Growth Response of *Hakonechloa macra* (Makino) ‘Aureola’ to Fertilizer Formulation and Concentration, and to Dolomitic Lime in the Potting Mix

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Abstract. The shade-tolerant, variegated grass *Hakonechloa macra* ‘Aureola’ is a valuable ornamental. In an experiment replicated in two growing seasons, *Hakonechloa* plants were fertilized at each irrigation (fertigation) with factorial combinations of three fertilizer formulations (N:P molar ratios 5:1, 10:1, and 20:1) at five N concentrations (2, 4, 8, 16, and 32 mmol·L⁻¹), along with an unfertilized control, to determine the effect of N:P ratio and N concentration on vegetative growth and to establish fertility guidelines for production. Root dry weight and tiller bud growth increased slightly as N:P ratio increased. Fertilizer N concentration of 16 mmol·L⁻¹ promoted the most shoot growth, whereas the number of tiller buds and root growth were greatest at 2 and 4 mmol·L⁻¹ N. No interaction occurred between N:P ratio and fertilizer concentration. Results indicate that an N concentration of 8 mmol·L⁻¹, with an N:P ratio of 10:1 or 20:1 is optimal for production of *Hakonechloa*. At this fertilizer concentration, the mean electrical conductivity of extracts obtained by a solution displacement extraction (pour-through) procedure was 2.3 ± 0.45 dS·m⁻¹ (mean $\pm$ standard deviation). Tissue nutrient concentrations of N, P, K, Ca, and Mg were (in mg·g⁻¹): 24.0, 2.8, 14.3, 2.1, and 2.1, respectively. In a concurrent study, *Hakonechloa* plants were grown in pine bark : peat : sand mix with dolomitic lime added at 0, 1.2, 3.6, and 9.5 kg·m⁻³ producing pH ranging from ≈ 4.5 to 7.2. Growth of *Hakonechloa* was greatest with no lime (pH 4.5) and declined markedly as the rate of lime increased. Concentrations of N, P, and K in shoot tissue were greatest at a pH between 4.5 and 5.6 (0 and 1.2 kg·m⁻³ dolomitic lime). These findings clearly support recommending production of *Hakonechloa* in soilless potting mix with pH ≈ 4.5 and constant fertigation with N at 8 mmol·L⁻¹.

Interest in the use of ornamental grasses for the landscape has lead to a significant increase in production and sales of these perennials (Lavis-Ham, 1993). Division is the standard means of propagating these plants because most cultivated varieties are either sterile or must be vegetatively propagated to maintain a desirable phenotype (Brand, 1999; Corley, 1989). Cultivated grass species and cultivars vary widely, with substantial variation in growth rates and landscape performance. Variegated cultivars are often slower to reach a marketable size than other ornamental grasses, leading to insufficient stock supply (Lavis-Ham, 1993).

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Despite the popularity of ornamental grasses, knowledge and research regarding their cultural requirements is limited (Brand, 1999). Little information is available regarding nutrition or fertilization of ornamental grasses, especially in soilless mixes used for container production. Mills and Jones (1996) report shoot nutrient concentration values for new growth of *Imperata cylindrica* (L.) Beau. ‘Rubra’ (Japanese blood grass), *Pennisetum alopecuroides* (L.) Spreng. ‘Hameln’ (dwarf fountain grass), and *Phalaris arundinacea* L. ‘Picta’ (ribbon grass) grown in container production. However, it is impossible to determine whether these particular levels were associated with optimal growth because sampling was not performed on plants grown under a range of fertilizer treatments. Brand (1996) evaluated the response of *Pennisetum alopecuroides* (fountain grass) to differing rates of resin coated fertilizer (RCF), and observed that rate affected the quality of foliage, plant shape, and flower production.

Forage grass responses to fertilization have been reported. McMurphy (1970) found that native forage grasses growing in a meadow had higher yields from combined nitrogen and phosphorus fertilization than with nitrogen applied alone. *Sorghastrum*

nutans (L.) Nash (Indiangrass), *Panicum virgatum* L. (switchgrass), and *Andropogon gerardii* Vitm. (big bluestem), three warm-season forage grasses also grown as ornamentals, were found to have significantly lower yields in mineral soils when nitrogen was applied alone than when nitrogen and phosphorus were applied together, indicating that phosphorus availability can be a limiting factor in growth of grass species in mineral soil (Taylor and Allinson, 1982). Potassium additions to nitrogen and phosphorus fertilization did not result in increased growth (Smith, 1979; Taylor and Allinson, 1982), indicating that warm-season grasses may have relatively low potassium requirements. However, response to fertilization is likely to be different in mineral soils than in soilless mixes in which initial fertility and nutrient retention is very low.

Van Auken and Bush (1997) observed that the availability of N and P for perennial grass growth is dependent on soil pH. Jurena and Van Auken (1996) found the above- and below-ground biomass and relative growth rate of the perennial grass *Schizochyrium scoparius* (Michx.) Nash (little bluestem) declined above and below a pH range of 5.4–6.0. As with mineral soils, pH of soilless media directly affects nutrient solubility and retention (cation exchange capacity) and, thus, availability of nutrients to plants (Peterson, 1981).

Research is needed to develop cultural procedures to optimize production of the slower-growing ornamental grasses. Our study focused on enhancing growth of *Hakonechloa macra* ‘Aureola’, a slow-growing, shade-tolerant, variegated grass that is popular in landscaping and commands a high price.

The overall goal of this study was to determine optimum fertilization and media pH for growth and container production of *Hakonechloa macra* ‘Aureola’. The specific objectives were to: 1) identify the fertilizer N concentration and N:P ratio for optimum growth; 2) establish targets for electrical conductivity (EC) levels and nutrient concentrations in solution displacement extracts for use in monitoring crop nutrition; 3) determine shoot tissue concentrations of N, P, K, Ca, and Mg under different fertility conditions; and 4) establish the quantity of lime and associated potting mix pH supporting the best growth.

Materials and Methods

Plant material. Dormant, container-grown *Hakonechloa macra* ‘Aureola’ plants were divided during the first week of April. The divisions were established in 325-mL containers in a 3 pine bark : 2 sphagnum peat : 1 sand (by volume) potting mix amended with dolomitic limestone at 5.75 kg·m⁻³, in a greenhouse maintained at 21 °C day/17 °C night. Plants were irrigated as needed, and fertilized weekly with a soluble 20N–8.74P–16.6K fertilizer (Peters 20–20–20 Peatlite Special, Scotts Co., Marysville, Ohio) with N concentration 11 mmol·L⁻¹.

Fertilizer study. Fertilizer solutions comprising a factorial combination of five fertilizer N concentrations (2, 4, 8, 16, and 32 mmol·L⁻¹) and three N:P ratios (5 : 1, 10 : 1 and 20 : 1), along with an unfertilized control, were formulated in

tap water using NH_4NO_3 , KH_2PO_4 and KNO_3 (Table 1). The N : K ratio was constant at 1:0.3, and the $\text{NH}_4^+ : \text{NO}_3^-$ ratio ranged from 0.9:1.1 to 0.7 : 1.3. The tap water used had conductivity $<0.2 \text{ dS}\cdot\text{m}^{-1}$, alkalinity $<1.0 \text{ meq}\cdot\text{L}^{-1}$, and negligible levels of N, P and K. Established divisions were transplanted during the last week of May into 2.6-L plastic nursery containers (Classic 300S; Nursery Supplies, Fairless Hills, Pa.) with the same potting mix used during establishment. Plants were placed outdoors on a gravel surface and were covered with woven black polypropylene cloth providing 30% shade, stretched over a hoop structure. Plants were irrigated based on subjective judgment of need, avoiding visible stress. Pots were hand-watered at each irrigation with 800 mL of the appropriate fertilizer solution. A randomized complete-block design with 20 replicates was employed in 1998, and repeated in 1999 with 10 replicates.

Aqueous displacement (pour-through) extractions (Wright 1986) were conducted biweekly on six replicates of each treatment, commencing after plants were moved to the outdoor nursery. Extracts were collected

at identical intervals in both years. Extract EC was measured with a Hanna HI 9039 Conductivity/Fertilizer meter (Hanna Instruments, Woonsocket, R.I.), pH was measured with an Orion model 230 portable meter with an Orion Triode combination electrode/automatic temperature compensation probe (Thermo Orion Corp., Beverly, Mass.) and NH_4^+ , NO_3^- , and PO_4^- were measured colorimetrically on a Spectronic 2001 spectrophotometer (Milton-Roy, Rochester, N.Y.) following the methods of Chaney and Marbach (1962), Cataldo et al. (1975), and Murphy and Riley (1962), respectively.

During the third week of September, plant height and width measurements were taken prior to destructive harvest. Height was measured from the potting medium surface to the apex of the leaves, without extending the overarching leaf blades. Plant width was measured twice at right angles, again without extending the leaf blades. Plant size was then calculated by multiplying height $\times$ width₁ $\times$ width₂.

All plants were harvested, and the number of tiller buds, shoots, and inflorescences per plant were counted. Shoot and root fresh weights were measured. Shoot weights included blades and culms cut within $\approx 1 \text{ cm}$ of the surface of the medium. Roots were washed to remove as much potting mix as possible. Root weights included all the above-ground portion not cut off, including rhizomes. Leaf area was measured using a LI-COR model LI-3100 leaf area meter (LI-COR, Lincoln, Nebr.). Shoot length was determined by measuring the length of the culm and leaf blade combined. Shoots and roots were dried at 70°C for $\approx 72 \text{ h}$ prior to dry weight measurements. Following dry weight measurements, shoot tissue from two to five plants was combined to form four pooled samples for each treatment. The pooled samples were ground to pass through a 40-mesh screen and thoroughly mixed. Subsamples ($0.30 \text{ g} \pm 0.02 \text{ g}$) were dry-ashed for 6 h at 500°C in a muffle furnace, cooled, then dissolved in 15 mL

of 10% HCL (Jones and Case, 1990). Concentrations of Ca, K, Mg, and P were determined by the Univ. of Massachusetts Plant and Soil Testing Lab (Amherst, Mass.) using inductively coupled argon plasma spectrometry. Shoot tissue sub-samples of $0.12 \text{ g} \pm 0.020 \text{ g}$ were analyzed for total nitrogen with an automated Dumas method using a Leco CNS-2000 analyzer (Leco Corp., St. Joseph, Mich.).

Statistical analysis was conducted using SAS (SAS OnlineDoc version 8). Analysis of variance (ANOVA) was used to determine main effects and interactions for data pooled from both years. Treatment responses were further analyzed using single degree-of-freedom orthogonal polynomial contrasts.

Lime study. Potting mix composed of 3 pine bark:2 sphagnum peat:1 sand (by volume) was amended with dolomitic lime incorporated at 1.2, 3.6, and $9.5 \text{ kg}\cdot\text{m}^{-3}$ and stored for 3 weeks together with an unamended control to obtain initial pH ranging from 4.5 to 7.2. Amounts of dolomitic lime required to obtain the desired pH ranges were determined in incubation trials as described by Elliott (1996).

Established divisions were transplanted during the last week in May into 2.6-L plastic nursery containers (Classic 300S; Nursery Supplies, Fairless Hills, Pa.). Following transplanting, containers were top-dressed with 15 g per pot of a RCF with an analysis of 17N-2.6P-8.3K (Sierrablend 17-6-10 plus micronutrients, 8- to 9-month formulation, The Scotts Co., Marysville, Ohio). Plants were irrigated with 2.7 L of water every other day, via a drip irrigation system, and were grown in a container nursery as described in the fertilizer study. A randomized complete-block design with 20 replicates was employed in 1998 and repeated with 10 replications in 1999. Pour-through extractions (Wright 1986) were performed biweekly on six replicates of each treatment, commencing after plants were moved to the outdoor nursery. Extract pH and EC were measured as previously described. During the third week of September, all plants

Table 1. Composition of fertilizer solutions.

N:P ratio	Fertilizer salt			
	N conc	NH_4NO_3	KH_2PO_4	KNO_3
		mmol·L ⁻¹		
5:1	2	0.9	0.4	0.2
	4	1.8	0.8	0.4
	8	3.6	1.6	0.8
	16	7.2	3.2	1.6
	32	14.4	6.4	3.2
10:1	2	0.8	0.2	0.4
	4	1.6	0.4	0.8
	8	3.2	0.8	1.6
	16	6.4	1.6	3.2
	32	12.8	3.2	6.4
20:1	2	0.7	0.1	0.6
	4	1.5	0.2	1.0
	8	3.0	0.4	2.0
	16	6.0	0.8	4.0
	32	12.0	1.6	8.0

Table 2. Growth responses of *Hakonechloa macra* 'Aureola' to fertilizer concentration and N:P ratio.

N conc mmol·L ⁻¹	Shoot fresh wt ^a	Shoot dry wt	Root fresh wt ^a	Root dry wt	Plant size ^b (dm ³)	No. of shoots	No. of tiller buds	Tiller bud/shoot ratio	No. of inflorescences	Shoot length (cm)	Leaf area (cm ²)
	g/plant										
0	4.1	1.2	21.3	4.5	12.0	11	23	2.2	2.8	18.7	205
2	19.4	6.1	30.7	6.9	32.7	27	42	1.6	3.9	27.5	869
4	25.4	7.8	31.7	6.8	41.0	30	45	1.5	4.9	28.3	1127
8	25.5	7.7	22.3	4.7	50.2	32	37	1.1	3.8	26.9	1112
16	32.9	9.7	24.0	4.8	44.0	47	39	0.8	4.5	24.5	1446
32	10.7	2.2	8.4	4.3	15.0	21	5	0.2	2.2	20.7	333
Contrast ^w											
Linear	***	***	***	***	***	***	***	***	***	***	***
Quadratic	***	***	***	***	***	***	***	***	***	***	***
N:P ratio											
5:1	21.4	6.2	21.3	4.1	37.3	31	28	0.9	3.6	25.5	900
10:1	23.4	7.1	23.0	5.3	41.0	31	37	1.2	4.2	25.9	1003
20:1	22.7	6.8	23.2	5.3	41.1	32	36	1.1	3.9	25.3	1031
Significance ^v	NS	NS	NS	**	NS	NS	*	NS	NS	NS	NS

^aData for control are means of 30 plants (20 plants in year 1 and 10 plants in year 2). Data for N treatments are means of 90 plants (20 plants for each fertilizer concentration $\times$ N:P ratio in year 1 and 10 plants in year 2). Data for N:P ratios are means of 210 plants.

^bRoot weight is the combined weight of crown, rhizomes, and roots.

^cPlant size = height $\times$ width₁ $\times$ width₂; width of each plant was measured twice, with the second width measured 90° from the first.

^wSignificance of linear and quadratic contrasts for fertilizer N concentration.

^vSignificance of main effect of N:P ratio.

NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or ≤ 0.01 , respectively.

were destructively harvested and growth and shoot nutrient concentrations were measured as described in the fertilizer study. Data from both years were pooled and statistically analyzed in the same way as in the fertilizer study.

Results and Discussion

Fertilizer study. Statistical analysis showed no interaction of treatments with year, so data from both years were pooled for further analysis. Growth responded to increasing N and to N:P ratio, but there was no interaction of the two variables. Shoot growth, including shoot fresh weight, shoot dry weight, the number of shoots per plant and leaf area, were maximized with N at 16 mmol·L⁻¹ (Table 2). Root growth (including rhizomes) was greatest with N at 2 to 4 mmol·L⁻¹. Based on subjective observation, visually attractive plants were obtained with N at 4 to 16 mmol·L⁻¹. Plants were either dead or moribund with N at 32 mmol·L⁻¹, and when no fertilizer was applied, *Hakonechloa* grew poorly and had pale foliage. With increases in soil N fertility, shoot growth increases more than root growth in most instances (Jones, 1985, Maizlish et al., 1980), because as little as one-third of the root system is needed to support the N demand of shoots in grasses (Drew and Saker, 1975). Because a relatively small portion of the root system is needed to supply the demands of shoot growth, soluble N compounds are translocated to the most active sink for N during vegetative growth, which is generally the shoot apical meristems and young, expanding leaves (Jones, 1985).

The number of tiller buds was greatest with N at 2 to 4 mmol·L⁻¹, indicating that the expansion and outgrowth of tiller buds is restricted with low amounts of N (Table 2). The greatest combined number of shoots and tiller buds, as well as the highest proportion of shoots relative to tiller buds, were produced with N at 16 mmol·L⁻¹ (Table 2). The steep decrease in the tiller bud : shoot ratio with increasing N clearly shows that tiller buds are converted into shoots as N fertility increases. As N fertilization rate increases, shoot development and tiller bud elongation increases in *Hakonechloa*, without the expense of increasing root growth. This supports the findings of Drew and Saker (1975), Jones (1985), Maizlish et al. (1980), and Van Auken et al. (1997).

Shoot growth and appearance was unaffected by fertilizer N:P ratio. Root dry weight increased with increasing N:P ratio, associated with the increased number of tiller buds (Table 2). It is unclear why reduced fertilizer P levels would result in an increase in tiller bud production, especially as it was not associated with restriction in the number of shoots. Taken as a whole, the data indicate P supply did not limit growth of *Hakonechloa* in any of the fertilizer treatments, even at the 20 N : 1 P ratio. In contrast, Taylor and Allinson (1982) and McMurphy (1970) observed that P was a limiting factor in the growth of warm-season forage grasses. The seeming discrepancy must be a consequence of the conditions of constant liquid fertilization in soilless potting mix, through which

Hakonechloa evidently obtained sufficient P for growth even with the lowest supply of P relative to N and K. In contrast, forage grasses are grown in mineral soils, usually with no more than one fertilizer application per year. The response of *Hakonechloa* to decreasing proportions of P underscores the fundamental differences between the fertilization of forage grasses and ornamental grass cultivars, and between mineral soil and bark : peat-based potting mixes. Although N:P ratio was inherently confounded with NH₄⁺ : NO₃⁻ ratio, the NH₄⁺ : NO₃⁻ ratio ranged from slightly <1:1 to slightly >1:2, while N:P ranged from 5:1 to 20:1 on a molar basis.

The combination of measured growth responses and appearance suggest that for *Hakonechloa* an optimum soluble fertilizer applied every irrigation should have a 10:1 or 20:1 N:P ratio and N concentration between 4 and 16 mmol·L⁻¹. Because crownroot growth was maximized at 4 mmol·L⁻¹, and shoot growth was maximized with N at 16 mmol·L⁻¹ (Table 2), an intermediate rate of 8 mmol·L⁻¹ represents the best compromise between optimizing both root and shoot growth. This concentration produced plants with attractive shoot growth, which tended to be compact and dense, while those grown at 16 mmol·L⁻¹ tended to be sprawling and leggy. Limiting fertilizer inputs to the lowest nutrient concentrations consistent with adequate plant growth is an important consideration for nursery production. It should be implemented whenever possible because it is a cost-saving technique that can significantly reduce the levels of contaminated runoff from horticultural nurseries (Tyler et al., 1995). This has particular relevance to the nursery industry because water quality standards being enacted are pressuring growers to develop "best management practices" to decrease nutrient runoff (Williams, 1990).

Tissue nutrient concentrations may be useful for tracking and optimizing crop fertility in *Hakonechloa*. Both fertilizer concentration and N:P ratio influenced shoot tissue nutrient content, although the N:P ratio affected only N and P concentrations, and the overall effect was much less than that of fertilizer N concentration (Table 3). There was no interaction between fertilizer concentration and the N:P ratio of the fertilizer. Shoot tissue N concentration increased continuously with fertilizer N concentration, while concentrations of P, K, and Ca in the shoots increased up to fertilizer N rates of 16 mmol·L⁻¹ N, decreasing thereafter (Table 3). Mg concentrations in shoot tissue peaked at a much lower fertilizer N rate of only 4 mmol·L⁻¹, and decreased thereafter. Ca, K, and Mg concentrations were not significantly influenced by fertilizer ratio (Table 3). The shoot concentrations of N and P decreased slightly as the N:P ratio increased. With fertilizer N at 8 mmol·L⁻¹ tissue N, P, K, Ca, and Mg were (in mg·g⁻¹): 25.9, 3.0, 15.0, 2.4, and 1.9, respectively. Plotting shoot tissue N concentration vs. growth indicates an optimum tissue N concentration of ≈25 mg·g⁻¹ (Fig. 1). Shoot tissue N concentration >30 mg·g⁻¹ would likely indicate excessive fertilization, whereas <20 mg·g⁻¹ would indicate inadequate N sup-

ply. Although it is possible that P fertilization prior to transplanting and initiation of fertilizer treatments might have affected the response to subsequent P fertilization, the pronounced effects of fertilizer concentration and N:P ratio on tissue P concentration (Table 3) suggests any effect of pretreatment P fertilization was negligible. Mills and Jones (1996) analyzed shoot tissue concentrations of N, P, K, Ca, and Mg for several ornamental grass cultivars grown in container production. There were virtually no differences between our findings for *Hakonechloa* and their findings for P, K, Ca, and Mg for *Imperata cylindrica* 'Rubra' (Japanese blood grass) and *Pennisetum alopecuroides* 'Hameln' (dwarf fountain grass) shoots. *Hakonechloa* shoot N concentration was 69% and 39% higher than that of *Imperata* and *Pennisetum*, respectively, whereas *Pennisetum* shoot K was 36% higher than that of *Hakonechloa*.

Tracking fertility levels of potting mixes by testing EC levels of solution displacement (pour-through) extractions is a recommended practice for nursery production (Wright, 1986). Our suggested optimum fertilizer N concentration of 8 mmol·L⁻¹ corresponds to an extract EC of ≈2.3 dS·m⁻¹ (Fig. 2A). The pH of pour-through extract decreased from 6.9 to 4.7 as fertilizer N concentration increased from 0 to 32 mmol·L⁻¹ (Fig. 1B). Fortunately, in light of the results of the concurrent lime study, acidification related to fertilizer reactions evidently overcame the effect of lime addition to the potting mix. However, the possibility that response to fertilizer concentration was confounded with potting mix pH cannot be excluded.

Concentrations of NH₄⁺, NO₃⁻ and PO₄⁻ in pour-through extracts increased with increasing fertilizer N concentration. Using a 10:1 or 20:1 N:P ratio fertilizer at the recommended N concentration of 8 mmol·L⁻¹, the

Table 3. Effect of fertilizer concentration (conc.) and N:P ratio on shoot macronutrient concentrations.

Fertilizer N conc. (mmol·L ⁻¹)	Shoot tissue conc. (mg·g ⁻¹) ^z				
	N	P	K	Ca	Mg
	mg·g ⁻¹				
0	9.5	1.9	5.9	2.1	1.9
2	18.9	1.9	12.6	1.6	1.9
4	22.2	2.5	13.6	1.9	2.1
8	25.9	3.0	15.0	2.4	1.9
16	30.3	3.5	16.5	2.5	1.8
32	36.5	3.1	9.9	2.2	1.3
Contrast ^y					
Linear	***	***	***	***	***
Quadratic	***	***	***	***	***
N:P Ratio					
5:1	27.5	3.4	13.4	2.1	1.8
10:1	26.4	2.7	13.7	2.1	1.8
20:1	26.3	2.3	13.5	2.1	1.8
Significance ^x	*	*	NS	NS	NS

^zData are means of six observations, three in each year.

^ySignificance of linear and quadratic contrasts for fertilizer N concentration

^xSignificance of main effect of N:P ratio

ns, *, **Nonsignificant or significant at $P \leq 0.05$ or <0.01, respectively.

Fig. 1. Relationship of shoot growth and tissue N concentration in *Hakonecloa macra*, 'Aureola' fertilized with liquid fertilizer with N:P ratio ranging from 5 : 1 to 20 : 1 and N concentrations ranging from 0 to 32 mmol·L⁻¹. Each datum is the mean of 8 observations (4 for each year).

Fig. 2. (A) Electrical conductivity and (B). pH of solution displacement extracts collected biweekly throughout two growing seasons. Each datum is the mean of 60 observations (6 observations at 5 dates for 2 years). Error bars indicate standard deviation.

pour-through extract concentrations of NH_4^+ and NO_3^- were ≈ 0.16 to $0.18 \text{ mmol}\cdot\text{L}^{-1}$ and 1.34 to $1.41 \text{ mmol}\cdot\text{L}^{-1}$, respectively (Fig. 3). Since NH_4^+ and NO_3^- were in roughly equal proportions in the fertilizer, this indicates that immobilization, nitrification, or preferential uptake of NH_4^+ decreased the proportion of NH_4^+ in the extract. As would be expected, PO_4^- concentrations in pour-through extracts decreased as N:P ratio increased.

Lime study. Statistical analysis showed no interaction of treatments with year, so data from both years were pooled for further analysis. Dolomitic lime addition increased the final pH of the mix from 4.5 without lime to 7.2 with the addition of lime at $9.5 \text{ kg}\cdot\text{m}^{-3}$ (Fig. 4). The pH tended to increase with time even in the no-lime treatment, indicating that the combination of irrigation water and RCF had a slightly alkaline net reaction in this potting mix. Shoot and root weight, leaf area, plant size, and the number shoots and tiller buds were reduced when dolomitic lime was added to the medium (Table 4). Shoot fresh weight with no lime in this experiment was similar to that obtained in

Fig. 3. Phosphate, nitrate and ammonium concentrations in solution displacement extracts collected biweekly throughout two growing seasons. Each datum is the mean of 60 observations (6 observations at 5 dates for 2 years). Error bars indicate standard deviation.

the fertilizer experiment with a N concentration of 16 mmol·L⁻¹ (Table 2). The largest decrease in shoot or root weight was obtained between 0 and 1 kg·m⁻³, whereas the effect of increasing dolomitic lime from 1.2 to 9.5 kg·m⁻³ was relatively small (Table 4). However, the additive detrimental effect of increasing dolomitic lime above 1.2 kg·m⁻³ was distinctly visible (data not shown). These findings clearly indicate that in container production *Hakonechloa* grows best in a potting mix with pH ≈4.5. The species is adapted to a low soil pH in its native habitat of mesic, forested mountains of Hakone, in central Pacific Japan (Watson and Dallwitz, 1992). Although mixes with alkaline components were not tested, it might be necessary to acidify mixes at or above pH 5.

Peterson (1981) reported that nutrient availability in organic container media is optimal at a pH range between about 5.0 and 6.0. In our study, concentrations of N, P, and K were the highest in shoot tissue from plants grown in potting mix with no lime or only 1.2 kg·m⁻³, corresponding to a pH of 4.5 to 6.0 (Table 6, Fig. 3). The N, P, and K concentrations in shoot tissue from the no lime treatment (Table 5) are similar to concentrations observed for plants in the fertilizer study grown at the recommended fertilizer N

concentration of 8 mmol·L⁻¹ (Table 3). Micro-nutrient concentrations in shoot tissue were not significantly affected by lime treatments (data not shown).

Addition of dolomitic limestone to soil tends to increase shoot concentrations of Ca and Mg, with Mg concentrations rising relatively more than Ca concentrations (Mills and Jones, 1996). Our results with a soilless potting mix follow a similar pattern, where increasing dolomitic limestone caused curvilinear increase in Ca and Mg shoot concentrations, with Mg increasing more than Ca (Table 5). Liming soil is known to decrease K concentrations in shoot tissue due to an increase in competition with Ca during uptake (Jacobsen et al., 1960; Mills and Jones, 1996). We observed a decrease in N, P, and K concentrations with increasing dolomitic lime (Table 5). However, these responses may simply be the result of root function and nutrient demand, since *Hakonechloa* produced appreciably less shoot growth when dolomitic lime was added to the potting medium (Table 4).

Optimum nutrition of *Hakonechloa macra* 'Aureola' can be accomplished by fertigation with N at 8 mmol·L⁻¹ using a 10:1 or 20:1 N:P formulation. Phosphorus is evidently not required in high concentrations in container

Table 5. Tissue nutrient concentrations (conc.) of *Hakonechloa macra* 'Aureola' grown in soilless potting mix with different amounts of dolomitic lime.

Dolomitic lime (kg·m ⁻³)	Shoot tissue conc. ^z				
	N	P	K	Ca	Mg
	mg·g ⁻¹ dry wt				
0	24.0	3.1	14.5	1.2	1.5
1.2	22.3	3.4	14.1	1.4	1.8
3.6	19.1	2.6	12.1	1.5	2.2
9.5	19.0	2.1	11.1	1.6	2.4
Contrast ^y					
Linear	***	***	***	***	***
Quadratic	**	NS	NS	**	***

^zData are means of six observations, three in each year.

^ySignificance of linear and quadratic contrasts for lime addition

NS, **, *** Nonsignificant, or significant at $P \leq 0.01$ and < 0.001 , respectively.

nursery production of *Hakonechloa*. Alternative fertilizer strategies such as preplant incorporation of P, or fertigation at different intervals with different concentrations are possible, if crop nutrition is monitored with the pour-through nutrient extraction method to maintain an EC level of ≈2.3 dS·m⁻¹, and NH₄⁺, NO₃⁻ and PO₄⁻ concentrations are maintained at ≈0.17 mmol·L⁻¹, 1.4 mmol·L⁻¹ and 0.4 to 0.9 mmol·L⁻¹, respectively. Tissue nutrient concentrations for N, P, K, Ca, and Mg (in mg·g⁻¹) should be ≈26, 3.0, 15, 2.4, and 1.9, respectively. Although we did not test different RCF rates or formulations, results of the lime experiments show that RCF as used is capable of producing plants similar in size and tissue nutrient concentrations to those produced with constant fertigation. *Hakonechloa* evidently prefers a growing medium pH of ≈4.5, as growth was significantly decreased by the addition of lime to a potting mix composed of aged pine bark, sphagnum peat, and sand.

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Fig. 4. pH of solution displacement extracts collected biweekly throughout two growing seasons. Each datum is the mean of 12 observations (six observations at each date for 2 years). Error bars indicate standard deviation.

Table 4. Growth responses of *Hakonechloa macra* 'Aureola' grown in soilless potting mix with different amounts of dolomitic lime.

Dolomitic lime (kg·m ⁻³)	Shoot fresh wt ^z	Shoot dry wt	Root ^y fresh wt	Root dry wt	Plant size ^x (dm ³)	No. of shoots	No. of tiller buds	Leaf area (cm ²)
	g/plant							
0	35.9	11.2	34.7	8.2	73.2	38	60	1627
1.2	19.7	6.6	22.7	5.4	33.4	27	38	859
3.6	19.5	6.2	21.7	5.1	32.3	21	35	831
9.5	15.2	5.2	19.2	4.9	31.8	21	31	668
Contrast ^w								
Linear	***	***	**	*	***	**	**	***
Quadratic	**	**	*	*	***	**	**	**

^zData are means of 30 plants per treatment (20 plants in year 1 and 10 plants in year 2).

^yRoot weight is the combined weight of crown, rhizomes and roots.

^xPlant size = height × width₁ × width₂; width of each plant was measured twice, with the second width measured 90° from the first.

^wSignificance of linear and quadratic contrasts for lime addition.

*, **, *** Significant at $P \leq 0.05$, ≤ 0.01 , and < 0.001 , respectively

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