Limestone Particle Size and Residual Lime Concentration Affect pH Buffering in Container Substrates

Jinsheng Huang[1], Paul R. Fisher[2] and W.E. Horner; Environmental Horticulture Dept., University of Florida, P.O. Box 110670, Gainesville FL 32611-0670, USA

William R. Argo[3], Blackmore Company, 10800 Blackmore Avenue, Belleville, MI 48111

Keywords: calcium carbonate, impatiens, gasometric, greenhouse, growing media, peat, substrate-pH

1. huangj@ufl.edu
2. Corresponding author: pfisher@ufl.edu
3. bargo@blackmoreco.com

Abstract
The objective was to quantify how the concentration and particle size of unreacted "residual" limestone affected pH buffering capacity for ten commercial and nine research container substrates that varied in residual calcium carbonate equivalents (CCE) from 0.3 to 4.9 g CCE·L^{-1}. The nine research substrates contained 70% peat:30% perlite (by volume) with dolomitic hydrated lime at 2.1 g·L^{-1}, followed by incorporation of one of four particle size fractions [850 to 2000µm (10 to 20 US mesh), 250 to 850µm (20 to 60 US mesh), 150 to 250µm (60 to 100 US mesh), or 75 to 150µm (100 to 200 US mesh)] of a dolomitic carbonate limestone at 0, 1.5 or 3.0 g·L^{-1}. Substrate-pH buffering was quantified by measuring the pH change following either (a) mineral acid drenches without plants, or (b) a greenhouse experiment where an ammonium-based (acidic) or nitrate-based (basic) fertilizer was applied to *Impatiens wallerana* Hook. F. Increasing residual CCE in commercial substrates was correlated with greater pH buffering following either the HCl drench or impatiens growth with an ammonium-based fertilizer. Research substrates with high applied lime rate (3.0 kg·m^{-3}) had greater pH buffering than at 0 or 1.5 g·L^{-1}. At 3 g·L^{-1}, the intermediate limestone particle size fractions of 250 to 850 µm and 150 to 250 (20 to 60 or 60 to 100 US mesh) provided the greatest pH-buffering with impatiens. Particle fractions finer than 150 µm reacted quickly over time, whereas buffering by particles coarser than 850 µm was limited because of the excessively slow reaction rate during the experimental periods. Addition of acid from either an ammonium-based fertilizer or HCl reduced residual CCE over time. Dosage with 40 meq acid from HCl per liter of substrate or titration with HCl acid to substrate-pH of 4.5 were well-correlated with pH buffering in the greenhouse trials and may be useful laboratory protocols to compare pH buffering of substrates. With nitrate fertilizer application, residual CCE did not affect buffering against increasing pH. Residual limestone is an important substrate property that should be considered for pH management in greenhouse crop production under acidic conditions.

Introduction
Substrate-pH and pH buffering capacity are important chemical properties for successful nutritional management in crop production. Substrate-pH measures the active acidity or alkalinity in soil solutions, whereas pH buffering capacity refers to the ability of a substrate to maintain a stable pH following addition of acid or base.

Peat moss sources differ in buffering capacity in the pH range of 5.4 to 6.2 (Rippy, 2005). These differences in buffering capacity, which occur over the pH range in which most horticultural crops are grown, could contribute to problems of rapid substrate-pH changes during the course of crop production. Major substrate properties that contribute to the buffering capacity of peat are cation exchange capacity (CEC) and base saturation [fractional calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and sodium (Na^{+})](BS) (Rippy and Nelson, 2007).

Limestone materials are incorporated into substrates to neutralize acidity and to buffer pH. When limestone is added to a substrate, it can be separated into two fractions, the reactive fraction and the residual fraction. The reactive fraction is the limestone that reacts initially after mixing to increase the substrate pH to an acceptable level for plant growth. The residual fraction is the limestone that remains undissolved in the substrate. The ratio of reactive:residual lime at the equilibrium pH is dependent on particle size, chemistry, crystalline structure, reactivity rate, and the acidity of substrate components such as peat.

Residual limestone increases substrate pH buffering capacity (Argo and Biernbaum, 1996), and is thought to consists mainly of calcium and/or magnesium carbonate, which react more slowly than a highly reactive base such as hydrated lime. The concentration of residual carbonate limestone (in units of calcium carbonate equivalents, CCE) can be quantified by a gasometric procedure using a Chittick apparatus where HCl acid is added to a substrate sample and released CO_2 gas is measured through volume displacement (Huang, et al, 2007a).

Effects on buffering capacity from lime particle size and residual lime concentration have not been previously quantified. Our objective was to quantify differences in pH buffering between commercial and research container substrates that varied in residual CCE, lime particle size distribution, and lime incorporation rate. Experiments included application of HCl to substrate without plants, and two greenhouse plant experiments where an acidic reaction (ammonium-based) or basic-reaction (nitrate-based) fertilizer was applied.

Materials and Methods

Nine research substrates were developed for the experiment that varied in the type, rate and particle size of limestone (Table 1). The research substrates were prepared with 70% peat + 30% perlite (by volume), where initial pH was raised to 6.10 with 2.1 $g \cdot L^{-1}$ of a dolomitic hydrated lime (97% $Ca(OH)_2 \cdot MgO$, 92% of which passed through a 45-μm screen, National Lime and Stone®, Findlay, Ohio). A dolomitic limestone [$CaMg(CO_3)_2$, Lawn & Garden limestone™, Oldcastle Stone Products®, Thomasville, PA] was screened to pass through four series of screen sizes (retained on 20, 60, 100 and 200 US mesh size) and each of the four particle size fractions was incorporated into the pre-limed substrate at 0, 1.5 or 3.0 $g \cdot L^{-1}$. The peat source used in research substrates was Canadian *Sphagnum* peat (Sun Gro Horticulture, Vancouver, Canada) with long fibers and little dust (Von Post scale 1-2; Puustjarvi and Robertson, 1975).

In addition, ten commercial container substrates (Table 2) were selected that represented a range of residual CCE concentrations typical for container plant production in North America. The commercial substrates were peat-based growing media, except for S1 (Oasis^R foam), produced by major substrate manufacturing companies in the US, Canada, and Europe.

Initial substrate-pH, EC and residual lime in CCE

Substrate-pH, EC and residual CCE were measured on 3 replicates for each substrate at the start of experiments. Substrate moisture was first brought to 95% container capacity (near saturation point at 450 mL water per L of substrate) in a partially open plastic bag (minimal evaporation occurred) and was incubated at room temperature (22^{o}C) for 7 days. The solution was squeezed from the substrate, and pH and EC were then measured on the extracted solution using a Corning 430 pH meter (Nova Analytics Corporation, 600 Unicorn Park, Woburn, MA 01801) and an Orion 130 EC meter (Thermo Scientific, 81 Wyman Street, Waltham, MA 02454). Residual CCE was measured using the gasometric method as described by Huang et al. (2007c).

Substrate-pH buffering evaluation

pH buffering was first evaluated in the laboratory by applying HCl acid to the substrate samples. 350 mL samples of each substrate were first placed in open plastic bags at 25^{o}C near 95%

container capacity (minimal evaporation occurred) for 7 days, and then received one dose of 0, 20, 40, 60, 80, or 100 meq of 0.5 N $HCl \cdot L^{-1}$ of substrate. Substrate-pH was measured 7 days after the drench with four replicates. Substrate-pH and delta pH (ΔpH, absolute pH – initial pH at day 7) data were analyzed using analysis of covariance (ANCOVA) using SAS PROC GLM across substrates and acid concentration. ANCOVA was also used to test the effect for each acid dose.

The amount of acid required to decrease substrate-pH from the initial pH to pH 4.5 was quantified as the "$pH_{4.5}$ Buffering Capacity" (in $meq \cdot L^{-1}$). The value of 4.5 was selected as the end point pH because (1) the pH value is below the target range for greenhouse crops (5.4 to 6.5), and (2) generally, a water solution having a pH below 4.5 contains no carbonate (CO_3^{2-}) or bicarbonate (HCO_3^-) alkalinity (Deffeyes, 1965). Substrate-pH was first plotted over the amount of acid drenches and a quadratic curve ($y = ax^2 + bx + c$, where x was the acid in meq, and y was the corresponding pH value) was fitted for each substrate. $pH_{4.5}$ Buffering Capacity (Table 2) was then calculated using the quadratic curve by solving the value of x when $y = 4.5$.

Substrate-pH buffering was also evaluated in two greenhouse experiments with hybrid impatiens (*Impatiens wallerana* Hook. F.). Impatiens was chosen because plants can be grown across a wide pH range (Smith et al., 2004). In the first experiment (Exp.I), an acid reaction fertilizer (15.2N-1.9P-12.7K, with 100% of N as NH_4-N, (Greencare, Ill.)) or a basic reaction fertilizer (12.6N-1.6P-10.4K, with 3% of N as NH4-N, (Greencare, Ill.)) at 150 $mg \cdot L^{-1}$ N were applied with each irrigation. Tested media included 6 commercial (S3, S5-9 in Table 2) and 9 research substrates. 'Super Elfin' hybrid impatiens seedling plugs were grown in a polycarbonate greenhouse for 42 days (average temperature 22.4 ± 4.3C, average daily light integral 10.9±3.0 $mol \cdot m^{-2} \cdot d^{-1}$, mean ± standard deviation) in 10-cm-diameter pots (350 mL azalea pots). Each pot was a replicate, with four replicates for each substrate per fertilizer per sample date. Media and lime applications were completely randomized within each fertilizer type, and the two fertilizer types were analyzed separately. Substrate-pH and EC were measured destructively at 21 and 42 days using Saturated Media Extract (SME) method, and residual CCE was measured destructively at 42 days, using the gasometric method (Huang, et al. 2007c).

In the second experiment (Exp.II), 'Super Elfin' hybrid impatiens seedlings were grown in the same greenhouse in 11.4-cm-diameter pots (580 mL azalea pots) for 54 days (average temperature 23.8 ± 3.3C, average daily light integral 15.0±4.0 $mol \cdot m^{-2} \cdot d^{-1}$, mean ± standard deviation). Only the acid reaction fertilizer was applied at 150 $mg \cdot L^{-1}$ N with each irrigation. Tested media included 7 commercial (S3, S5, S7-11 in Table 2) and 9 research substrates. Substrate-pH and EC were measured at 21 and 42 days using Pour-through method. Final substrate-pH and EC were measured destructively at day 54 using SME. Residual CCE was measured destructively at day 54, using the gasometric method. Data were analyzed using SAS PROC GLM by week.

Results and Discussion

Commercial Substrates

Initial substrate-pH values of commercial substrates and one research substrate (S4) ranged from 4.96 to 6.45 (average pH =5.9) one week after being moistened to container capacity (Table 2).

The residual CCE ranged from 0.27 to 4.91 $g \cdot L^{-1}$. The lowest residual CCE measured for a commercial substrate was 0.45 $g \cdot L^{-1}$ (substrate S2). The applied CCE from lime reported by companies ranged from 2.23 to 7.06 $g \cdot L^{-1}$. Although the measured residual CCE was lower than the applied CCE, differences in substrate compaction during mixing by companies versus compaction during measurement with the gasometric method may cause errors in comparing applied versus residual CCE. In addition, substrate S11 had the highest residual CCE, and this substrate contained vermiculite which may have also contributed to residual CCE (Huang et al. 2007c).

Increasing the residual CCE in substrates tended to reduce the change in substrate-pH (i.e. increase buffering) following different drench rates of HCl (Figure 1A). When substrates received 40 meq rate of HCl acid per liter of substrate, which was an intermediate experimental rate that had a wide range in pH levels between substrates, the change in pH (ΔpH) for commercial substrates varied from -0.6 to -4.1, with an average of -1.65 (Fig. 1B). The $pH_{4.5}$ Buffering Capacity (meq acid per liter of substrate required to drop substrate-pH to 4.5) estimated for each commercial substrate using the acid HCl drenches is shown in Table 2 and was positively correlated with the initial residual lime concentration (Fig. 2A).

The final substrate-pH varied from 3.7 to 5.9 in Exp. I (Fig. 3A) and 3.8 to 5.7 in Exp. II (Fig. 3B) following fertigation with 100% NH_4-N acidic-reaction fertilizer. The ΔpH (drop in pH from the start to the end of the experiment) was smaller as initial residual CCE increased (Fig. 2B, 2C). Trends in pH change were therefore consistent for both HCl drenches and the application of an ammonium-based fertilizer. ΔpH from 40 meq HCl and ΔpH from the ammonium-based fertililizer were positively correlated with an r^2 of 0.917, as were $pH_{4.5}$ Buffering Capacity and ΔpH from the ammonium-based fertilizer ($r^2 = 0.918$, data not shown).

Substrate-pH increased in Exp. I following 6 weeks of fertigation with 97% nitrate basic-reaction fertilizer (Fig. 3C). The increase in substrate-pH varied from 0.5 to 1.2 between substrates, but was not affected by the initial residual CCE (Fig. 2D).

Research Substrates

Initial pH of research substrates increased as limestone particle size decreased and lime incorporation rate increased (Table 1). EC values for research substrates were similar, ranging from 0.4 to 0.5 $S \cdot m^{-1}$ (data not shown).

pH response to a mineral HCl acid application at 40 meq per liter of substrate was influenced by both lime incorporation rate and lime particle size. Substrates amended with 3 $g \cdot L^{-1}$ had a smaller ΔpH (i.e., greater buffering) than with 1.5 $g \cdot L^{-1}$ (Fig. 4A, 4B). The overall ΔpH for substrates amended with 1.5 and 3 $g \cdot L^{-1}$ was -2.85 ± 0.23 and -2.37 ± 0.29, respectively (means ± 95% CI). Research substrates containing only hydrated lime or the coarsest lime particle fraction (850 to 2000 µm) for both lime rates had the greatest ΔpH (least buffering) following drench of 40 meq of HCl (Fig. 4A-B). Substrates amended with the finest particle fractions (150 to 250 µm and 75 to 150 µm) had the highest pH buffering at the rate of 3 $g \cdot L^{-1}$, with a corresponding ΔpH -1.97 and -2.12, respectively (Fig. 4B). ΔpH for research substrates ranged from -1.97 to -3.14. Similar trends in pH buffering between different particle fractions occurred when research substrates received doses of HCl other than 40 meq (data not shown).

Research substrates with 3 $g \cdot L^{-1}$ were more buffered against a drop in pH for impatiens grown with the ammonium-based fertilizer compared with those grown in substrates containing the low lime rate (1.5 $g \cdot L^{-1}$), with ΔpH averaging -2.1 and -2.5, respectively in Exp. I. At the low lime rate (1.5 $g \cdot L^{-1}$), there were no significant differences between particles sizes for either final substrate-pH or ΔpH (Fig. 4C).

At the high lime rate (3 $g \cdot L^{-1}$) in Exp. I, final substrate-pH and ΔpH varied between different particle fractions. The coarsest particles (retained on a US 20 mesh screen, 850 to 2000 µm) provided no pH buffering compared with hydrated lime only, as shown in Fig. 4C and 4D, and previous research has shown this coarse fraction has little reactivity in peat substrates over a period of weeks (Huang, et al. 2007b). Substrates amended with the lime particle fractions of 150 to 250µm (passed through 60 but retained on 100 mesh screen, pH=5.6, ΔpH= -1.5) and 250 to 850 µm (passed through 20 but retained on 60 mesh screen, pH=4.92, ΔpH= -1.9) had the greatest buffering (Fig. 4D). The finest particle fraction (passing a 100 US mesh but retained on a 200 mesh, 75-150µm) was very reactive resulting in a high initial substrate-pH, but provided less pH buffering following 6 weeks of plant growth.

There was greater pH buffering in Exp. II than Exp. I at a given lime rate and particle size, probably because plants were grown in larger (580 mL) pots in Exp. II compared with the 10-cm-diameter pots (350 mL in volumn) in Exp. I, resulting in a greater residual lime pool per pot in Exp. II. Overall effects of particle size were consistent in Exp. II with the previous experiment, whereby the 150 to 250µm fraction had the smallest ΔpH, followed by the 250 to 850µm fraction (Fig. 4E-F).

When impatiens were grown in the research substrates for 6 weeks with the nitrate-based fertilizer in Exp I, final substrate-pH was 6.8 to 7.1, becoming more even across lime application rates and particle sizes (Fig. 5A-B). pH decreased slightly over time in substrates with fine lime particles (75-150 µm for both lime rates, and 150 to 250 µm at the high lime rate only). In contrast, the pH increased by up to 0.68 pH units at the coarse 850 to 2000µm fraction applied at the low lime incorporation rate. Substrate-pH buffering, in terms of change of pH from the start to end of this experiment, therefore tended to increase with increasing lime particle fineness. However, the final pH levels were fairly consistent across lime sizes and rates whereas initial pH varied widely. Trends in increasing pH with coarse lime may therefore be related more to differences in initial substrate-pH, rather than to residual CCE, when plants were grown with a basic, nitrate-based fertilizer.

Conclusions

Residual lime concentration in substrates plays a key role in pH buffering. Results with commercial substrates emphasize the importance of residual CCE in substrate formulation when developing growing substrate that are resistant to a downward trend in pH over time. Increasing residual CCE in commercial substrates was correlated with greater pH buffering in both greenhouse plant experiments using a 100% ammonium-N, acid-reaction fertilizer, or when substrates were drenched with mineral HCl acid. Dosage with 40 meq acid from HCl per liter of substrate and $pH_{4.5}$ Buffering Capacity, may provide quick tests for greenhouse performance of

substrates, because the pH response from HCl was closely correlated with the pH response for impatiens grown with an ammonium-based fertilizer.

A moderately coarse lime particle size provided the most effective pH buffering. At the high lime rate (3 $g \cdot L^{-1}$), the particle size fraction of 150 to 250 (60 to 100 US mesh) and 250 to 850 µm (20 to 60 US mesh) provided the greatest buffering in both experiments where ammonium-based fertilizers were applied. A combination of moderately coarse fractions (150 to 850 µm (20 to 100 US mesh)) for pH buffering and fine fractions (<150 µm (100 US mesh)) for rapid neutralization of substrate acidity could be formulated to provide a "customized lime". If lime particle intended to provide buffering is too fine (<150 µm), lime will react quickly, resulting in excessively high substrate-pH. In contrast, a limestone with very coarse particles (> 850 µm) reacts so slowly that it is not horticulturally useful for a short term crop grown over a period of weeks.

Increasing lime application rate can increase pH buffering. Research substrates with high applied lime rate (3.0 $g \cdot L^{-1}$) trended to have greater pH buffering than at 1.5 $g \cdot L^{-1}$. To formulate well-buffered substrates, both lime particle sizes and lime rate should therefore be considered. At appropriate lime particle sizes, increasing lime rate would increase pH buffering. Differences between Exp. I and II suggest that pH buffering increases when plants are grown in larger pots.

With high nitrate-basic fertilizer application, residual lime concentration did not show significant effect on pH buffering, similar to the results found by Argo and Biernbaum (1996). Providing residual CCE therefore did not have detrimental effects when plants were grown with a basic fertilization program.

ACKNOWLEDGEMENTS
We thank the American Floral Endowment, and Young Plant Research Center partners including U.S. greenhouse firms and Blackmore Co., Ellegaard, Fafard, Greencare Fertilizers, Pindstrup, Premier Horticulture, Quality Analytical Laboratories, and Sun Gro Horticulture for financial support of this project. The use of trade names in this publication does not imply endorsement of the products named or criticism of similar ones not mentioned.

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Figure 1. Substrate-pH responses to a drench of HCl to one research substrate (Substrate S4) and ten commercial substrates (S1 to S3 and S5 to S11, described in Table 2). (A) Titration curves were developed by plotting the meq of HCl applied versus average substrate-pH. (B) Detailed substrate-pH responses to 40 meq of HCl per liter of substrate. Numbers above bars in (B) represent the ΔpH for each substrate. Error bars represent 95% confidence interval (A), or Tukey's $HSD_{0.05}$ for corresponding initial and final pH (B).

Figure 2. The relationship between initial residual CCE and pH4.5 Buffering Capacity (A) when substrates received a drench of HCl and the relationship between the pH change (ΔpH) and initial residual CCE when substrates received an acidic-reaction (ammonium-based) fertilizer in either a greenhouse experiment I (B) or in experiment II (C), or a nitrate basic-reaction fertilizer in experiment I (D). Symbols represented an average (n=4) for each substrate. Substrate-pH was measured 7 days after HCl drench, or after either 42 days (Exp 1) or 54 days (Exp 2) of fertigation with an ammonium-based fertilizer.

Figure 3. Substrate-pH responses for impatiens plants grown with either an acidic-reaction (ammonium-based) fertilizer for 42 days in Exp. I (A) or 54 days in Exp. II (B), or a nitrate basic-reaction fertilizer after 42 days in Exp. I (C). Six substrates (S3, and S5 to S9) were tested in Exp. I and seven substrates (S3, S5, and S7 to S11) in Exp. II, along with one research substrate (S4). Numbers above bars represent ΔpH (final pH – initial pH) for each substrate. Error bars represent corresponding Tukey's $HSD_{0.05}$ for initial pH, and final pH.

Figure 4. Substrate-pH responses to different lime particle size and incorporation rate for nine research substrates. Research substrates included either hydrated lime only or hydrated lime plus four different particle size fractions of dolomitic carbonate lime at two rates (1.5 and 3.0 $g \cdot L^{-1}$). (A) and (B) show pH response to a drench of HCl (40 meq per liter of substrate) at either low or high lime rate. (C) and (D) show initial pH and pH at Day 42 in the first greenhouse experiment with an acidic-reaction (ammonium-based) fertilizer for low or high lime rate. (E) and (F) show initial pH and pH at day 54 in the second greenhouse experiment with acidic-reaction (ammonium-based) fertilizer for low or high lime rate. Numbers above bars represent delta-pH for each substrate. Error bars represent Tukey's $HSD_{0.05}$ for initial pH and final pH, respectively.

Figure 5. Substrate-pH responses to a basic fertilizer in Exp. I for research substrates with hydrated dolomitic lime only or hydrated lime only plus four particle size fractions of dolomitic carbonate lime at two lime rates. Substrate-pH response is shown at 42 days for lime rate of 1.5 (A) or 3.0 $g \cdot L^{-1}$ (B). Numbers above bars in each chart represent ΔpH for each substrate. Error bars represent Tukey's $HSD_{0.05}$.

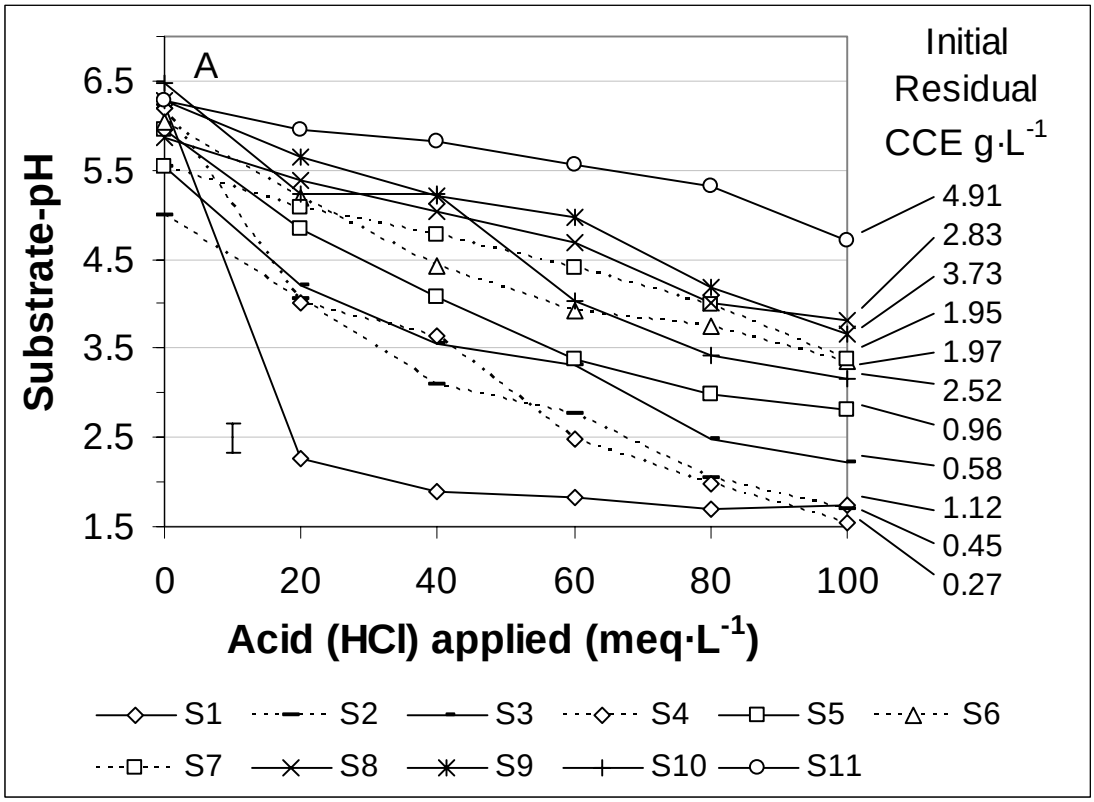
Table 1. Lime particle size, lime incorporation rate, initial pH, and residual CCE concentration (initial and final) for nine research substrates. Substrates were composed of 70% peat and 30% perlite by volume. Substrates were first pre-limed with hydrated dolomite to pH 6.1, and were then blended with a dolomitic carbonate limestone at either 0, 1.5 or 3.0 $g \cdot L^{-1}$ using different particle size fractions. Residual CCE was measured using the gasometric method, and substrate-pH and EC were measured using the saturated medium extract method (3 replicates per substrate). Final residual CCE is shown for Exp. II where impatiens were grown with an ammonium-based fertilizer. Error limits are 95% confidence intervals.

Carbonate Lime Particle Size (μm)	Carbonate Lime Particle Size (U.S. mesh)	Carbonate Lime Incorporation Rate ($g \cdot L^{-1}$)	Total Lime Rate Including Hydrated and Carbonate Lime (g CCE$\cdot L^{-1}$)	Initial Substrate-pH	Initial Residual Lime (g CCE$\cdot L^{-1}$)	Residual Lime at 54 Days in Greenhouse Exp. II (g CCE$\cdot L^{-1}$)
None	None	0	3.38	6.10 ± 0.06	0.27 ± 0.04	0.23 ± 0.05
850-2000	10-20	1.5	4.86	6.22 ± 0.10	1.99 ± 0.33	1.22 ± 0.12
250-850	20-60	1.5	4.83	6.39 ± 0.10	1.77 ± 0.23	0.61 ± 0.09
150-250	60-100	1.5	4.83	6.83 ± 0.19	1.56 ± 0.24	0.66 ± 0.12
75-150	100-200	1.5	4.83	7.04 ± 0.03	1.57 ± 0.35	0.67 ± 0.11
850-2000	10-20	3.0	6.35	6.24 ± 0.13	3.09 ± 0.12	2.88 ± 0.14
250-850	20-60	3.0	6.28	6.80 ± 0.08	3.00 ± 0.27	1.25 ± 0.08
150-250	60-100	3.0	6.28	7.13 ± 0.06	2.75 ± 0.15	1.33 ± 0.19
75-150	100-200	3.0	6.28	7.33 ± 0.03	2.58 ± 0.33	1.14 ± 0.20

Table 2. Residual CCE concentration (g CCE·L^{-1}), initial substrate-pH, and the estimated $pH_{4.5}$ Buffering Capacity (meq·L^{-1}) for one research substrate ("S4") and ten commercial substrates (S1 to S3, S5 to S11). "Lime Incorporation Rate" was reported by substrate manufacturers. Initial residual CCE concentration was measured using the gasometric method, and substrate-pH was measured using the saturated medium extract method (3 replicates per substrate). $pH_{4.5}$ Buffering Capacity (meq of acid needed to drop pH to pH 4.5 per liter of substrate) was estimated using a quadratic regression curve from the corresponding acid drench data.

No.	Substrate components	Lime Incorporation Rate (g CCE·L^{-3})	Initial Residual CCE (g CCE·L^{-1}) Mean ± 95%	Initial pH Mean ± 95%	$pH_{4.5}$ Buffering Capacity (meq·L^{-1})
S1	Oasis^{R} foam, dolomitic lime	Unknown	1.12 ± 0.48	5.97 ± 0.05	9.1
S2	peat, perlite and dolomitic lime	2.23	0.45 ± 0.39	4.96 ± 0.05	9.8
S3	peat, perlite, vermiculite, hydrated and calcitic lime	2.58	0.58 ± 0.28	5.49 ± 0.05	18.6
S4	peat, perlite, hydrated dolomitic lime	3.38	0.27 ± 0.04	6.10 ± 0.06	20.4
S5	peat, calcitic lime	3.39	0.96 ± 0.10	6.04 ± 0.07	28.5
S6	peat, calcitic and dolomitic lime	4.95	1.97 ± 0.31	6.21 ± 0.04	38.8
S7	peat, vermiculite, calcitic and dolomitic	7.06	1.95 ± 0.14	5.46 ± 0.05	54.5
S8	peat, perlite, dolomitic lime	6.05	2.83 ± 0.13	5.79 ± 0.04	64.0
S9	peat,perlite, calcitic and dolomitic lime	5.32	3.73 ± 0.35	6.11 ± 0.05	70.6
S10	peat, perlite, dolomitic lime	5.99	2.52 ± 0.21	6.32 ± 0.03	48.3
S11	peat, perlite, vermiculite, dolomitic lime	6.36	4.91 ± 0.02	6.45 ± 0.11	112.6

Figure 1


A
Initial Residual CCE g·L-1
Substrate-pH
6.5
5.5
4.5
3.5
2.5
1.5
0
20
40
60
80
100
Acid (HCl) applied (meq·L-1)
4.91
2.83
3.73
1.95
1.97
2.52
0.96
0.58
1.12
0.45
0.27
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11

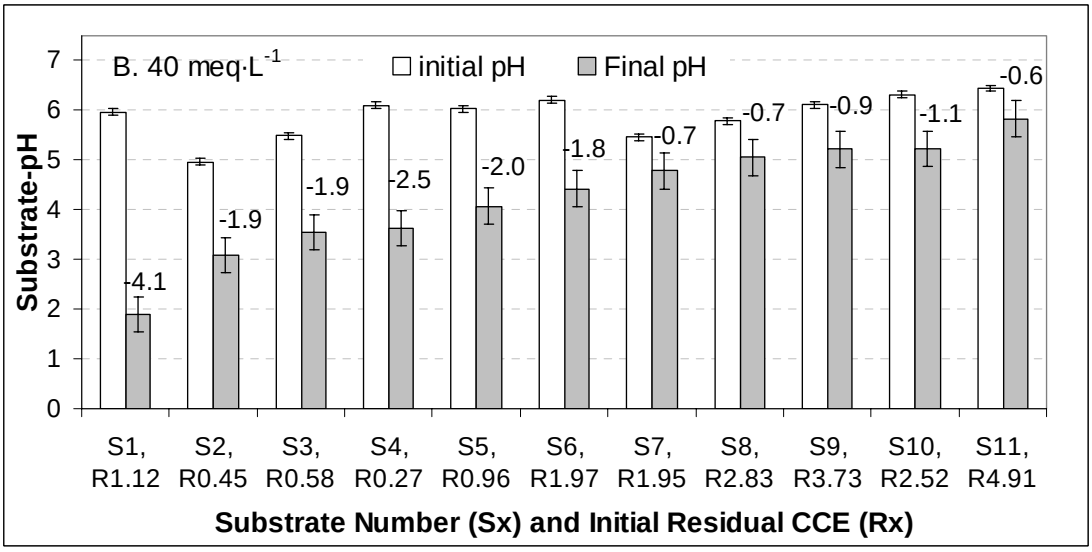

B. 40 meq·L-1
initial pH
Final pH
Substrate-pH
7
6
5
4
3
2
1
0
-4.1
-1.9
-1.9
-2.5
-2.0
-1.8
-0.7
-0.7
-0.9
-1.1
-0.6
S1, R1.12
S2, R0.45
S3, R0.58
S4, R0.27
S5, R0.96
S6, R1.97
S7, R1.95
S8, R2.83
S9, R3.73
S10, R2.52
S11, R4.91
Substrate Number (Sx) and Initial Residual CCE (Rx)

Figure 2.

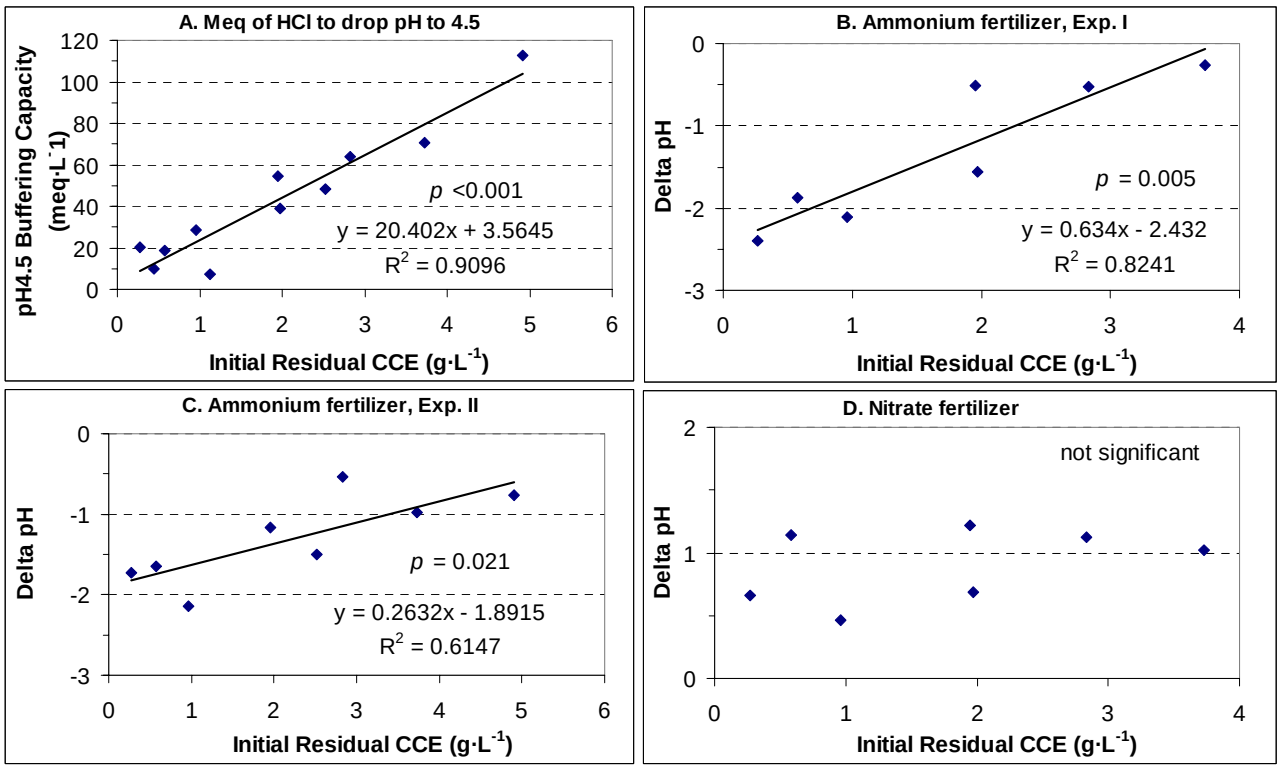

A. Meq of HCl to drop pH to 4.5
pH4.5 Buffering Capacity (meq·L-1)
p <0.001
y = 20.402x + 3.5645
R2 = 0.9096
Initial Residual CCE (g·L-1)
B. Ammonium fertilizer, Exp. I
Delta pH
p = 0.005
y = 0.634x - 2.432
R2 = 0.8241
Initial Residual CCE (g·L-1)
C. Ammonium fertilizer, Exp. II
Delta pH
p = 0.021
y = 0.2632x - 1.8915
R2 = 0.6147
Initial Residual CCE (g·L-1)
D. Nitrate fertilizer
Delta pH
not significant
Initial Residual CCE (g·L-1)

Figure 3.

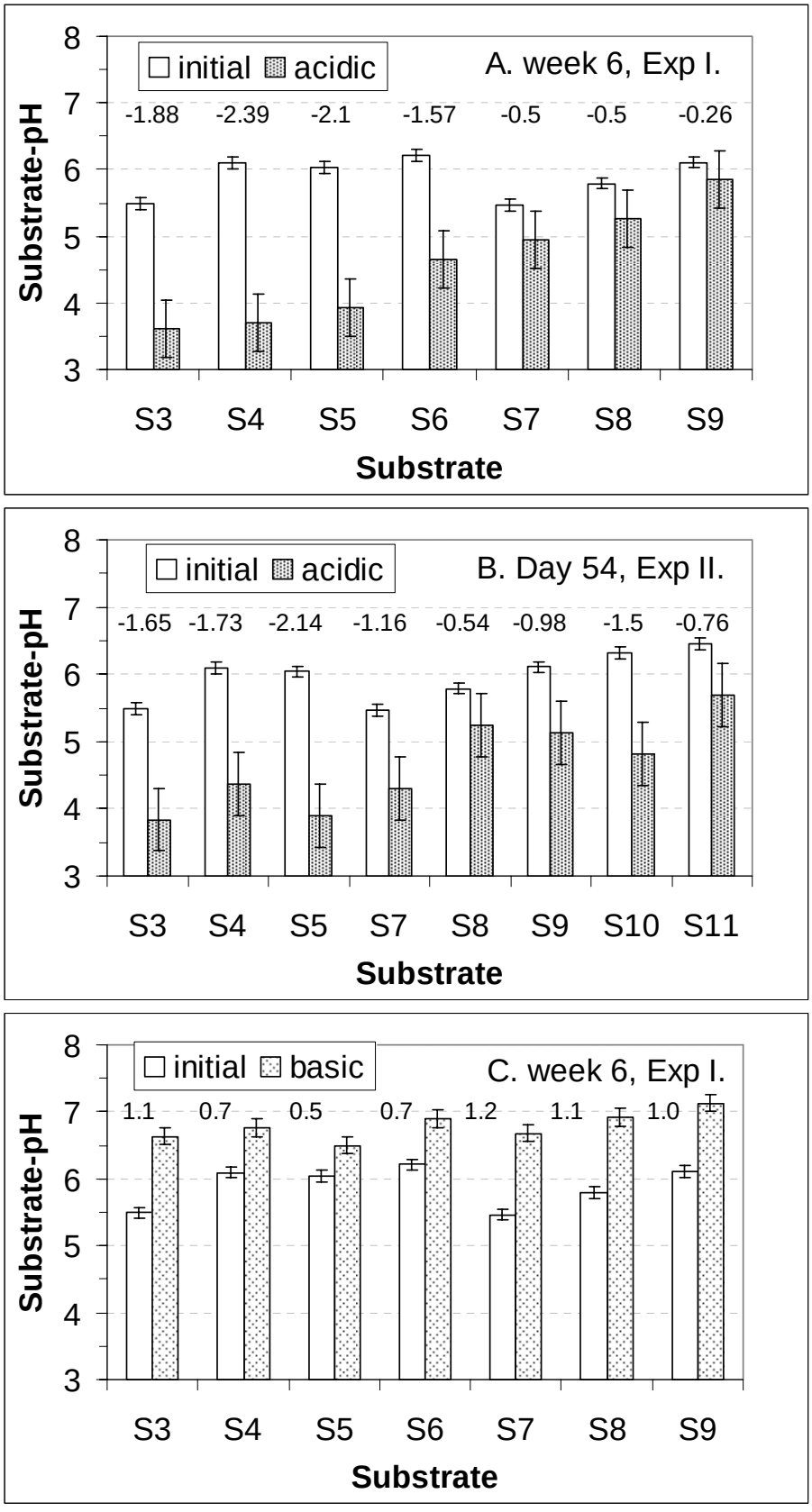

initial
acidic
A. week 6, Exp I.
-1.88
-2.39
-2.1
-1.57
-0.5
-0.5
-0.26
Substrate-pH
8
7
6
5
4
3
S3
S4
S5
S6
S7
S8
S9
Substrate
initial
acidic
B. Day 54, Exp II.
-1.65
-1.73
-2.14
-1.16
-0.54
-0.98
-1.5
-0.76
Substrate-pH
S3
S4
S5
S7
S8
S9
S10
S11
Substrate
initial
basic
C. week 6, Exp I.
1.1
0.7
0.5
0.7
1.2
1.1
1.0
Substrate-pH
S3
S4
S5
S6
S7
S8
S9
Substrate

Figure 4.

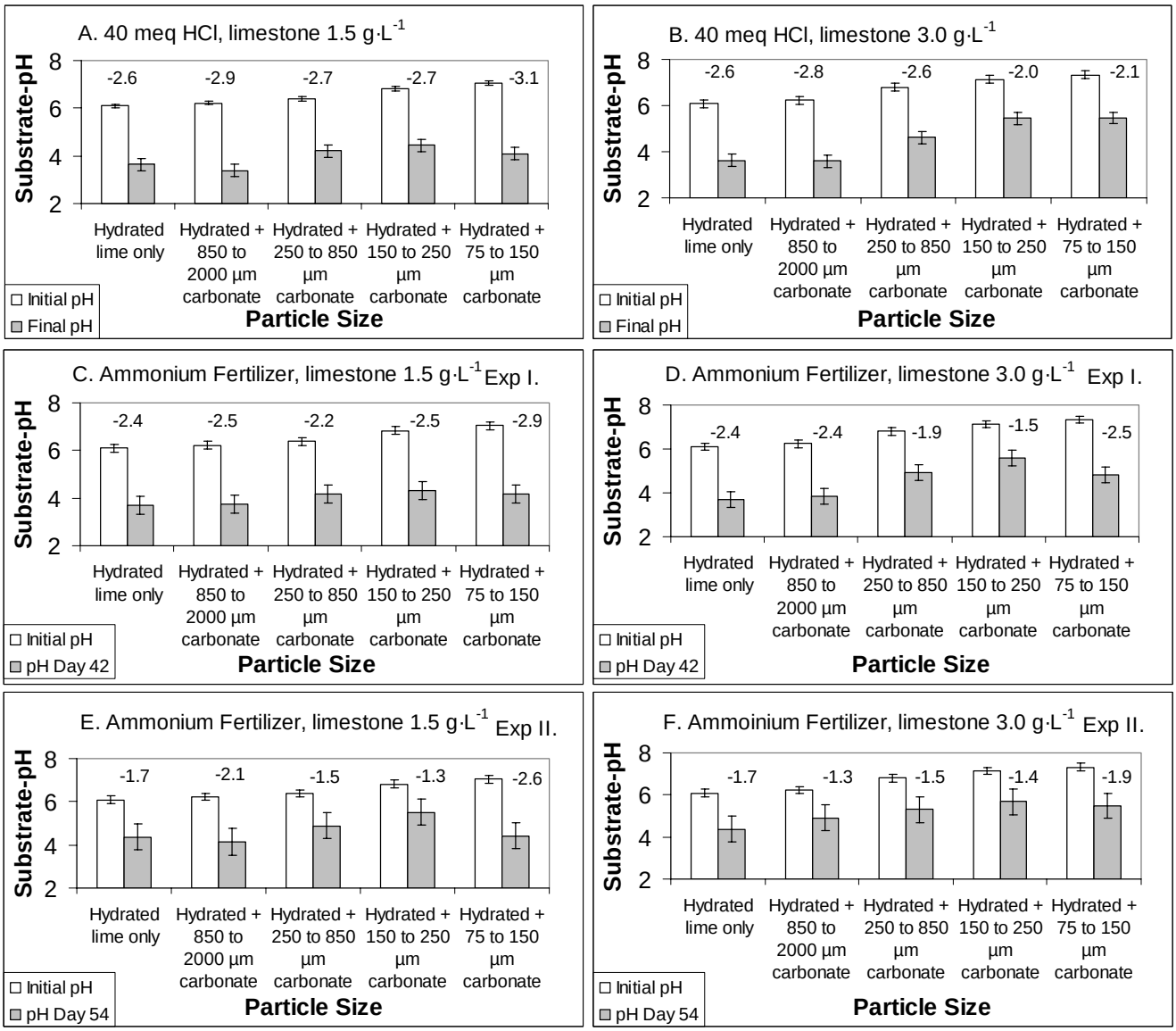
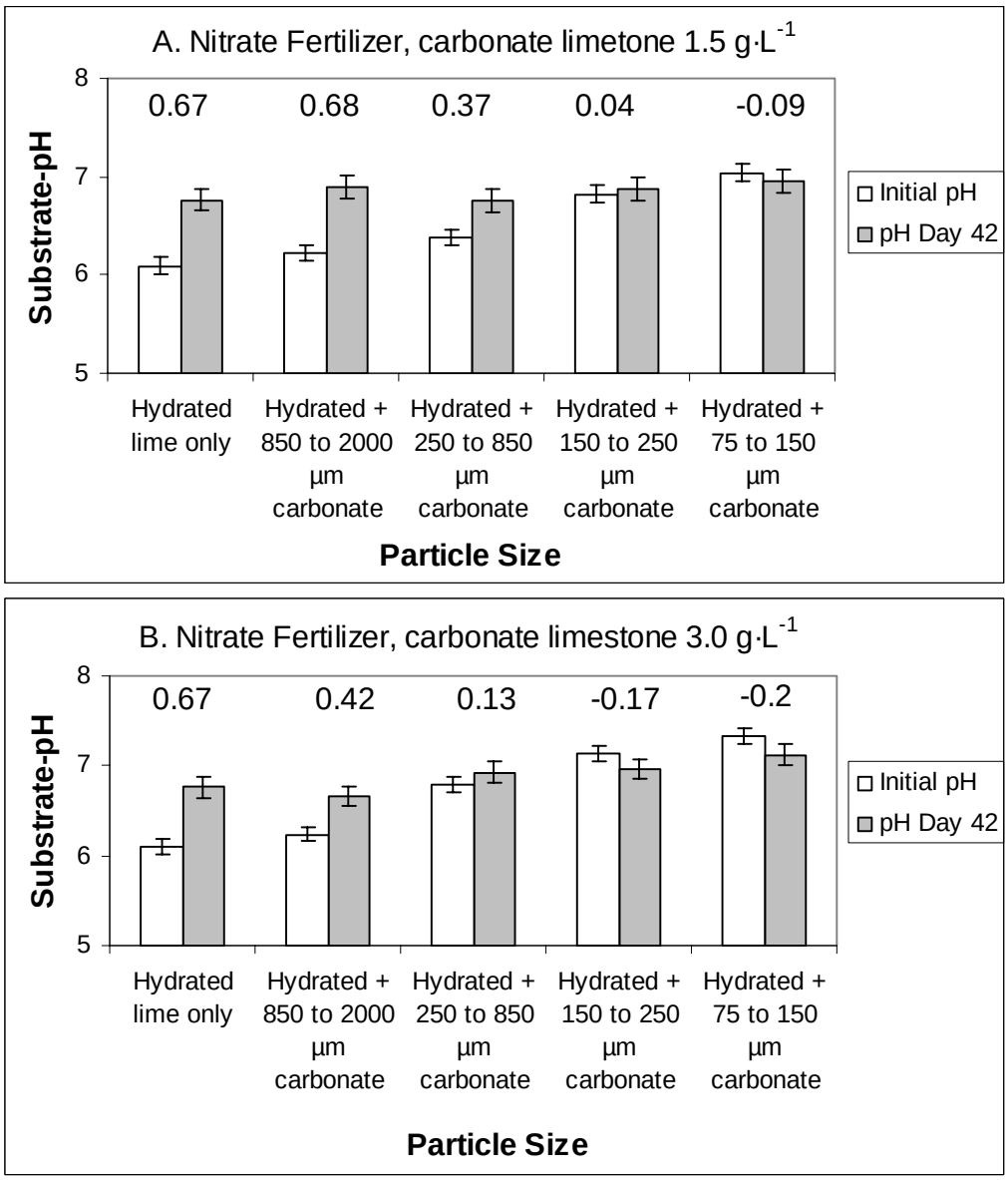

A. 40 meq HCl, limestone 1.5 g·L-1
B. 40 meq HCl, limestone 3.0 g·L-1
C. Ammonium Fertilizer, limestone 1.5 g·L-1 Exp I.
D. Ammonium Fertilizer, limestone 3.0 g·L-1 Exp I.
E. Ammonium Fertilizer, limestone 1.5 g·L-1 Exp II.
F. Ammoinium Fertilizer, limestone 3.0 g·L-1 Exp II.
Substrate-pH
Particle Size
Hydrated lime only
Hydrated + 850 to 2000 µm carbonate
Hydrated + 250 to 850 µm carbonate
Hydrated + 150 to 250 µm carbonate
Hydrated + 75 to 150 µm carbonate
Initial pH
Final pH
pH Day 42
pH Day 54

Figure 5.


A. Nitrate Fertilizer, carbonate limetone 1.5 g·L-1
Substrate-pH
8
7
6
5
0.67
0.68
0.37
0.04
-0.09
Initial pH
pH Day 42
Hydrated lime only
Hydrated + 850 to 2000 µm carbonate
Hydrated + 250 to 850 µm carbonate
Hydrated + 150 to 250 µm carbonate
Hydrated + 75 to 150 µm carbonate
Particle Size
B. Nitrate Fertilizer, carbonate limestone 3.0 g·L-1
Substrate-pH
8
7
6
5
0.67
0.42
0.13
-0.17
-0.2
Initial pH
pH Day 42
Hydrated lime only
Hydrated + 850 to 2000 µm carbonate
Hydrated + 250 to 850 µm carbonate
Hydrated + 150 to 250 µm carbonate
Hydrated + 75 to 150 µm carbonate
Particle Size