were applied to each container on February 1, 2004. Data collected included substrate pH 34, 60 and 74 DAP, percent germination 34 DAP, percent creeping woodsorrel coverage 60 and 74 DAP, flower number 74 DAP, seed pod number 74 DAP, and SFW 74 DAP. Substrate pH was measured with the same pour-through technique, but with an Accumet AR15 pH meter (Fisher Scientific, New York, NY).

Experiment 3. This experiment was conducted similarly to Experiment 1 with the following exceptions. It was conducted outside on a gravel container yard at OSU. Containers were topdressed with a uniform layer of pulverized or pelletized dolomitic limestone at 0, 5, 10, 20, or 40 g (0, 0.18, 0.35, 0.71 or 1.14 oz) per container on June 25, 2004. Topdress rates were calculated to deliver the same amount lime per container as would have occurred with the incorporated rates used in Experiments 1 and 2. Topdress lime applications at the aforementioned rates resulted in a physical layer of lime from immeasurable to 1 mm (0.04 in) thick. Pulver-

Table 1. Influence of lime rate on substrate solution pH, creeping woodsorrel (*Oxalis corniculata*) germination, growth, flowering and shoot fresh weight (SFW) (Experiment 1).

	40 DAP[z]		70 DAP			81 DAP		
Lime rate (kg/m^3)	pH	Germination (%)	pH	Coverage (%)	Flower number	pH	Coverage (%)	SFW[y] (g)
0	4.9	96	5.1	91	16	5.3	100	21.0
6	7.2	87	6.1	84	21	6.2	100	25.0
12	7.7	87	6.8	66	17	6.6	99	17.0
24	8.0	69	7.6	15	11	7.5	68	5.0
47	8.4	17	8.2	3	4	8.2	4	0.4
Significance[x]	L***Q***	L***Q***	L***Q***	L***Q***	L***Q**	L***Q***	L***Q***	L***Q***

[z]Days after potting.

[y]Shoot fresh weight.

[x]L and Q represent linear and quadratic rate responses, respectively. *, **, and *** represent significance when P ≤ 0.05, 0.01, and 0.001.

ized and pelletized lime are from the same source material, however, pelletized lime is prilled to facilitate handling in agricultural operations. Twenty seeds of creeping woodsorrel were applied to each container on July 5, 2004. Substrate pH was measured in 2.5 cm (1 in) layers from the substrate surface down through the container profile (five layers). The substrate was scraped away in 2.5 cm (1 in) layers with a metal spoon. Substrate from each layer was placed in a 250 ml (8.5 oz) beaker, filling it to the 200 ml (6.8 oz) demarcation. Deionized water was subsequently added to saturate the substrate up to the 200 ml (6.8 oz) demarcation. The saturated substrate was allowed to incubate at room temperature for 60 minutes, and then was filtered gravimetrically with Whatman No.1 qualitative filter paper (Whatman International Ltd., Maidstone, England). The pH of the extractant was measured with an Accumet AR15 pH meter. The experimental design was completely randomized with 10 single container replications. Data collected included substrate pH in each of the five layers 32 and 87 DAP. Five replications from each treatment were destructively harvested for pH measurement on each date. Established creeping woodsorrel plants were counted at 32 DAP, and SFW was measured 81 DAP.

*Experiment 4***.** The experiment was conducted similarly to Experiment 3 with the following exceptions. It was conducted in a greenhouse at OSU. Containers were topdressed with a uniform layer of pulverized or pelletized dolomitic limestone on November 19, 2004. Twenty seeds of creeping woodsorrel were applied to each container on November 21, 2004. Data collected included substrate pH in five layers of each container 22 and 58 DAP. Established creeping woodsorrel plants were counted at 18 DAP, and SFW was measured 54 DAP.

Experiment 5. This experiment was conducted simultaneously at OSU and NWREC in outdoor gravel container yards. Containers 3.8 liter (#1) were filled with 100% Douglas fir bark amended with 9.5 kg/m^3 (16 lb/yd^3) Apex 14N–6P–12K (14–14–14, Simplot Turf and Horticulture, Lathrop, CA) and 0.9 kg/m^3 (1.5 lb/yd^3) Micromax micronutrients. Azalea (*Rhododendron* 'Rosebud') and pieris (*Pieris japonica* 'Claventine') were potted on April 7, 2005. Containers were either incorporated with pulverized or pelletized lime at 0, 6, 12, 24, or 47 kg/m^3 (0, 10, 20, 40, or 80 lb/yd^3), or topdressed with the same materials at 0, 5, 10, 20, or 40 g (0, 0.18, 0.35, 0.71 or 1.14 oz) per container. Topdress rates were calculated to deliver the same amount lime as was contained in the respective incorporated rates. Containers were overhead irrigated with 0.6 cm (0.25 in) water per day. Substrate pH was measured with the same pour-through procedure described in Experiment 1. The experimental design was completely randomized with eight single container replications of azalea and six single container replications of pieris. Data collected included substrate pH 46 DAP, leaf chlorophyll content measured with a Minolta SPAD-502 Chlorophyll Meter (Spectrum Technologies, Inc., Plainfield, IL) 86 and 125 DAP, and growth index ((height + width + width) / 3) 125 DAP.

Results and Discussion

Experiment 1. Substrate pH increased linearly and quadratically with increasing lime rate (Table 1). Research has shown that pH in pine bark substrates also increased with increasing lime rates (11). Germination rate decreased linearly and quadratically with increasing lime rates (Table 1). Germination at 40 DAP was negatively correlated to substrate pH ($r = –0.67$, $p = 0.0001$) dropping from 96% at a pH of 4.9 to 17% at pH 8.4. Pink woodsorrel leaf number, plant height and dry weight also decreased with increasing soil pH in a field soil (6).

By 70 DAP, substrate pH increased linearly and quadratically with increasing lime rate. Substrate pH decreased almost one point for the 6 and 12 kg/m^3(10 and 20 lb/yd^3) treatments from 40 to 70 DAP, but did not change substantially at other rates of incorporation. Coverage of the container surface by creeping woodsorrel decreased linearly and quadratically with increasing lime rates. Coverage was also negatively and strongly correlated to substrate pH ($r = –0.91$, $p = 0.000l$), although reduced coverage with increasing lime rate could also be a function of reduced germination. Flower number also decreased linearly and quadratically with increasing lime rate and was negatively correlated to substrate pH ($r = –0.80$, $p = 0.0001$). This and other species in the genus *Oxalis* disseminate seed by explosive dehiscence (13); thus, reduced flower numbers could have a major impact on spread in container production systems.

Substrate pH changed very little between 70 and 81 DAP. Coverage still decreased linearly and quadratically with increasing lime rates and was highly correlated with substrate pH ($r = –0.83$, $p = 0.0001$). Creeping woodsorrel completely

Table 2. Influence of lime incorporation rate on substrate solution pH, creeping woodsorrel *(Oxalis corniculata)* germination, growth, flowering and shoot fresh weight (Experiment 2).

	32 DAP[z]		60 DAP		74 DAP				
Lime rate (kg/m^3)	**pH**	**Germination (%)**	**pH**	**Coverage (%)**	**pH**	**Coverage (%)**	**Flower number**	**Seed pod number**	**SFW[y] (g)**
0	4.4	82	4.5	100	4.4	100	12	9	10.6
6	6.0	55	6.0	70	5.4	94	12	2	9.5
12	6.4	54	6.1	54	6.2	75	16	6	7.8
24	6.7	62	6.3	31	6.8	67	5	0	3.6
47	7.5	49	7.3	7	7.4	8	0	0	0.5
Significance[x]	L***Q***	L**Q***	L***Q***	L***Q***	L***Q**	L***Q**	L***Q***	L***Q***	L***Q***

[z]Days after potting.

[y]Shoot fresh weight.

[x]L and Q represent linear and quadratic rate responses, respectively. *, **, and *** represent significance when $P \leq 0.05$, 0.01, and 0.001.

Table 3. Effect of surface applications of dolomitic lime on substrate solution pH in depth of five layers of the container substrate (Experiment 3).

Depth (cm)	Pulverized lime application rate: 0 g	5 g	10 g	20 g	40 g		Pelletized lime application rate: 0 g	5 g	10 g	20 g	40 g	
	Substrate solution pH						Substrate solution pH					
32 DAP[z]												
0.0 to 2.5	3.8	4.8	5.5	5.9	6.3	L***Q***[x]	3.8	4.2	4.5	4.7	4.9	L***Q***
2.5 to 5.1	3.6	3.9	4.1	4.3	4.2	L***Q***	3.6	3.7	3.8	3.8	4.4	L***
5.1 to 7.6	3.4	3.8	4.0	3.7	3.8	Q*	3.4	3.6	3.6	3.7	4.1	L***
7.6 to 10.2	3.5	3.6	3.8	3.7	3.8	NS	3.5	3.6	3.6	3.6	4.0	L***
10.2 to 12.7	3.5	3.7	3.9	3.7	3.7	NS	3.5	3.6	3.6	3.7	4.1	L***
	LSD[y] = 0.3											
81 DAP												
0.0 to 2.5	4.1	5.0	5.3	5.7	6.1	L***Q***	4.1	4.6	4.7	5.2	5.3	L***Q***
2.5 to 5.1	3.5	4.0	4.6	5.0	5.5	L***Q***	3.5	3.8	4.0	4.2	4.6	L***
5.1 to 7.6	3.4	3.6	3.8	4.5	5.0	L***Q*	3.4	3.3	3.5	3.7	3.8	L***
7.6 to 10.2	3.4	3.4	3.6	4.0	4.8	L***	3.4	3.3	3.4	3.5	3.5	NS
10.2 to 12.7	3.6	3.6	3.7	4.0	4.4	L***	3.6	3.4	3.5	3.6	3.5	NS
	LSD = 0.3											

[z]Days after potting.

[y]Fisher's protected least significant difference ($\alpha = 0.05$).

[x]L and Q represent linear and quadratic rate responses, respectively. *, **, and *** represent significance when $P \leq 0.05$, 0.01, and 0.001. NS represent no significance.

covered the surface of containers treated with 0 to 12 kg/m^3 (20 lb/yd^3) lime. Containers treated with 24 and 47 kg/m^3 (40 and 80 lb/yd^3) lime had substrate pH of 8.0 and 8.2 respectively, and significantly reduced creeping woodsorrel coverage. Creeping woodsorrel SFW was negatively correlated to substrate pH (r = –0.84, p = 0.0001) and positively correlated with creeping woodsorrel coverage (r = 0.84, p = 0.0001).

Experiment 2. By 34 DAP, substrate pH increased linearly and quadratically with increasing lime rate (Table 2). Substrate pH readings were lower compared to those in Experiment 1. Lower pH could have been caused by using a substrate with 10% peat moss in Experiment 2 and 100% bark in Experiment 1. However, Altland (1) reported that adding up to 50% peat moss to Douglas fir bark had no effect on substrate pH, regardless of lime rate. Substrate pH readings were lower in Experiment 2 because either irrigation water at the OSU greenhouses have lower alkalinity levels than those at NWREC (34 ppm vs. 111 ppm), or bark used in each of the experiments was from a different lot with slightly different chemical properties. Experiments 1 and 2 were conducted at different sites, however, all experiments were irrigated and managed similarly such that differences cannot be explained by growing site. Creeping woodsorrel germination rate decreased linearly and quadratically with increasing lime rate. Germination at 32 DAP was negatively correlated to substrate pH (r = –0.50, p = 0.0003) although the decrease in germination rate over the range of 6 to 47 kg/m^3 (10 to 80 lb/yd^3) was 6%.

By 60 DAP, substrate pH still increased linearly with increasing lime rate. Within a given incorporation rate, substrate pH changed little between 32 and 60 DAP. Coverage decreased linearly and quadratically with increasing lime rates and was more highly correlated with substrate pH (r = –0.79, p = 0.0001) than germination rates at 32 DAP. Despite the weak response of germination to substrate pH, subsequent growth as measured by percent coverage of the container surface was responsive to increasing lime rate. Although plants germinated, they grew poorly thereafter.

Substrate pH changed little within a given rate of lime incorporation between 60 and 74 DAP. Surface coverage by creeping woodsorrel still decreased linearly and quadratically with increasing lime rates and was highly correlated with substrate pH (r = –0.70, p = 0.0001). Creeping woodsorrel flower number was negatively correlated to substrate pH (r = –0.45, p = 0.0009) as was seed pod number (r = –0.50, p = 0.0002). At 47 kg/m^3 (80 lb/yd^3), no flowers or seeds were produced. Similar to Experiment 1, SFW was negatively correlated to substrate pH (r = –0.67, p = 0.0001).

Experiments 1 and 2 demonstrate that creeping woodsorrel germination and subsequent growth are dependent on substrate pH. However, substrate pH needs to exceed 7.5 to reduce creeping woodsorrel growth to an acceptable level. Unfortunately, a substrate pH of 7.5 would not be conducive to growth of most crops in container production (2).

Experiment 3. At 32 DAP, there was a three-way interaction between lime type, lime rate, and substrate layer (Table 3). Among containers receiving no lime, substrate pH was higher on the surface layer than the bottom three layers. Irrigation water alkalinity can cause increases in substrate pH over time (14). These data suggest that alkalinity-related changes in substrate pH may be greater on the surface compared to the bottom layers of a container.

The pH of the surface layer increased linearly and quadratically with increasing lime rate among both pulverized and pelletized lime. At each lime rate, pH was greater when topdressed with pulverized lime compared to pelletized lime.

Within containers receiving pulverized lime, substrate pH increased in the 0 to 2.5 cm (0 to 1 in) and 2.5 to 5.1 cm (1 to

Table 4. **Effect of surface application of dolomitic lime of on surface substrate solution pH, creeping woodsorrel (*Oxalis corniculata*) germination and shoot dry weight (Experiment 3).**

Lime type	Lime rate (g)	32 DAP[z] pH on substrate surface	32 DAP[z] Germination number	81 DAP pH on substrate surface	81 DAP Shoot dry weight (g)
	0	3.8	10.9	4.1	1.7
Pulverized lime	5	4.8	7.5	5.0	1.9
	10	5.5	2.5	5.3	1.4
	20	5.9	0.9	5.7	0.8
	40	6.3	0.0	6.1	0.3
			L***Q***[x]	L***Q***	L**
Pelletized lime	5	4.2	9.5	4.6	2.1
	10	4.5	6.0	4.7	2.1
	20	4.7	3.4	5.2	2.5
	40	4.9	0.0	5.3	1.8
			L***	L***Q***	NS

[z]Days after potting.

[x]L and Q represent linear and quadratic rate responses, respectively. *, **, and *** represent significance when $P \leq 0.05$, 0.01, and 0.001. NS represent no significance.

2 in) layers compared to non-treated controls. Within the 5.1 to 7.6 cm (2 to 3 in) layer, substrate pH increased quadratically up to the 10 g (0.35 oz) rate then decreased slightly. Below this layer there was no rate response to lime rate. Among containers receiving pelletized lime at 32 DAP, pH of all substrate layers below the surface layer increased linearly with increasing lime rate. However, this rate response may have been heavily influenced by the 40 g (1.41 oz) rate. According to LSD comparisons, substrate pH below the surface layer in containers treated with 5 to 20 g (0.18 to 0.71 oz) lime was similar to non-limed containers.

Across all lime types and rates (except for non-limed controls), pH was lower in the 2.5 to 5.1 cm (1 to 2 in) layer compared to the surface layer. This indicates that the most significant pH effect occurs on the surface layer. Only containers that were topdressed with 20 or 40 g (0.71 or 1.41 oz) of pulverized lime and 40 g (1.41 oz) of pelletized lime had a higher substrate pH in the 2.5 to 5.1 cm (1 to 2 in) layer greater compared to the 5.1 to 7.6 cm (2 to 3 in) layer. Within each lime rate, there were no differences in substrate pH from the 5.1 to 7.6 cm (2 to 3 in) layer and below at 32 DAP.

By 81 DAP, the influence of lime throughout the container substrate was more evident than 32 DAP. Among containers receiving pulverized lime, substrate pH increased with increasing lime rate within each layer. Substrate pH was highest in the surface layer, however, pH increased higher than non-limed containers when topdressed with 20 or 40 g (0.71 to 1.41 oz) throughout the container profile. Within each lime rate, substrate pH decreased from the surface to the container bottom.

By 81 DAP, substrate pH among containers topdressed with pelletized lime increased with increasing lime rate in the surface and 2.5 to 5.1 cm (1 to 2 in) layers. Substrate pH also increased in the 5.1 to 7.6 cm (2 to 3 in) layer, although only slightly. Substrate pH in the bottom two layers of the same containers did not respond to lime rate.

Substrate pH is higher at the container surface, and in some cases in layers as low as 5.1 cm (2 in) below the container surface. However, at least within 81 DAP, substrate pH below the surface 5.1 cm (2 in) is relatively unaffected unless very high rates of pulverized lime were applied. In this experiment, both pulverized and pelletized lime products at 20 or 40 g (0.71 or 1.41 oz) rates aggregated to form a hard shell across the container surface. This aggregation may have formed a physical barrier that not only impeded movement of lime particles into the substrate thus limiting its influence on substrate pH, but that also suppressed creeping woodsorrel germination. Among containers treated with pulverized lime, creeping woodsorrel SDW declined most dramatically with the 20 and 40 g (0.71 and 1.41 oz) rate (Table 4). However, similar aggregation among containers treated with the pelletized lime did not affect creeping woodsorrel SDW. This indicates that the suppressive effects from topdressed lime are caused more by changes in substrate pH than the occurrence of the lime aggregation on the substrate surface.

At 32 DAP, as substrate pH on the surface layer increased with lime rate, creeping woodsorrel numbers decreased (Table 4). Creeping woodsorrel produce small seed, and thus must germinate near the substrate surface. Substrate pH on the surface layer will influence creeping woodsorrel germination more than pH of layers deeper in the container substrate.

By 81 DAP, substrate surface pH in containers topdressed at the 40 g (1.41 oz) pulverized lime rate increased to 6.1 and resulted in reduced SDW of creeping woodsorrel (Table 4). However, substrate surface pH in containers topdressed with pelletized lime only increased to 5.3 and did not affect creeping woodsorrel SDW. Despite reduced germination numbers at 32 DAP, by 81 DAP plants that established in containers topdressed with pelletized lime were able to grow to a similar size as those in non-limed containers.

Experiment 4. Results in Experiment 4 were similar to those in Experiment 3 with one major exception. At 22 DAP, substrate pH increased with increasing pulverized lime rate in each layer of the container while pelletized lime only influenced the top three layers (Table 5). This is different from what occurred in Experiment 3 when pH was measured 32 DAP where pelletized lime affected substrate pH throughout all layers of the container while pulverized lime only affected the top three layers. Based on results in Experiments 1 and 2 and other similar research (1), one would expect pulverized

Table 5. Effect of surface applications of dolomitic lime on substrate solution pH in layered sections of the container substrate (Experiment 4).

Depth (cm)	Pulverized lime application rate: 0 g	5 g	10 g	20 g	40 g		Pelletized lime application rate: 0 g	5 g	10 g	20 g	40 g	
	Substrate solution pH						Substrate solution pH					
22 DAP[z]												
0.0 to 2.5	3.9	4.7	5.1	5.4	6.3	L***Q***[x]	3.9	4.3	4.6	4.7	5.2	L***Q***
2.5 to 5.1	3.5	3.8	4.4	4.5	4.3	L***Q*	3.5	3.7	3.4	3.8	4.0	L**
5.1 to 7.6	3.4	3.8	3.8	4.5	4.4	L***Q*	3.4	3.5	3.4	3.7	3.5	Q*
7.6 to 10.2	3.5	3.9	4.0	4.3	4.4	L*Q***	3.5	3.7	3.6	3.7	3.7	NS
10.2 to 12.7	3.4	4.0	4.1	4.2	4.2	L***	3.4	3.7	3.5	3.5	3.6	NS
	LSD[y] = 0.2											
58 DAP												
0.0 to 2.5	3.9	5.0	5.4	5.6	6.0	L***Q*	3.9	4.5	4.5	4.9	5.2	L***
2.5 to 5.1	3.8	4.2	4.2	4.4	4.6	L**Q***	3.8	4.1	4.0	4.0	4.2	L*
5.1 to 7.6	3.8	4.0	4.1	4.2	4.3	L***Q*	3.8	3.9	4.0	4.0	3.9	NS
7.6 to 10.2	3.7	3.9	4.0	4.1	4.1	L***	3.7	3.9	3.9	3.9	3.8	NS
10.2 to 12.7	3.8	3.8	4.0	4.0	4.1	L**Q*	3.8	3.9	3.9	3.8	3.8	NS
	LSD = 0.5											

[z]Days after potting.

[y]Fisher's protected least significant difference ($\alpha = 0.05$).

[x]L and Q represent linear and quadratic rate responses, respectively. *, **, and *** represent significance when P ≤ 0.05, 0.01, and 0.001. NS represent no significance when P = 0.05.

Table 6. Azalea, pieris, and substrate solution pH response to dolomitic lime type, application method, and rate (Experiment 5).

Lime placement	Lime type	Lime rate (g/pot)	Substrate pH 46 DAP[z]	Azalea Chlorophyll 86 DAP	Azalea Chlorophyll 125 DAP	Azalea Growth index 125 DAP	Pieris Chlorophyll 86 DAP	Pieris Chlorophyll 125 DAP	Pieris Growth index 125 DAP
Control		0	4.0	39.5	56.0	25.3	48.6	54.1	20.8
Topdressed	Pulverized	5	4.2	34.3	50.3	25.5	51.9	50.5	21.3
		10	4.2	27.6	54.6	32.1	38.3	48.9	19.4
		20	4.3	26.7	55.4	23.4	49.1	51.9	20.1
		40	4.6	24.0	55.6	22.6	49.0	49.3	20.6
			L***[y]	L***Q***	NS	NS	NS	NS	NS
	Pelletized	5	4.2	36.2	57.1	23.2	48.9	51.8	19.8
		10	4.2	28.2	60.0	22.9	45.2	55.3	20.0
		20	4.3	29.7	53.8	21.1	42.3	53.3	18.9
		40	4.4	30.7	52.7	22.9	42.2	50.5	20.3
			L***Q*	L**Q***	NS	NS	L*	NS	NS
Incorporated	Pulverized	5	4.9	25.9	54.8	19.6	39.8	48.8	19.8
		10	5.4	23.3	49.1	20.6	27.0	42.8	17.2
		20	5.8	23.7	43.7	18.2	21.5	43.8	16.6
		40	5.9	16.3	32.9	18.4	21.2	40.7	15.1
			L***Q***	L***Q***	L***	L*	L***Q***	L**	L***Q*
	Pelletized	5	4.7	40.0	56.1	24.0	41.9	53.4	18.5
		10	4.7	32.0	54.8	19.4	42.8	54.2	20.0
		20	5.0	31.4	55.1	24.0	50.1	51.7	20.2
		40	5.2	24.1	51.5	20.7	40.3	49.1	20.1
			L***Q***	L***	L*	NS	NS	NS	NS
LSD $_{(\alpha = 0.05)}$			0.15	4.7	5.5	5.5	5.8	8.1	2.1

[z]Days after potting.

[y]L and Q represent linear and quadratic rate responses, respectively. *, **, and *** represent significance when P ≤ 0.05, 0.01, and 0.001. NS represent no significance when P = 0.05.

lime to affect substrate pH in the bottom layers of the container more than pelletized lime.

Creeping woodsorrel response to lime applications was similar to that observed in Experiment 3 (data not shown).

Experiment 5. All lime treatments increased substrate pH above non-treated controls as measured by the pour-through technique (Table 6), with pH increasing with increasing lime rate. Among topdressed containers, pulverized lime increased pH more than pelletized lime at the highest rate only. Topdressing lime even at the highest rate only increased substrate pH in this experiment to 4.6 (46 DAP, as measured with the pour-through technique). Within each lime type and rate, incorporating lime had greater impact on substrate pH than topdressing. These results concur with Experiments 1 through 4.

At 86 DAP all lime treatments, except for the low rate of topdressed pulverized lime and incorporated pelletized lime, decreased azalea chlorophyll content (Table 6). However, by 125 DAP none of the topdressed lime applications reduced chlorophyll content or plant growth. Incorporated lime treatments decreased azalea chlorophyll content with increasing lime rates with both pelletized and pulverized lime. Pulverized lime had a greater influence on azalea chlorophyll content, with each rate reducing chlorophyll content more than that of pelletized lime (except for the 5 g (0.18 oz) rate). Incorporating pulverized lime also decreased azalea growth linearly with increasing lime rate, while incorporated pelletized lime had no effect.

Pieris chlorophyll content at 86 DAP decreased with 20 and 40 g (0.71 and 1.41 oz) of topdressed pelletized lime and all rates of incorporated lime. Topdressed pulverized lime at 10 g (0.35 oz) resulted in plants with inexplicably low chlorophyll content, and in contrast incorporated pelletized lime at 20 g (0.71 oz) resulted in plants with inexplicably high chlorophyll content. Similar to results with azalea, no topdressed treatment reduced pieris chlorophyll 125 DAP. Incorporated pulverized lime reduced pieris chlorophyll content and growth with increasing lime rate while pelletized lime had no effect.

Prior to potting, azalea and pieris plants were well established in their propagation flats and suffering from slight nutrient deficiency. Reduced chlorophyll content of azalea at 86 DAP was probably due to those plants taking longer to 'green up' after potting. By 125 DAP, plants with topdressed lime were as green and large as non-limed control plants. Azalea and pieris are in the family Ericaceae, and are especially sensitive and responsive to high substrate pH. Their growth in containers with topdressed lime is considered a severe test of ornamental tolerance to such applications. Because these two species did not respond negatively, it is unlikely that others would.

Alternatives to preemergence herbicides are needed for some facets of nursery production. Our data shows that creeping woodsorrel establishment and growth is inhibited by elevated substrate pH, with commercially acceptable control (>90%) occurring in containers with pH higher than 8.4 and 7.5 in Experiments 1 and 2, respectively. However, creeping woodsorrel grew vigorously in our experiment with substrate pH in the range of 4.4 to 6.4, which is the same general range that most nursery crops are grown.

This research further shows that surface-applied lime will change pH of the substrate surface, without dramatically changing pH through the bulk of the container substrate. Topdressing containers with 40 g (1.41 oz.) of pulverized lime provided 82 and 94% creeping woodsorrel control in Experiments 3 and 4, respectively; however, this application rate could not be practically applied in a commercial nursery setting. Assuming containers were placed pot to pot, the 40 g (1.41 oz) per container rate is equivalent to topdressing 20 t/ha (18,000 lbs/A) of lime compared to 111–222 kg/ha (100–200 lb/A) for most granular preemergence herbicides.

Despite a lack of practical application in using surface-applied lime for weed control, these data also demonstrate how lime from different sources moves through the container profile. In our experiments, lime tended to form a hard crust on the container surface, and thus was physically impeded from filtering down through the container profile. Situations sometimes occur when substrate pH is too low after the crop is potted and the nursery desires to raise substrate pH. These data show that surface applications of dolomitic lime are largely ineffective at raising pH throughout the entire substrate. These data also show that among containers receiving no lime, irrigation water alkalinity affects pH on the substrate surface and less so in lower layers.

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