Nursery Production of *Helleborus* x *hybridus*: Management of Nitrogen and Substrate pH[1]

Helen T. Kraus and Stuart L. Warren[2]
Dept. of Horticultural Science
North Carolina State University
Raleigh, NC 27695-7609

Abstract

One-year-old seedlings of *Helleborus* x *hybridus* Hort. Ex Vilmorin (Lenten rose) were potted into 3.8 liter (#1) containers filled with a pine bark substrate amended with one of five rates of dolomitic limestone [0, 1.4, 2.7, 4.1, or 5.4 kg/m^3 (0, 3, 6, 9, or 12 lb/yd^3)]. Substrate pH responded quadratically with increasing rate of dolomitic limestone (DL) producing a range of substrate pH from 4.5 to 6.9. Nitrogen application rates (NARs) ranging from 10, 20, 40, 80, and 160 mg/liter were applied with every irrigation. Top dry weight was affected by NAR, DL, and NAR × DL rate interaction. When no DL was added to the substrate, top dry weight increased quadratically with increasing NARs with maximum dry weight occurring with N at 124 mg/liter. However, when the substrate was amended with DL at 1.4, 2.7, 4.1, or 5.4 kg/m^3 (3, 6, 9, and 12 lb/yd^3) top dry weight increased linearly with increasing NARs with maximum top dry weight of 15 g to 16 g (0.53 oz and 0.56 oz) occurring with N at 160 mg/liter. Contrast analysis comparing DL rates within each NAR revealed DL rates of 1.4, 2.7, 4.1, and 5.4 kg/m^3 (3, 6, 9, and 12 lb/yd^3) produced greater top growth compared to growth at the DL rate of 0 kg/m^3 (0 lb/yd^3) at NARs of 40, 80, and 160 mg/liter. Furthermore, when fertilized with N at 40, 80 or 160 mg/liter, top dry weight produced with DL rates of 1.4, 2.7, 4.1, and 5.4 kg/m^3 (3, 6, 9, and 12 lb/yd^3) did not differ within each NAR. Root dry weight was unaffected by NARs and NAR × DL rate interaction. Rate of DL affected root dry weight with the largest increase in root growth occurring with DL between 0 kg/m^3 and 1.4 kg/m^3 (0 lb/yd^3 and 3 lb/yd^3). Root-to-top ratio (RTR) responded quadratically with increasing NAR with the lowest RTR occurring with N at 140 mg/liter. Foliar N, P, K, Ca, Mg, S, and Fe concentrations were unaffected by rate of DL and NAR × DL rate, whereas foliar N, P, K, Ca, Mg, and S were affected by NARs. Foliar N, P, K, and S concentrations responded quadratically to increasing NARs; foliar Ca and Mg concentrations were linear; and foliar Fe concentration was unaffected by NARs.

Index words: lenten rose, dolomitic limestone, mineral nutrient concentration, herbaceous perennial, fertilization, mineral nutrition.

Significance to the Nursery Industry

Results from this study indicate that optimum growth of *Helleborus* x *hybridus* (Lenten rose) in a pine bark substrate can be obtained by maintaining an average substrate pH of 5.4 in combination with N fertigation at 40 to 160 mg/liter using a 4:1:2 N:P:K formulation. Nutrient solutions supplying N at160 mg/liter provided maximum top growth but decreased the root:top ratio by stimulating top growth at the expense of root growth. A nutrient solution containing N at 40 to 80 mg/liter applied with each irrigation will result in recommended foliar nutrient concentrations and is a good choice if a more balanced root and top system is desired. Even though *Helleborus* x *hybridus* appears to be very tolerant to high substrate pH, there was no growth benefit with a pH > 5.4 which suggests that a pH between 5.0 and 6.0 may be adequate for growth. Lime additions higher than 1.4 kg/m^3 (3 lb/yd^3) resulted in higher substrate pH but did not increase or decrease plant growth or foliar nutrient concentrations. In contrast to many woody and herbaceous perennials, *Helleborus* x *hybridus* may be unique in its ability to maintain similar growth rates even with high substrate pH.

Introduction

Herbaceous perennials are planted worldwide in public gardens, and commercial and home landscapes. Trade journals have used herbaceous perennials repeatedly as their cover story in recent years (4, 7, 20). As such, nursery production of herbaceous perennials by nurseries has also increased. In 1999, perennials accounted for 27% of all U.S. plant sales with $642 million wholesale value among 7,391 producers (14).

The genus *Helleborus* L. includes many exciting species and selections that provide winter to early spring flowers for shade gardens of the southeastern United States (27). In the landscape, *Helleborus* x *hybridus* Hort. Ex Vilmorin (Lenten rose) is quite easy to cultivate having few disease and insect problems and tolerating a wide range of soils (27). However, such is not the case with container-grown plants. In containerized production *Helleborus* x *hybridus* is susceptible to phytophthora (*Phytophthora* sp.), botrytis (*Botrytis cinerea*), mineral nutrient deficiencies, and slow rates of growth (personal communication, Judith Knot Tyler and Richard Tyler, Pine Knot Farms Perennials, Clarksville, VA). Growers complain of apparently healthy one-year-old seedlings dying and surviving plants requiring 3 to 5 years to flower, which is critical since *Helleborus* x *hybridus* is sold by flower color.

When a plant is not growing well in an existing program, fertility and substrate pH may need to be modified. Recommendations for nutrient solution applications for production of herbaceous perennials range from N at 100 to 200 mg/liter applied with every irrigation to between 100 and 150 mg/liter applied weekly (3, 24). Dubois et al. (11) reported that N applied three times weekly at 150 mg/liter maximized growth of *Anemone* x *hybrida* Paxton (fall flowering anemone). Maximum growth of *Nephrolepsis exaltata* (L.) Schott 'Whitmanii' ('Whitmanii' fern) was achieved with N at 75 mg/liter applied with every irrigation (3 times weekly) (9)

Milled pine bark is a common substrate in the southeastern United States nursery industry and pre-plant incorpora-

[1]Received for publication December 8, 2005; in revised form March 9, 2006. This research was funded, in part, by the North Carolina Agricultural Research Service, Raleigh, NC 27695-7643, and by a grant from the Perennial Plant Association, 3383 Schirtzinger Rd., Hilliard, OH 43026. Appreciation is extended to William M. Reece for technical assistance and to Pine Knot Farm Perennials, Clarksville, VA, for providing plants.

[2]Lecturer and Professor, respectively.

tion of dolomitic limestone (DL) to pine bark is routine. Several studies with herbaceous and woody perennials have reported that plant growth decreased with increasing rate of DL with the best growth occurring when no DL was added (6, 15, 34, 38). In contrast, *Buddleia davidii* L. 'Royal Red' ('Royal Red' butterfly bush) (12), *Juniperus chinensis* L. 'San Jose' ('San Jose' juniper) (6), *Photinia* x fraseri Dress (Fraser photinia) (23), and *Juniperus virginiana* L. (eastern redcedar) (36) growth was best with lime rates ranging from 2.0 to 4.2 kg/m^3 (3.3 to 7.0 lb/yd^3).

While no nutrition nor substrate pH guidelines for container-grown production of the lenten rose were found, a common recommended pH range for container-grown floriculture crops is 5.6 to 6.2 due mainly to the effect pH has on micronutrient availability (5). Wright and Niemira (27) recommended a pH of 5.0 to 5.5 for container-grown nursery crops. Peterson (26) reported that mineral nutrient availability in organic container media was optimal at a pH of 5.0 to 6.0. In the landscape, *Helleborus* x *hybridus* has been reported to perform best in an alkaline soil (pH > 7) while also growing well in acidic soils (27).

Development of a fertility program that addressed both the nutritional and substrate pH requirements of *Helleborus* x *hybridus* may be a first step in resolving some of the production issues associated with this plant. Due to the variability of commercial practices, Smith et al. (29) stated that recommended substrate pH (rate of DL addition) should be based on trials under a range of nutritional conditions. Therefore, the following research was conducted to evaluate NARs in combination with rates of DL for their effects on growth and foliar nutrient concentrations of *Helleborus* x *hybridus*.

Materials and Methods

The experiment was a 5 × 5 factorial in a split plot design with nitrogen application rates (NARs) (10, 20, 40, 80, or 160 mg/liter) as the main plots and aged pine bark substrate [≤ 1.3 cm (0.5 in)] amended with dolomitic lime (DL) at rates of 0, 1.4, 2.7, 4.1, or 5.4 kg/m^3 (0, 3, 6, 9, and 12 lb/yd^3) as the subplots with four replications. DL used in the study contained 54% $CaCO_3$, 43% $MgCO_3$, 3.0% SiO_2, 0.5% Al_2O_3, 0.4% Fe_2O_3, and 0.04% SO_3; 70% of which passed a 250-µm screen (Rockydale Quarries Corp., Roanoke, VA). Uniform one-year-old seedlings were potted into 3.8 liter (#1) containers on August 23, 2001, with a pine bark substrate that was amended with the different rates of DL. Containers were placed in a glass greenhouse under natural photoperiod and 50% shade with day/night temperatures of 24 ± 3C (75 ± 5F)/18 ± 3C (65 ± 5F). Tap water containing NO_3–N, NH_4–N, P, K, Ca, Mg, and alkalinity at 0.10, 0.96, 0.5, 7.0, 10.0, 4.0, and 20.0 mg/liter respectively, with a pH of 7.4 was applied until NARs were initiated on September 29, 2001. NARs were applied with every irrigation, every other day, to maintain an approximate 0.25 leaching fraction using pressure compensated spray stakes (Acu-Stick, Wade Mfg. Co., Fresno, CA) at a rate of 200 ml/min (0.3 in/min). No other irrigation was required. As the NAR increased in the nutrient solution from 10 mg/liter to N at 160 mg/liter, P and K rates were also increased to maintain a 4:1:2 N:P:K ratio (Table 1). Reagent grade ammonium nitrate, potassium phosphate, and potassium sulfate supplied the N, P, and K, respectively. A modified Hoagland's solution supplied the micronutrients in the nutrient solutions (Table 1). No additional sources of Ca and Mg were applied to the DL treatment of 0 kg/m^3 (0 lb/yd^3) since the irrigation water contained adequate Ca and Mg for plant growth (31).

Table 1. Nutrient sources and concentrations of nutrient solutions.

	N rate, mg/liter				
Nutrient source	**10**	**20**	**40**	**80**	**160**
N (NH_4NO_3)	10.0	20.0	40.0	80.0	160.0
P (KH_2PO_4)	2.5	5.0	10.0	20.0	40.0
K (KH_2PO_4)	3.2	6.3	12.5	25.0	50.0
K (K_2SO_4)	1.8	3.7	7.5	15.0	30.0
Micronutients[z]			**mg/liter**		
B (H_3BO_3)			0.5		
Cu ($CuSO_4 \cdot H_2O$)			0.02		
Mn ($MnCl_2$)			0.5		
Mo ($(NH_4)_6(Mo_7O_{24})$)			0.1		
Zn ($ZnSO_4 \cdot 7H_2O$)			0.05		
Fe (chelated)			5.0		

[z]Applied to all N rates.

Substrate leachate was collected to determine electrical conductivity (EC) and pH of each substrate solution on October 24, November 8, November 20, December 4, December 18, 2001, and January 9 and January 22, 2002, using the pour-through nutrient extraction method (35). On January 24, 2002, 115 days after initiation of the NARs, plants were harvested. Roots were washed to remove substrate and roots and tops were dried at 62C (144F) for 5 days. After drying, tops and roots were weighed and used for growth comparisons and calculation of root:top ratios (root dry weight ÷ top dry weight). After weighing, tops were ground in a Wiley mill to pass a 40 mesh (0.425 mm) screen. Each tissue sample (1.25 g) was combusted at 490C (914F) for 6 hr. The resulting ash was dissolved in 10 ml (0.03 oz) 6N HCl and diluted to 50 ml (1.5 oz) with distilled deionized water. Phosphorus, K, Ca, Mg, S, and Fe concentrations were determined by inductively coupled plasma emission spectroscopy. Tissue N concentration was determined using 10 mg (0.03 oz) samples in a Perkin Elmer 2400 CHN elemental analyzer. All tissue analyses were conducted at the Analytical Service Laboratory, Dept. of Soil Science, North Carolina State University, Raleigh.

Data were subjected to analysis of variance (ANOVA) and regression analysis and were considered significant at $P \leq 0.05$ (28). Treatment comparisons among rates of DL were made by single degree of freedom linear contrast tests. Recent reports examining the response of *Thuja* L. x 'Green Giant' ('Green Giant' arborvitae) (13), *Ternstroemia gymnanthera* L. (Japanese ternstroemia) (8) and *Anemone* x *hybrida* (fall flowering anenome) (11) to NARs found the measured parameters best described by a quadratic plateau model in lieu of a quadratic or linear model. Therefore, a segmented linear regression (quadratic plateau) was also fit to the data using PROC NLIN (28).

Results and Discussion

Top dry weight of *Helleborus* x *hybridus* was affected by NARs, rate of DL, and NAR × DL rate. In contrast to previous reports, none of the measured parameters for *Helleborus* x *hybridus* fit the quadratic plateau (data not presented). When no DL [0 kg/m^3 (0 lb/yd^3)] was added to the substrate, top dry weight increased quadratically with increasing NARs with

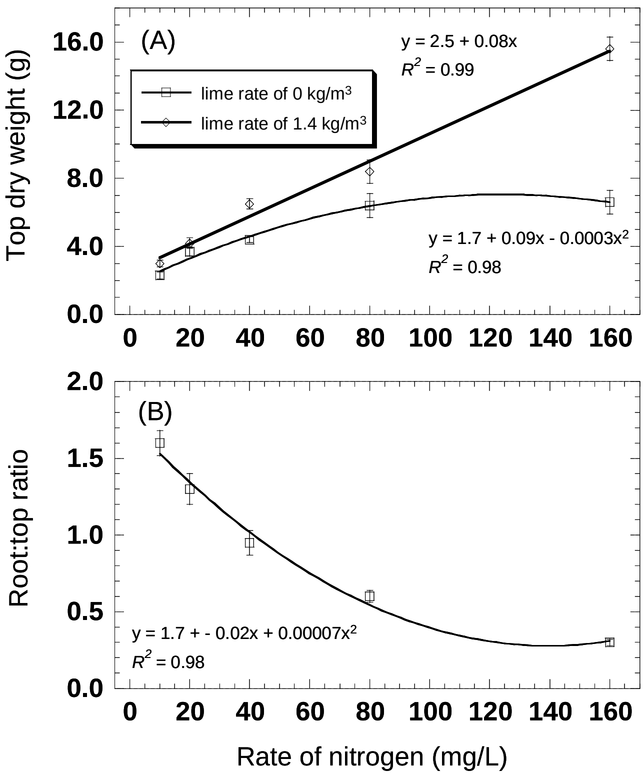

Fig. 1. Effect of nitrogen application rate on (A) top dry weight and (B) root:top ratio of *Helleborus* x *hybridus*. In (A), data are means of four observations and in (B), data are means of 20 observations. Vertical bars represent ±SE.

maximum growth occurring with N at 124 mg/liter (Fig. 1A). However, when the substrate was amended with DL rates of 1.4, 2.7, 4.1, or 5.4 kg/m^3 (3, 6, 9, or 12 lb/yd^3), top dry weight increased linearly with increasing NARs. Maximum top dry weight (15 to 16 g) (0.53 to 0.56 oz) occurred with N at 160 mg/liter [Fig. 1A, only DL at 1.4 kg/m^3 (3 lb/yd^3) is presented]. Based on the reputation of *Helleborus* x *hybridus* for slow growth, we expected to find a much lower NAR required to attain maximum growth. However, the herbaceous perennials, *Melampodium leucanthum* Ton. & Gray (Blackfoot daisy) (18), *Anemone* x *hybrida* 'Margarete' ('Margarete' fall flowering anemone) (11), *Salvia greggii* Gray. (autumn sage) (17), and *Leucophyllum candidum* I.M. Johnst. (violet silverleaf) (16), all attained maximum growth at similar NARs: N at 166, 158, 200, and 170 mg/liter, respectively. Electrical conductivity of substrate solution at maximum growth averaged 0.94 dS/m (Fig. 2A), which is within the recommended range for liquid fertilization of container-grown nursery crops (30). Based on subjective observations, visually attractive plants were obtained with N at 40 to 160 mg/liter.

Within each NAR, rate of DL affected top dry weight with the largest increase in top dry weight occurring with DL between 0 kg/m^3 and 1.4 kg/m^3 (0 lb/yd^3 and 3 lb/yd^3) (Table 2). Contrast analysis comparing DL rates within each NAR revealed DL rates of 1.4, 2.7, 4.1, or 5.4 kg/m^3 (3, 6, 9, or 12 lb/yd^3) produced greater top growth compared to DL at 0 kg/m^3 (0 lb/yd^3) at NARs of 40, 80, and 160 mg/liter. Furthermore, when fertilized with N at either 40, 80 or 160 mg/liter, top dry weight produced with DL rates of 1.4, 2.7, 4.1, or 5.4 kg/m^3 (3, 6, 9, and 12 lb/yd^3) within each NAR did not differ. Increased growth with the addition of DL may have resulted from the increase in pH. Substrate pH responded quadratically with increasing rate of DL (Fig. 1B). Pine bark substrate without limestone had a pH of 4.4 while DL at 1.4 kg/m^3 (3 lb/yd^3) raised the substrate pH to 5.4 (Fig. 2B). This is within the range recommended by Wright and Niemiera (1987). While two studies have reported a growth increase when DL is increased from 0 kg/m^3 (0 lb/yd^3) to a low rate [1 to 2 kg/m^3 (2 to 4.5 lb/yd^3)] (6, 12), results herein are in contrast to the majority of reports where growth decreased often dramatically with increasing rates of DL (15, 37). Thus, it was surprising that growth did not decrease as the rate of DL increased. Under our research conditions, *Helleborus* x *hybridus* tolerated a wide range of substrate pH as top dry weight was unaffected from pH 5.3 to 6.8. *Helleborus* x *hybridus* is adapted to an alkaline pH in its native habitat (27). Argo and Biernbaum (2) reported that *Impatiens wallerana* Hook. F. (impatiens) were also unafffected by a wide range of substrate pH levels.

Wright and Hinesley (36) reported that amending pine bark substrate with DL was beneficial to growth of *Juniperus virginiana* only when micronutrients were also added to the substrate. They hypothesized that an increase in substrate pH could act as a buffer against potentially toxic effects of excess micronutrients. In this study, micronutrients were added with every irrigation so this may be an alternative explanation of the response of *Helleborus* x *hybridus* to increasing

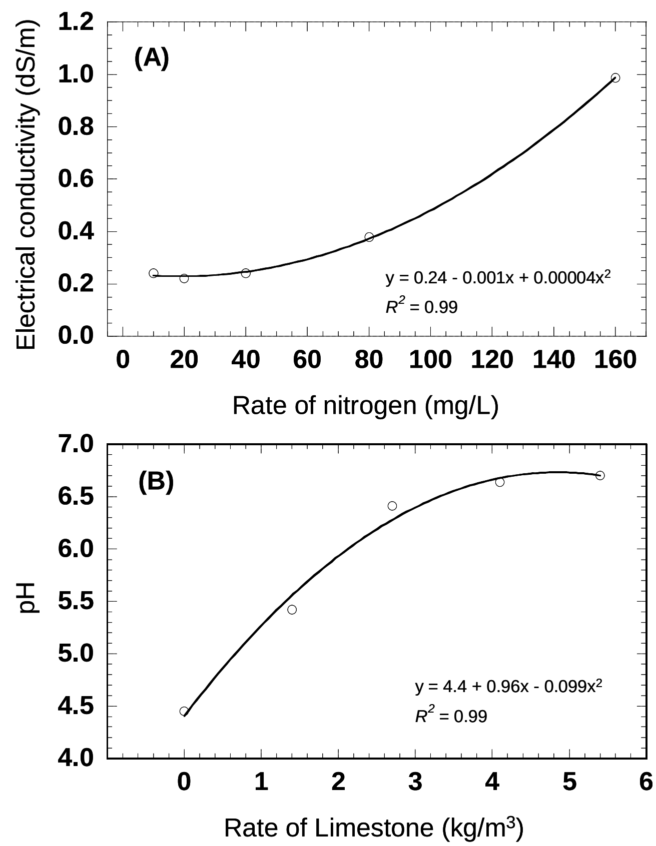

Fig. 2. (A). Effect of nitrogen application rate on substrate electrical conductivity and (B) effect of rate of dolomitic limestone on substrate pH.

Table 2. **Effect of dolomitic limestone rate within each nitrogen application rate (NAR) on top dry weight of *Helleborus* x *hybridus*. A significant NAR × lime rate interaction exists.**

Lime rate (kg/m^3)	NARs (mg/liter)				
	10	20	40	80	160
	Top dry weight (g)[z]				
0	2.3	3.7	4.4	6.4	6.6
1.4	3.0	4.2	6.5	8.4	15.6
2.7	2.6	3.3	5.7	8.2	15.9
4.1	3.3	3.3	5.6	9.3	13.9
5.4	2.7	3.6	5.6	9.1	15.7
Contrasts[y]					
0 vs. 1.4	NS	NS	0.001	0.001	0.001
0 vs. 2.7	NS	NS	0.01	0.001	0.001
0 vs. 4.1	NS	NS	0.01	0.001	0.001
0 vs. 5.4	NS	NS	0.01	0.001	0.001
1.4 vs. 2.7	NS	NS	NS	NS	NS
1.4 vs. 4.1	NS	NS	NS	NS	NS
1.4 vs. 5.4	NS	NS	NS	NS	NS
2.7 vs. 4.1	NS	NS	NS	NS	NS
2.7 vs. 5.4	NS	NS	NS	NS	NS
4.1 vs 5.4	NS	NS	NS	NS	NS

[z]Data are means of four observations.

[y]Treatment comparisons made by single degree of freedom linear contrast. Nonsignificant (NS) at $P > 0.05$, P value stated otherwise.

rates of DL (increasing pH). However, since plant growth was unaffected by any of the DL rates greater than zero, this hypothesis may not apply.

Root dry weight was unaffected by NARs and NAR × DL rate interaction (data not presented). Lack of effect on root dry weight by NARs was unexpected. This is in sharp contrast to *Anemone* x *hybrida* (11) and *Hemerocallis* Murr. x 'Stella de Oro' ('Stella de Oro' day lily) (25), both herbaceous perennials, which responded quadratically to increasing NARs with maximum root dry weight with N at 119 and 400 mg/liter, respectively. Jull et al. (19), however, working with *Crytomeria japonica* (L. f.) D. Don 'Elegans Aurea' ('Elegans Aurea' Japanese cedar) also reported that root growth was unaffected by NARs.

Rate of DL affected root dry weight with the largest increase in root growth occurring between 0 kg/m^3 (0 lb/yd^3) [mean root dry weight = 3.4 g (0.12 oz)] and 1.4 kg/m^3 (3 lb/yd^3) [mean root dry weight = 5.1 g (0.18 oz)] (Table 3). Root dry weight of plants grown with DL rates of 1.4, 2.7, 4.1, or 5.4 kg/m^3 (3, 6, 9, or 12 lb/yd^3) were not significantly different. Thus, a DL rate of 1.4 kg/m^3 (3 lb/yd^3) resulting in a substrate pH of 5.4, is apparently sufficient for top and root growth of *Helleborus* x *hybridus* when grown in a pine bark substrate. Management of substrate pH is based on the inherent properties of the substrate components and quality of irrigation water. Therefore, rates of DL for production of *Helleborus* x *hybridus* should take these factors into consideration and target the substrate pH range between 5.0 and 6.0.

Root-to-top ratio (RTR) responded quadratically with increasing NAR with the lowest RTR occurring with N at 140 mg/liter (Fig. 1B). Low NARs (10 and 20 mg/liter) resulted in RTR > 1 (1.6 and 1.3, respectively). Plants fertilized with N at 40 mg/liter had a RTR of 0.95 implying that similar amounts of energy were directed towards root and top growth. As NAR increased, the RTR decreased (0.6 and 0.3 for N at 80 and 160 mg/liter, respectively). Other researchers working with woody perennials have noted a similar response to increasing NAR (8, 13). Ameziane et al. (1) observed root lengths of *Cichorim intybus* L. (common chicory) were similar when plants were grown with N at 37 or 248 mg/liter, and concluded a decrease in RTR was a result of the greater increase in top dry weight. Data herein support this conclusion as root dry weight remained constant across all NARs; whereas, top weight continued with N increases up to 160 mg/liter. RTR was unaffected by rate of DL and NAR × DL rate interaction (data not presented).

The combination of measured growth responses and appearance suggest that for *Helleborus* x *hybridus* a soluble fertilizer applied every irrigation should have N at 40 to 160 mg/liter. Since RTR was maximized with N at 10 mg/liter and minimized at 160 mg/liter an intermediate rate of N at 40 to 80 mg/liter might represent the best compromise between optimizing both root and top growth. Limiting fertilizer inputs to the lowest nutrient concentrations consistent with adequate plant growth should be an important consideration for nursery production as this can significantly reduce levels of contaminated runoff (33).

Foliar N, P, K, Ca, Mg, and S concentrations were significantly affected by NARs (Figs. 3 and 4); whereas, foliar N (mean = 22.4 mg/g ± 1.80 SE), P (mean = 3.4 mg/g ± 0.20 SE), K (mean = 26.0 mg/g ± 1.12 SE), Ca (mean = 12.3 mg/g ± 0.51 SE), Mg (mean = 8.0 mg/g ± 0.29 SE), S (mean = 2.8 mg/g ± 0.66 SE), and Fe (mean = 124 μg/g ± 9.8 SE) concentrations were unaffected by rate of DL and NAR × DL rate interaction (data not presented). Lack of response of foliar nutrient concentration to rate of limestone was another surprise. Other studies have found that foliar Ca and Mg concentrations increased with increasing rate of DL; whereas, foliar N, P, and K typically decreased linearly or quadratically with increasing rate of DL (15, 22). Peterson (26) reported that mineral nutrient availability in organic container media was optimal at a pH range of 5.0 to 6.0; therefore, one would expect to see foliar nutrient concentrations decreasing in our

Table 3. **Effect of dolomitic limestone rate on root dry weight of *Helleborus* x *hybridus*.**

Lime rate (kg/m^3)	Root dry weight (g)[z]
0	3.4
1.4	5.1
2.7	5.2
4.1	4.7
5.4	5.1
Contrast[y]	
0 vs. 1.4	0.005
0 vs. 2.7	0.003
0 vs. 4.1	0.02
0 vs. 5.4	0.005
1.4 vs. 2.7	NS
1.4 vs. 4.1	NS
1.4 vs. 5.4	NS
2.7 vs. 4.1	NS
2.7 vs. 5.4	NS
4.1 vs. 5.4	NS
0 vs. average of 1.4, 2.7, 4.1, and 5.4	0.001

[z]Data are means of 20 observations.

[y]Treatment comparisons made by single degree of freedom linear contrast. Nonsignificant (NS) at $P > 0.05$, P value stated otherwise.

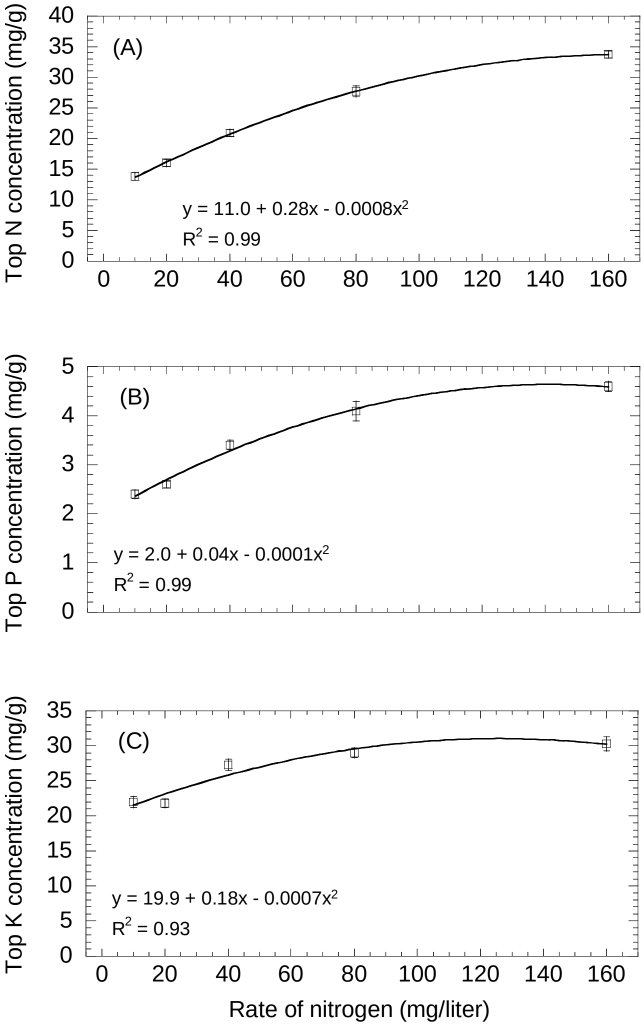

Fig. 3. Effect of nitrogen application rate on top (A) N, (B) P, and (C) K mineral nutrient concentrations of *Helleborus* x *hybridus*. Data are means of 20 observations. Vertical bars represent ±SE.

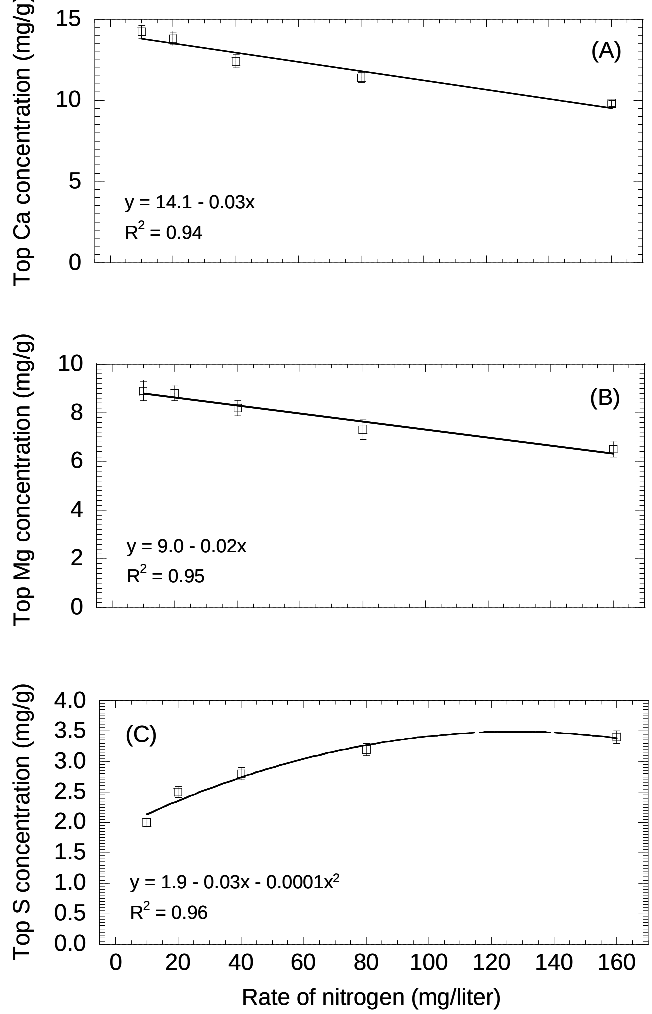

Fig. 4. Effect of nitrogen application rate on top (A) Ca, (B) Mg, and (C) S mineral nutrient concentrations of *Helleborus* x *hybridus*. Data are means of 20 observations. Vertical bars represent ±SE.

study at 2.7, 4.1, and 5.4 kg·m^3 (6, 9, and 12 lb/yd^3) which produced an average substrate pH of 6.4, 6.7, and 6.9, respectively (Fig. 2B). These data indicate that *Helleborus* × *hybridus* can maintain nutrient uptake across a wide range of substrate pH, which supports dry weight results reported above.

Foliar N, P, K, and S concentrations increased quadratically with increasing NARs with maximum concentrations occurring with N at 164, 141, 126, and 127 mg/liter, respectively (Figs. 3A–C and Fig. 4C). Harvey et al. (15) also reported a quadratic response to increasing NARs for N, P, and K concentrations of *Hakonechloa macra* Makino 'Aureola', a perennial grass. Dubois et al. (11) reported similar results for foliar N, P, and S of *Anemone* x *hybrida*. The quadratic response of foliar K concentrations was unexpected since uptake of K is usually influenced negatively by NH_4-N as they compete for binding sites (21). Foliar Ca and Mg concentration decreased linearly with increasing NARs (Fig. 4A and 4B). Foliar Ca and Mg concentrations commonly decrease with increasing NARs due to competition by NH_4-N for binding sites (8, 19, 21, 32). This also suggests that Ca and Mg were not limiting growth at DL rate of 0 kg/m^3 (0 lb/yd^3). Foliar N, K, and S concentrations fertilized with NARs ≥ 40 mg/liter N were in or higher than the listed range of values reported by Mills and Jones (22) for new growth of container-grown *Helleborus* x *hybridus*. In contrast, even the lowest value of foliar P, Ca, Mg, and Fe concentrations were higher than the range of listed values in Mills and Jones (22). It is not possible to determine whether the values reported by Mills and Jones (22) were associated with optimum growth because sampling was not performed on plants grown under a range of fertilizer treatments. Foliar nutrient concentrations (Figs. 3 and 4) were also within the range recommended as necessary for high quality plant growth for the species (10). These data support our conclusion that NARs ≥ 40 mg/liter N produced a healthy plant.

Foliar N concentration resulting from N at 40 mg/liter was 21 mg/g; therefore, we conclude that foliar concentrations < 21 mg/g would be indicative of less than optimal top growth. For all other mineral nutrients (P, K, Ca, Mg, S, and Fe), foliar concentrations observed in the present study at a NAR ≥ 40 mg/liter should be considered indicative of good plant vigor, although optimal levels were not determined directly. Caution should thus be exercised in interpreting the behavior of mineral nutrients other than N when applied N is not optimal. In particular, this study did not generate data regarding foliar concentrations that might constitute deficiency for mineral nutrients other that N.

In summary, adequate N nutrition of *Helleborus* x *hybridus* can be attained by fertigation with N at 40 to 160 mg/liter using a 4:1:2 N:P:K formulation. Alternative strategies such as fertigation at different intervals with different concentrations are possible, if crop nutrition is monitored to maintain EC levels between 0.4 and 0.94 dS·m. Tissue nutrient concentrations for N, P, K, Ca, Mg, and S (mg/g) should be ≈ >21, >3.4, >27, >9.8, >6.5, and >2.8, respectively. Even though *Helleborus* x *hybridus* appears to be tolerant to high substrate pH there were no growth benefits with a pH > 5.4 which suggests a pH between 5.0 and 6.0 should be adequate for growth. In contrast to many woody and herbaceous perennials, *Helleborus* x *hybridus* may be unique in its ability to maintain similar growth rates even with high substrate pH.

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