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# Nitrogen:Phosphorus:Potassium Ratios Affect Production of Two Herbaceous Perennials

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***Abstract*. A series of experiments were undertaken to determine the effects of nitrogen (N), phosphorus (P), and potassium (K) concentrations and N:P:K ratio on flowering and vegetative growth of two herbaceous perennials, *Hibiscus moscheutos* L. (hibiscus) and *Rudbeckia fulgida* var. *sullivantii* Ait. 'Goldsturm' (rudbeckia). Plant growth and flowering of both hibiscus and rudbeckia were influenced by concentration and ratio of N, P, and K. When N was held constant at 100 mg·L$^{-1}$, 4:1 N:K (25 mg·L$^{-1}$ K) and 16:1 N:P (6.3 mg·L$^{-1}$ P) were optimal for growing hibiscus, whereas higher K concentration (1:2 N:K, 200 mg·L$^{-1}$ K) and lower P concentration (32:1 N:P, 3.1 mg·L$^{-1}$ N) were required for optimal growth of rudbeckia. However, when holding N constant at 100 mg·L$^{-1}$ and varying both P and K in the fertilizer solutions, higher P and K concentrations and a 2:1:2 (50 mg·L$^{-1}$ P, 100 mg·L$^{-1}$ K) N:P:K ratio best supported hibiscus growth, whereas 3:1:2 (33 mg·L$^{-1}$ P, 66 mg·L$^{-1}$ K) N:P:K was needed for growth of rudbeckia. Finally, when both N concentration and N:P:K ratio were altered, optimum growth of both hibiscus and rudbeckia was achieved at similar and lower P and K concentrations (25 mg·L$^{-1}$ P and 50 mg·L$^{-1}$ K) and 200 mg·L$^{-1}$ N. An 8:1:2 N:P:K ratio was optimum for production of both hibiscus and rudbeckia, although 12:1:2 N:P:K (200 mg·L$^{-1}$ N, 17 mg·L$^{-1}$ P, 33 mg·L$^{-1}$ K) produced similar growth of rudbeckia. Based on results of these two herbaceous perennials, it appears herbaceous perennials have N requirements similar to annual plants and P and K requirements similar to woody plants. Furthermore, the two herbaceous perennials used in this study required nutrients in the fertilizer solution at a higher N:P:K ratio than either annual or woody plants. Foliar concentrations of 2.2% N, 0.4% P, and 1.9% K were adequate for growth of hibiscus, whereas 2.4% N, 0.2% P, and 2.6% K were required to maximize growth of rudbeckia.**

Although successful container-grown plant production requires management of many variables, nutrient management is critical, requiring appropriate selection and use of fertilizers to optimize plant growth and limit waste and cost of fertilizer. Mineral nutrient recommendations for woody, perennial plant production include daily applications of 50 to 100 mg·L$^{-1}$ N, 10 to 20 mg·L$^{-1}$ P, and 25 to 50 mg·L$^{-1}$ K in a 5:1:3 N:P:K ratio (Wright and Niemiera, 1987). Schnelle and White (2004) provided similar recommendations for P (5 to 15 mg·L$^{-1}$) and K (25 to 75 mg·L$^{-1}$) but with substantially higher N concentrations of 100 to 200 mg·L$^{-1}$ in a traditional ratio of 3:1:2. In contrast, N recommendations for annual, herbaceous plant production are generally higher ranging from 90 to 255 mg·L$^{-1}$ N applied daily with a 2:1:2 N:P:K ratio (Bailey and Nelson, undated). Although many herbaceous perennials have the same accelerated growth rate as annual plants, they also store nutrients in roots for regrowth after a dormant season like a woody plant. Thus, herbaceous perennials may have different requirements for concentration and ratio of nutrients than either woody, perennial or herbaceous, annual plants.

Research to date has provided few recommendations for appropriate concentrations and ratios of nutrients for container production of herbaceous perennials. Adam and Sluzis (2005) suggest 136 mg·L$^{-1}$ N applied every other day for production of a wide range of container-grown shade and sun-tolerant herbaceous perennials, whereas Hipp et al. (1989) recommended 166 mg·L$^{-1}$ N applied weekly for *Melampodium leucanthum* Ton & Gray (blackfoot daisy). Additionally, little information is available regarding appropriate concentrations of P and K, and even fewer studies have examined N:P:K ratio for production of herbaceous perennials. Maximum growth of *Melampodium leucanthum*, *Salvia greggii* Gray (autumn sage), and *Scaevola aemula* R. Br. 'New Wonder' (fanflower) was achieved with P concentrations of 30, 50, and 14.5 mg·L$^{-1}$, respectively, and N:P ratios of 5.5:1, 4:1, and 14:1, respectively (Hipp et al., 1988, 1989; Zhang et al., 2004), whereas growth of *Hakonechloa macra* Makino 'Aureola' (Hakone grass) was maximized with 48 mg·L$^{-1}$ P and a N:P ratio of 10:1 to 20:1 (Harvey et al., 2004). Complicating the nutrient concentration recommendations for herbaceous perennials is the tendency for luxury consumption of nutrients. Both Adam and Sluzis (2005) and Scoggins (2005) reported more than 20 different species of herbaceous perennials absorbed more nutrients than were required to maintain maximum growth. Furthermore, these authors indicated higher-quality plants were often produced with lower concentrations of nutrients. Although the ratio of N:P:K can affect flowering and growth (Higaki et al., 1992; Melton and Dufault, 1991), it also affects the cost of fertilizer manufacturing. Fertilizer manufacturers make decisions on the application concentration and ratio of nutrients based on targeted cost for the grower, environmental conditions during production, and the nutrient needs of the plant.

More definitive recommendations are needed for the concentrations and ratio of N, P, and K for container production of herbaceous perennials. Thus, four experiments were conducted during 2005–2007 to determine the effects of N, P, and K concentration and N:P:K ratio on flowering and vegetative growth of two herbaceous perennials.

## Materials and Methods

*Cultural practices and data management for all experiments.* Seedlings of *Rudbeckia fulgida* var. *sullivantii* Ait. 'Goldsturm' (rudbeckia) and *Hibiscus moscheutos* L. (hibiscus) grown in 16.39-cm$^3$ containers were transferred into 3.8-L black plastic containers filled with an 8 aged pine bark:1 sand (by volume) substrate amended with 1.2 kg·m$^{-3}$ dolomitic limestone [providing calcium (Ca) and magnesium (Mg)] in all experiments. The cultivar of hibiscus differed as a result of plant availability. 'Luna Blush' hibiscus, 'Luna White' hibiscus, and 'Luna Red' hibiscus were used in 2005, 2006, and 2007, respectively. Plants

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were grown in a greenhouse with 27 ± 1.0/18 °C ± 1.0 d/night temperatures in Raleigh, NC, between May and August with natural irradiance and photoperiod. Concentrated stock solutions were prepared for each treatment and the treatments were applied with a fertigation system using two Dosatron D16I proportional injectors (Dosatron, Inc., Clearwater, FL) connected in series. Reagent-grade ammonium nitrate, monoammonium phosphate, and potassium sulfate were used to supply N, P, and K, respectively, using one Dosatron injector (Table 1). Micronutrients were supplied from a concentrated modified Hoagland's solution (Hoagland and Arnon, 1950) using boric acid, copper sulfate, manganese chloride, ammonium molybdate, zinc sulfate, and chelated iron to supply the boron (B), copper (Cu), manganese (Mn), molybdenum (Mo), zinc (Zn), and iron (Fe) at a constant concentration (0.5, 0.02, 0.5, 0.1, 0.05, and 5 mg·L$^{-1}$ for B, Cu, Mn, Mo, Zn, and Fe, respectively) through a second Dosatron injector. The injectors diluted the stock solutions with tap water having a pH of 7.4 and 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·L$^{-1}$, respectively. The N, P, and K treatments and micronutrient solution were delivered to each container through a single pressure-compensated spray stake (Accu-Stick; Wade Mfg. Co., Fresno, CA). Between each treatment the Dosatrons and appropriate irrigation lines were flushed with tap water, drained, and primed with the next treatment before application.

Leaching fractions (LF = volume leached ÷ volume applied) were measured every 2 weeks, and irrigation volume was adjusted to maintain a 0.2 LF for each treatment. Additionally, substrate solution was collected to determine electrical conductivity (EC) and pH every 2 to 4 weeks depending on the experiment using the pour-through nutrient extraction method (Wright, 1986). EC and pH were determined through a combination EC/pH meter (Accumet 50; Fisher Scientific Co., Pittsburgh, PA).

Flower buds were counted, removed, and dried to a constant weight at 62 °C when they began to open (show color). At harvest, plants were separated into flower buds, flowers, leaves, stems, and roots. Leaf area was measured using a LI-COR 3000 leaf area meter (LI-COR, Lincoln, NE). Roots were washed to remove substrate. Before drying, all leaves were triple-rinsed in deionized water. All plant parts were dried to a constant weight at 62 °C.

After drying, flower buds, flowers, leaves, stems, and roots were weighed and used to calculate top dry weight (leaf + stem dry weight), flower dry weight (flower + flower bud dry weight), and total dry weight (leaf + stem + root + flower + flower bud dry weight). After weighing, leaves were ground with a Foss Tecator Cyclotec™ 1093 sample mill (Analytical Instruments, LLC, Golden Valley, MN) to pass a 0.5-mm sieve or smaller. Foliar N concentration was determined by oxygen combustion gas chromatography with an elemental analyzer (NA 1500; CE Elantech Instruments, Lakewood, NJ.) (Campbell and Plank, 1992). Foliar P, K, Ca, Mg, sulfur (S), B, Cu, Fe, Mn, and Zn concentrations were determined with an inductively coupled plasma (ICP) spectrometer (Donohue and Aho, 1992) (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corp., Shelton, CT) following open-vessel $HNO_3$ digestion in a microwave digestion system (CEM Corp., Matthews, NC) (Campbell and Plank, 1992). Tissue samples were analyzed by the North Carolina Department of Agriculture and Consumer Services, Agronomic Division, Raleigh, NC.

All variables were subjected to analysis of variance (ANOVA) and regression analyses, where appropriate, using Proc ANOVA and Proc REG in SAS Version 9.01 (SAS Institute Inc., 2001) and were considered significant at $P \leq 0.05$. Species × treatment interactions were evaluated for all variables measured except foliar nutrient concentrations. If the species × treatment interaction was significant, data were reanalyzed by species, whereas when the interaction was nonsignificant, treatment main effects were discussed. Species × treatment interactions were not evaluated for foliar nutrient concentrations so recommendations could be provided for each species. Treatment mean comparisons between N concentrations and N:P:K ratios in the 2007 experiment were made by single df linear contrast tests (SAS Institute, Inc., 2001). Simple linear or polynomial curves were fitted to the data when significant trends were identified. The maximum of the polynomial curve was calculated as a first-order derivative of the independent variable where the dependent variable equaled zero.

*Nitrogen:potassium ratio and nitrogen:phosphorus ratio experiments.* During Summer 2005, two concurrent but separate 2 × 6 factorial experiments were conducted in a randomized

Table 1. Nutrient solutions used in 2005, 2006, and 2007.[z]

| Nutrient source | mg·L$^{-1}$ | mM | mg·L$^{-1}$ | mM | mg·L$^{-1}$ | mM | mg·L$^{-1}$ | mM | mg·L$^{-1}$ | mM | mg·L$^{-1}$ | mM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2005 | | | | | | | | | | | |
| | 1:1 N:P | | 2:1 N:P | | 4:1 N:P | | 8:1 N:P | | 16:1 N:P | | 32:1 N:P | |
| $NH_4NO_3$ | 100 | 7.1 | 100 | 7.1 | 100 | 7.1 | 100 | 7.1 | 100 | 7.1 | 100 | 7.1 |
| $NH_4H_2PO_4$ | 100 | 3.2 | 50 | 1.6 | 25 | 0.8 | 12.5 | 0.4 | 6.25 | 0.2 | 3.1 | 0.1 |
| $K_2SO_4$ | 50 | 1.3 | 50 | 1.3 | 50 | 1.3 | 50 | 1.3 | 50 | 1.3 | 50 | 1.3 |
| | 2005 | | | | | | | | | | | |
| | 1:1 N:K | | 1:2 N:K | | 2:1 N:K | | 4:1 N:K | | 8:1 N:K | | 16:1 N:K | |
| $NH_4NO_3$ | 100 | 7.1 | 100 | 7.1 | 100 | 7.1 | 100 | 7.1 | 100 | 7.1 | 100 | 7.1 |
| $NH_4H_2PO_4$ | 25 | 0.8 | 25 | 0.8 | 25 | 0.8 | 25 | 0.8 | 25 | 0.8 | 25 | 0.8 |
| $K_2SO_4$ | 200 | 5.1 | 100 | 2.6 | 50 | 1.3 | 25 | 0.6 | 12.5 | 0.3 | 6.25 | 0.2 |
| | 2006 | | | | | | | | | | | |
| | 2:1:2 N:P:K[y] | | 3:1:2 N:P:K | | 4:1:2 N:P:K | | 8:1:2 N:P:K | | 12:1:2 N:P:K | | 24:1:2 N:P:K | |
| $NH_4NO_3$ | 100 | 5.5 | 100 | 6.1 | 100 | 6.3 | 100 | 6.7 | 100 | 6.9 | 100 | 7.0 |
| $NH_4H_2PO_4$ | 50 | 1.6 | 33 | 1.1 | 25 | 0.8 | 12.5 | 0.4 | 8 | 0.3 | 4 | 0.1 |
| $K_2SO_4$ | 100 | 2.6 | 66 | 1.7 | 50 | 1.3 | 15 | 0.6 | 16 | 0.4 | 8 | 0.2 |
| | 2007 | | | | | | | | | | | |
| | 4:1:2 N:P:K | | 4:1:2 N:P:K | | 4:1:2 N:P:K | | 8:1:2 N:P:K | | 8:1:2 N:P:K | | 8:1:2 N:P:K | |
| $NH_4NO_3$ | 50 | 3.2 | 100 | 6.3 | 200 | 12.7 | 50 | 3.4 | 100 | 6.7 | 200 | 13.5 |
| $NH_4H_2PO_4$ | 12.5 | 0.4 | 25 | 0.8 | 50 | 1.6 | 6.25 | 0.2 | 12.5 | 0.4 | 25 | 0.8 |
| $K_2SO_4$ | 25 | 0.6 | 50 | 1.3 | 100 | 2.6 | 12.5 | 0.3 | 25 | 0.6 | 50 | 1.3 |
| | 12:1:2 N:P:K | | 12:1:2 N:P:K | | 12:1:2 N:P:K | | | | | | | |
| $NH_4NO_3$ | 50 | 3.4 | 50 | 3.4 | 200 | 13.7 | | | | | | |
| $NH_4H_2PO_4$ | 4.2 | 0.1 | 4.12 | 0.1 | 16.6 | 0.5 | | | | | | |
| $K_2SO_4$ | 8.3 | 0.2 | 8.3 | 0.2 | 33.3 | 0.9 | | | | | | |

[z] Micronutrient solutions were identical for all years. Micronutrient solution was the same for all experiments and contained: 0.5 mg·L$^{-1}$ (0.009 mM) $MnCl_2 \cdot 4H_2O$, 0.1 mg·L$^{-1}$ (0.001 mM) $(NH_4)_6Mo_7O_{24}$, 0.05 mg·L$^{-1}$ (0.0008 mM) $ZnSO_4 \cdot 7H_2O$, and 5 mg·L$^{-1}$ (0.09 mM) chelated iron.

[y] In 2006, 8:0:1 N:P:K [100 mg·L$^{-1}$ (7.1 mM) from $NH_4NO_3$ and 12.5 mg·L$^{-1}$ (0.3 mM) from $K_2SO_4$), 12:1:0 N:P:K (100 mg·L$^{-1}$ (6.9 mM) from $NH_4NO_3$, 8 mg·L$^{-1}$ (0.3 mM) from $NH_4H_2PO_4$, and 8 mg·L$^{-1}$ (0.3 mM) from $Ca(SO_4)$], and 1:0:0 N:P:K [100 mg·L$^{-1}$ (7.1 mM) from $NH_4NO_3$, and 8 mg·L$^{-1}$ (0.3 mM) from $Ca(SO_4)$] were included as treatments for comparison purposes.

N = nitrogen; P = phosphorus; K = potassium.

complete block design (RCBD) with six replications. The main factors were two species (hibiscus and rudbeckia) and six treatments consisting of either six N:P or six N:K ratios. Six N:P ratios (1:1, 2:1, 4:1, 8:1, 16:1, or 32:1) were evaluated with the N and K concentrations held constant at 100 and 50 mg·L$^{-1}$, respectively, resulting in P concentrations of 100, 50, 25, 12.5, 6.25, or 3.13 mg·L$^{-1}$. Six N:K ratios (1:2, 1:1, 2:1, 4:1, 8:1, or 16:1) with N and P concentrations held constant at 100 and 25 mg·L$^{-1}$, respectively, evaluated K concentrations of 200, 100, 50, 25, 12.5, and 6.25 mg·L$^{-1}$. For both experiments, rudbeckia and hibiscus were potted on 8 Apr. and 15 Apr., respectively. Fertigation for each experiment began 23 May with harvest on 27 July and 5 Aug. for hibiscus and rudbeckia, respectively. For both N:K and N:P experiments, substrate EC and pH were measured at treatment initiation and every 2 weeks thereafter (Table 2).

*Nitrogen:phosphorus:potassium ratio experiment holding nitrogen concentration constant (2006).* Based on results from the 2005 experiments, a 2 × 6 × 6 factorial experiment in a RCBD with six replications was conducted in 2006. The main effects were two species (hibiscus and rudbeckia) with six concentrations of P (50, 33, 25, 12.5, 8, or 4 mg·L$^{-1}$) and six concentrations of K (100, 66, 50, 25, 16, or 8 mg·L$^{-1}$) producing six N:P:K ratios (2:1:2, 3:1:2, 4:1:2, 8:1:2, 12:1:2, and 24:1:2) with the concentration of N held constant at 100 mg·L$^{-1}$. Plants were potted 11 May and fertigation began 22 May. Hibiscus and rudbeckia were harvested 14 July and 21 July, respectively. Substrate EC and pH were measured at treatment initiation and every 3 weeks thereafter (Table 2).

*Nitrogen concentrations and nitrogen: phosphorus:potassium ratio experiment (2007).* Because concentration of P and K along with ratio of nutrients affected plant growth in 2006, a factorial arrangement of three N concentrations × three N:P:K ratios in a RCBD with six replications was evaluated during Summer 2007. Nitrogen concentrations of 200, 100, or 50 mg·L$^{-1}$ were combined with P concentrations of 50, 25, 16.7, 12.5, 8, 6.3, or 4.2 mg·L$^{-1}$ and K concentrations of 100, 50, 33.3, 25, 16, 12.5, or 8.3 mg·L$^{-1}$ resulting in N:P:K ratios of 4:1:2, 8:1:2, and 12:1:2. The plants were potted 1 May, fertigation began 14 May, and hibiscus and rudbeckia were harvested 23 July. Substrate EC and pH were measured at treatment initiation and every 2 weeks thereafter (Table 2).

## Results and Discussion

*Nitrogen:phosphorus ratio (2005).* Stem and flower dry weights, number of flowers, and leaf area of both species were unaffected by species × N:P ratio, N:P ratio, and P concentration (data not presented). Thus, these parameters responded similarly across a wide range of N:P ratio and P concentrations. Zhang et al. (2004) also reported that flowering of *Scaevola aemula* 'New Wonder' was unaffected by concentrations of P ranging from 0 to 43.5 mg·L$^{-1}$. In addition, substrate pH and EC were unaffected by species × N:P ratio (data not presented). Substrate solution pH was unaffected by N:P ratio, whereas EC increased slightly as N:P ratio decreased (P concentration increased) (Table 2). However, the species × N:P ratio interaction was significant for leaf, root, and total dry weights so results were reanalyzed by species. In addition, total dry weight of each species responded similarly to leaf and root dry weight so only total dry weight is presented.

Table 2. Substrate solution pH and electrical conductivity (EC) for each nutrition experiment.[z]

| N:P ratio (2005) | P concn (mg·L$^{-1}$)[y] | pH | EC (dS·m$^{-1}$) |
|---|---|---|---|
| 32:1 | 3.13 | 5.5 | 0.33 |
| 16:1 | 6.25 | 5.4 | 0.34 |
| 8:1 | 12.5 | 5.5 | 0.31 |
| 4:1 | 25 | 5.4 | 0.32 |
| 2:1 | 50 | 5.0 | 0.38 |
| 1:1 | 100 | 5.3 | 0.38 |
| N:K ratio (2005) | K concn (mg·L$^{-1}$)[x] | | |
| 16:1 | 6.25 | 5.4 | 0.25 |
| 8:1 | 12.5 | 5.5 | 0.29 |
| 4:1 | 25 | 5.4 | 0.33 |
| 2:1 | 50 | 5.4 | 0.42 |
| 1:1 | 100 | 5.3 | 0.56 |
| 1:2 | 200 | 5.4 | 0.45 |
| N:P:K/N held constant (2006) | P/K concn (mg·L$^{-1}$)[w] | | |
| 24:1:2 | 4/8 | 5.2 | 0.33 |
| 12:1:2 | 8/16 | 5.3 | 0.31 |
| 8:1:2 | 12.5/25 | 5.4 | 0.30 |
| 4:1:2 | 25/50 | 5.2 | 0.34 |
| 3:1:2 | 33/66 | 5.2 | 0.35 |
| 2:1:2 | 50/100 | 5.0 | 0.44 |
| N concn/N:P:K ratios (2007) | P/K concn (mg·L$^{-1}$) | | |
| 50 mg·L$^{-1}$/4:1:2 | 12.5/25 | 5.8 | 0.25 |
| 100 mg·L$^{-1}$/4:1:2 | 25/50 | 5.4 | 0.30 |
| 200 mg·L$^{-1}$/4:1:2 | 50/100 | 5.1 | 0.62 |
| 50 mg·L$^{-1}$/8:1:2 | 6.25/12.5 | 5.7 | 0.23 |
| 100 mg·L$^{-1}$/8:1:2 | 12.5/25 | 5.5 | 0.27 |
| 200 mg·L$^{-1}$/8:1:2 | 25/50 | 5.2 | 0.47 |
| 50 mg·L$^{-1}$/12:1:2 | 4.17/8 | 5.7 | 0.25 |
| 100 mg·L$^{-1}$/12:1:2 | 8/16 | 5.5 | 0.27 |
| 200 mg·L$^{-1}$/12:1:2 | 16.67/33 | 5.3 | 0.46 |

[z] Species × treatment interactions were non-significant; thus, data are averaged over species. Additionally, trends in treatment effects were similar across sampling thus averages across sample date are presented.

[y] N and K concentrations held constant at 100 and 50 mg·L$^{-1}$, respectively.

[x] N and P concentrations held constant at 100 and 25 mg·L$^{-1}$, respectively.

[w] N concentration held constant at 100 mg·L$^{-1}$.

N = nitrogen; P = phosphorus; K = potassium.

Total dry weight of hibiscus responded quadratically to decreasing N:P ratio (increasing P concentration) with a calculated maximum growth attained with a 5:1 N:P ratio and 20 mg·L$^{-1}$ P (Fig. 1). The 1:1 N:P ratio (100 mg·L$^{-1}$ P) resulted in a substantial decrease in growth. Similarly, Zhang et al. (2004) reported growth of *Scaevola aemula* 'New Wonder' was reduced when fertilized with greater than 44 mg·L$^{-1}$ P (4:1 N:P ratio). *Euphorbia pulcherrima* Wind., *Hordeum vulgare* L., and some cultivars of *Glycine max* L. are also reported to be sensitive to high P (Foote and Howell, 1964; Richard and Rees, 1962; Whipker and Hammer, 1994). When the 1:1 N:P (100 mg·L$^{-1}$ P) data were removed and the data reanalyzed, all significance was lost. Thus, hibiscus grew similarly when fertigated with N:P ratios ranging from 2:1 to 32:1 N:P (50 to 3.1 mg·L$^{-1}$ P). *Ilex crenata* Thunb. 'Helleri', a woody perennial, and *Hakonechloa macra* 'Aureola', a herbaceous ornamental grass, also grew well with lower P concentrations (10 and 8 mg·L$^{-1}$ P, respectively) and higher N:P ratios (10:1 or 20:1) (Harvey et al., 2004; Yeager and Wright, 1982). In contrast, Hipp et al. (1988, 1989) reported maximum growth of *Melampodium leucanthum* and *Salvia greggii* occurred between P concentrations of 30 and 50 mg·L$^{-1}$ and 4:1 to 5.5:1 N:P ratios.

Foliar N and P concentration of hibiscus responded quadratically to decreasing N:P ratio (increasing P concentration), whereas foliar K (mean, 2.2%), Ca (mean, 2.1%), Mg (mean, 1.0%) and S (mean, 0.4%) concentrations were unaffected by N:P ratio (Ca, Mg, and S data not presented) (Fig. 1). Additionally, foliar Fe, Mn, Cu, B, and sodium (Na) concentrations were unaffected by N:P ratio; whereas, Zn concentration decreased as P concentration increased (N:P ratio decreased) (data not presented). In contrast to total dry weight, when the 1:1 N:P (100 mg·L$^{-1}$ P) was removed from the analyses, foliar N and foliar P concentrations were still affected by N:P ratio and increased linearly as P concentration increased (N:P ratio decreased). Because growth was maintained over a wide range of N:P ratios, it may be possible to fertilize hibiscus with as little as 3.1 mg·L$^{-1}$ P (32:1 N:P). In addition, foliar N, P, and K concentrations of 2.4%, 0.4%, and 2.2%, respectively, would be adequate to achieve 90% of maximum growth (Fig. 1).

Similar to hibiscus, total dry weight of rudeckia was unaffected by N:P ratio (Fig. 2). Thus, maximum dry weight was obtained with N:P ratios ranging from 1:1 to 32:1 (100 to 3.1 P mg·L$^{-1}$). However, unlike hibiscus, rudbeckia was not negatively affected by high N:P ratios (1:1, 100 mg·L$^{-1}$ P) and maximum growth was predicted with 46 mg·L$^{-1}$ P (2:1 N:P ratio).

Foliar N and P concentrations of rudbeckia increased linearly with decreasing N:P ratio (increasing P concentration), whereas foliar K concentration decreased linearly with decreasing N:P ratio (increasing P concentration) (Fig. 2). Similar to hibiscus, foliar Ca (mean, 2.8%), Mg (mean, 1.0%), and S (mean, 0.7%) concentrations and foliar Fe, Mn, Zn, B, and Na (data not presented) were unaffected by N:P ratio. Harvey et al. (2004) reported similar results to trends reported here with foliar N, P, Ca, and Mg concentrations of *Hakonechloa macra* 'Aureola' when grown with N:P ratios from 5:1 to 20:1. Yeager and Wright (1982) also reported increased foliar P levels with increased P concentration without an equivalent increase in growth of 'Helleri' holly. The aforementioned authors attributed the increased P uptake to luxury consumption.

*Nitrogen:potassium ratio (2005).* Substrate pH and EC, leaf, stem, root, and total dry weights and leaf area were unaffected by the species × N:K interaction (data not presented). Thus, only main effects, averaged over species, are presented. Substrate solution pH was unaffected by N:K ratio, whereas EC increased as N:K ratio decreased (K concentration increased) (Table 2). Total dry weight was representative of the stem and root dry weight response so only total dry weight is presented. Total dry weight increased linearly as K concentration increased to 200 mg·L$^{-1}$ K and N:K ratio decreased to 1:2; however, plants fertilized with a 16:1 N:K (6.25 mg·L$^{-1}$ K) ratio achieved 90% of maximum growth (Fig. 3). Soundy et al. (2001) found that lettuce (*Lactuca sativa* L.) shoot growth was unaffected by K concentrations between 0 and 60 mg·L$^{-1}$ K and Melton and Dufault (1991) reported that tomato (*Lycopersicon esculentum* Mill. *var. esculentum*) growth was unaffected by K concentrations of 25, 75, and 225 mg·L$^{-1}$. Thus, it may be possible to produce adequate growth with dramatically reduced N:K ratio and K concentrations.

Foliar K (Fig. 3), S, and Fe (data not presented) concentrations of hibiscus increased with decreasing N:K ratio (increasing K concentration), whereas foliar Ca, Mg, and B concentrations of hibiscus decreased linearly with decreasing N:K ratio (increasing K concentration) (data not presented). Calcium and Mg were not provided by fertigation and were only supplied by initially amending the substrate with dolomitic lime. Thus, as plant growth increased, uptake of Ca and Mg did not increase proportionally. There was a quadratic response in foliar P concentration with maximum foliar P concentration attained with 25 mg·L$^{-1}$ K and

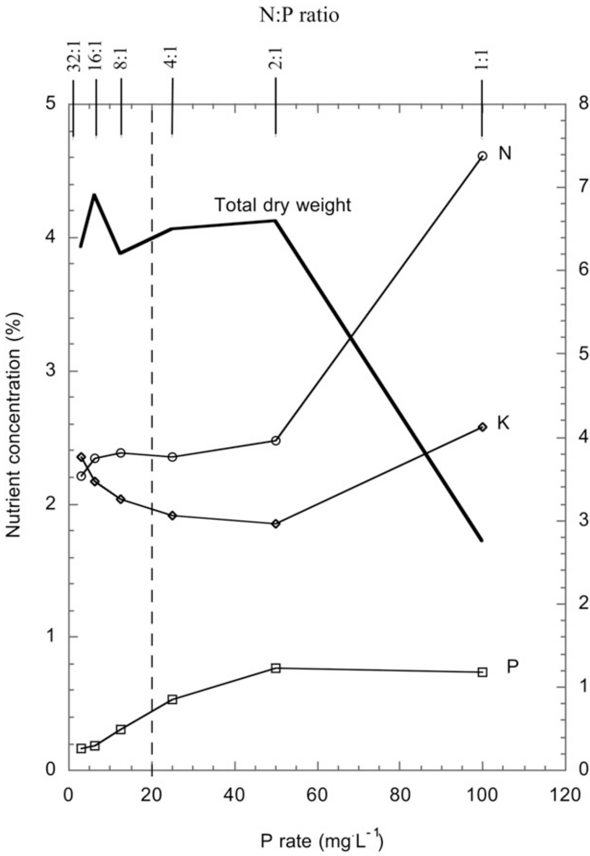

Fig. 1. Effects of phosphorus (P) concentration and nitrogen (N):P ratio on nutrient concentration and total plant dry weight of 'Luna Blush' hibiscus (2005). N and potassium (K) concentrations held constant at 100 mg·L$^{-1}$ and 50 mg·L$^{-1}$, respectively. Vertical dashed line represents the calculated P concentration required to achieve maximum growth. Data are means of six observations.

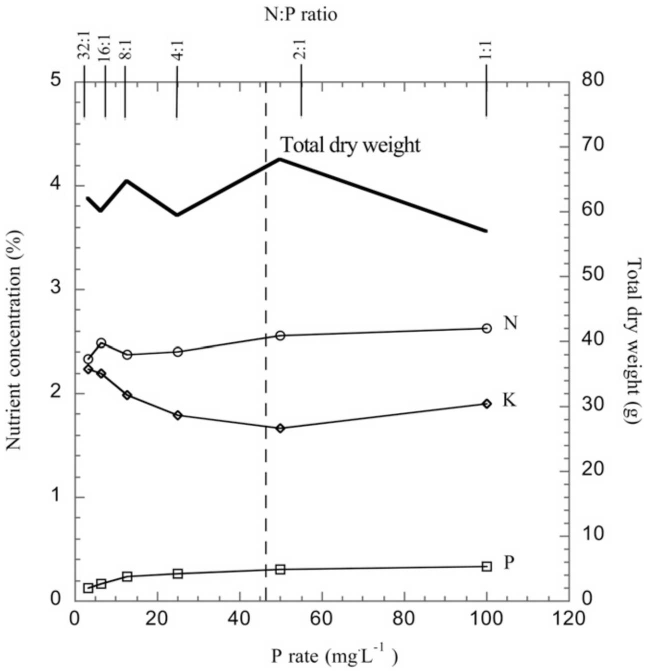

Fig. 2. Effects of phosphorus (P) concentration and nitrogen (N):P ratio on nutrient concentration and total plant dry weight of 'Goldsturm' rudbeckia (2005). N and potassium (K) concentrations held constant at 100 mg·L$^{-1}$ and 50 mg·L$^{-1}$, respectively. Vertical dashed line represents the calculated P concentration required to achieve maximum growth. Total dry weight of rudbeckia unaffected by P concentration. Data are means of six observations.

a 4:1 N:K ratio (Fig. 3). Foliar N (Fig. 3), Zn, and Cu concentrations were unaffected by N:K ratio (data not presented). Based on foliar nutrient concentration and growth, a 4:1 N:K ratio with 100 mg·L$^{-1}$ N and 25 mg·L$^{-1}$ K and 2.4% N, 0.4% P, and 2.4% K provided maximum growth of hibiscus.

Similar to hibiscus, foliar K (Fig. 3) and S (data not presented) concentrations of rudbeckia increased with decreasing N:K ratio (increasing K concentration), whereas foliar P, Ca, Mg, Zn, and Cu concentrations decreased with decreasing N:K ratio (increasing K concentration), and foliar N, Fe, and B (Fig. 3) concentrations were unaffected by N:K ratio. Yeager and Wright (1982) reported interactions between cationic micronutrients (Fe, Zn, and Mn) and P concentration. No such micronutrient accumulation reductions were found in our research (data not presented). Maximum growth of rudbeckia was achieved with foliar nutrient concentrations of 2.4% N, 0.2% P, and 3.2% K (Fig. 3).

*Nitrogen:phosphorus:potassium ratio with nitrogen held constant (2006).* Substrate pH and EC were unaffected by the species × nutrient ratio interaction; thus, data are averaged over species. Substrate pH remained constant, whereas EC increased as N:P:K ratio decreased (P and K concentrations increased) (Table 2). Root, flower bud, and total dry weights were significantly affected by the species × nutrient ratio interaction so data were reanalyzed by species (data not presented). In contrast, number of flower buds, leaf dry weight, and leaf area were unaffected by the species × ratio interaction so only main effects of species and ratio are presented. Number of flower buds, leaf dry weight, and leaf area increased linearly with decreasing N:P:K ratio (increasing P and K concentrations) to a maximum at a ratio of 2:1:2 (data not presented). However, for all three parameters, there appeared to be a maximum threshold between 8:1:2 and 12:1:2 as number of flowers, leaf dry weight, and leaf area only decreased 7%, 4% and 7%, respectively, from the maximum at 2:1:2 to 8:1:2, whereas number of flowers, leaf dry weight, and leaf area when grown with 12:1:2 decreased 27%, 14%, and 39%, respectively, from the maximum at 2:1:2. The N, P, and K concentrations at 8:1:2 (100 mg·L$^{-1}$ N, 12.5 mg·L$^{-1}$ P, and 25 mg·L$^{-1}$ K) are similar to those recommended by Wright and Niemiera (1985) for production of 'Helleri' holly. In 2005, a similar N:K ratio maximized growth; however, much higher ratios of N:P (16:1 N:P for hibiscus and 32:1 N:P for rudbeckia) resulted in greater growth.

Total dry weight of each species accurately reflected root, stem, and flower bud dry weights so only total dry weight is presented. Total dry weight of hibiscus and rudbeckia increased linearly as N:P:K ratio decreased (increasing P and K concentrations) (Figs. 4 and 5).

However, similar to flower bud number and leaf area, total dry weights of hibiscus and rudbeckia were not reduced to less than 90% of maximum until the N:P:K solution ratio increased to 12:1:2 (8 mg·L$^{-1}$ P, 16 mg·L$^{-1}$ K). When 12:1:2 and 24:1:2 ratios were removed

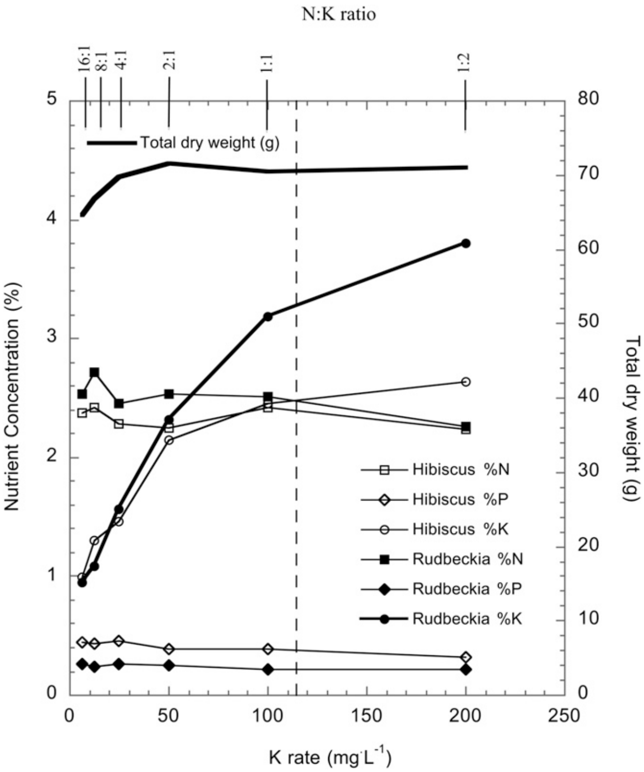

Fig. 3. Effects of potassium (K) concentration and nitrogen (N):K ratio on nutrient concentration and total plant dry weight of 'Luna Blush' hibiscus and 'Goldsturm' rudbeckia (2005). N and phosphorus (P) concentrations held constant at 100 mg·L$^{-1}$ and 25 mg·L$^{-1}$, respectively. Vertical dashed line represents the calculated K concentration required to achieve maximum growth. Nonsignificant N:K ratio × species interaction for dry weight. Data are means of six observations.

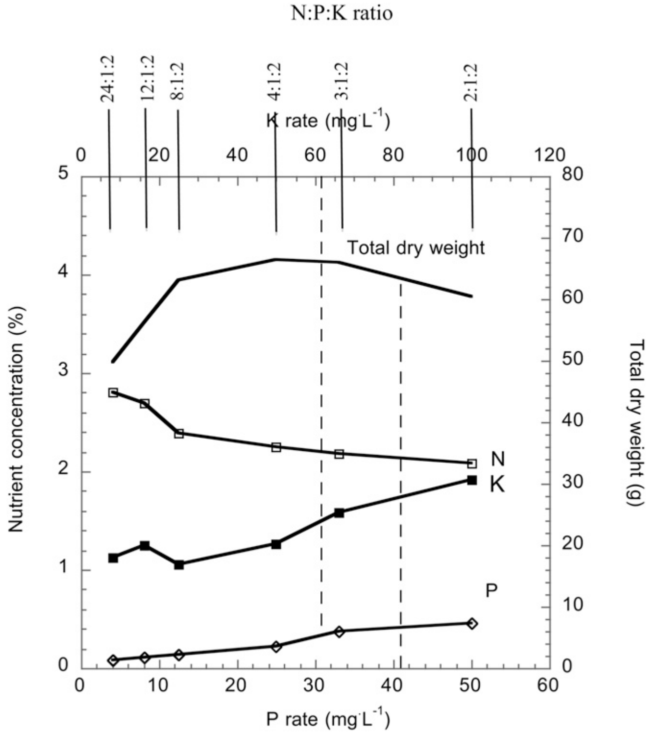

Fig. 4. Effects of phosphorus (P) and potassium (K) concentrations and nitrogen (N):P:K ratio on total plant dry weight of 'Luna White' hibiscus (2006). N concentration held constant at 100 mg·L$^{-1}$. Vertical dashed lines represents the calculated P and K concentrations required to achieve maximum growth. Data are means of six observations.

from the analysis, total dry weights of both species were unaffected by nutrient ratio indicating similar growth was obtained with nutrient ratios ranging from 2:1:2 to 8:1:2. Other studies have reported that low concentrations of K were adequate to support plant growth. Melton and Dufault (1991) reported growth of tomato transplants was unaffected by K concentration (25, 75, or 225 mg·L$^{-1}$ K) but required relatively high concentrations of N and P (225 and 45 mg·L$^{-1}$ N and P, respectively) in a 9:1.8:1 N:P:K ratio. Rodriguez et al. (2002) reported a ratio of 1:0:0.8 or 1:0:1.7 N:P:K was sufficient to support bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy] during establishment (root growth) and ratios higher than 1:0:0.8 N:P:K decreased shoot growth.

Foliar N concentration for both species decreased linearly with decreasing N:P:K ratio (increasing P and K concentrations) (Figs. 4 and 5), possibly as a result of dilution because the N concentration was constant and growth increased with increasing P and K concentrations. In contrast, foliar P, K, and S (data not presented) concentrations increased linearly with decreasing N:P:K ratio (increasing P and K) for both hibiscus and rudbeckia (Figs. 4 and 5). Foliar Ca (mean, 1.7% and 2.3% for hibiscus and rudbeckia, respectively) and Mg (mean, 0.8% and 0.8% for hibiscus and rudbeckia, respectively) concentrations were not impacted by N:P:K ratio (data now presented). Foliar nutrient concentrations of 2.2% N, 0.4% P, and 1.4% K were required for maximum growth of hibiscus (Fig. 4), whereas nutrient concentrations of 2.2% N, 0.2% P, and 1.8% K were needed for maximum growth of rudbeckia (Fig. 5). Mills and Jones (1996) reported slightly lower foliar N (2.0%) and slightly higher foliar N (2.4%) and foliar P (0.4%, 0.4%) and higher foliar K (2.9%, 2.1%) concentrations for *Hibiscus coccineus* Walt. and *Rudbeckia fulgida* var. sullivantii 'Goldsturm', respectively. Although similar foliar mineral nutrient concentrations were required to maximize growth of both hibiscus and rudbeckia, rudbeckia required lower P and higher K concentrations in fertilizer solutions because maximum total dry weight of rudbeckia was achieved with 100 mg·L$^{-1}$ N, 36 mg·L$^{-1}$ P, and 72 mg·L$^{-1}$ K in a 2.8:1:1.4 N:P:K ratio (Fig. 5), whereas maximum dry weight for hibiscus was obtained with a fertilizer solution containing 100 mg·L$^{-1}$ N, 43 mg·L$^{-1}$ P, and 62 mg·L$^{-1}$ K in a 2.3:1:1.6 N:P:K ratio (Fig. 4).

Based on foliar mineral nutrient concentrations, a 2:1:2 N:P:K ratio was required for nutrient solutions applied to hibiscus and a 3:1:2 N:P:K ratio for rudbeckia. However, growth of both species was similar over a range of N:P:K ratios even as high as 8:1:2. Therefore, optimum growth of both species may occur with higher N:P:K ratios and lower P and K concentrations if an appropriate N concentration is also determined. Both Harvey et al. (2004) and Soundy et al. (2001) indicated optimum tissue nutrient levels should be evaluated over a range of fertilizer treatments. Data here have been produced with a fixed N concentration of 100 mg·L$^{-1}$; therefore, our last experiment consisted of three N concentrations in combination with three N:P:K ratios.

*Nitrogen concentrations and nitrogen: phosphorus:potassium ratios (2007).* Analyses of these data showed a significant species × N concentration × N:P:K ratio interaction so the data were reanalyzed by species. Substrate pH and EC did not vary by species so the data were averaged over species. For all N:P:K ratios, substrate pH decreased slightly and EC increased as N concentration increased (Table 2). For hibiscus, the N concentration × N:P:K ratio interaction was significant for all growth variables measured except number of flower buds (data not presented). The highest N concentration (200 mg·L$^{-1}$) resulted in the greatest number of flower buds, whereas number of flower buds was unaffected by N:P:K ratio (data not presented).

Similar to our previous studies, total dry weight accurately reflected all dry weight responses. Within each N:P:K ratio, total dry weight of hibiscus increased with increasing N concentration (Table 3). Within 50 mg·L$^{-1}$ N,

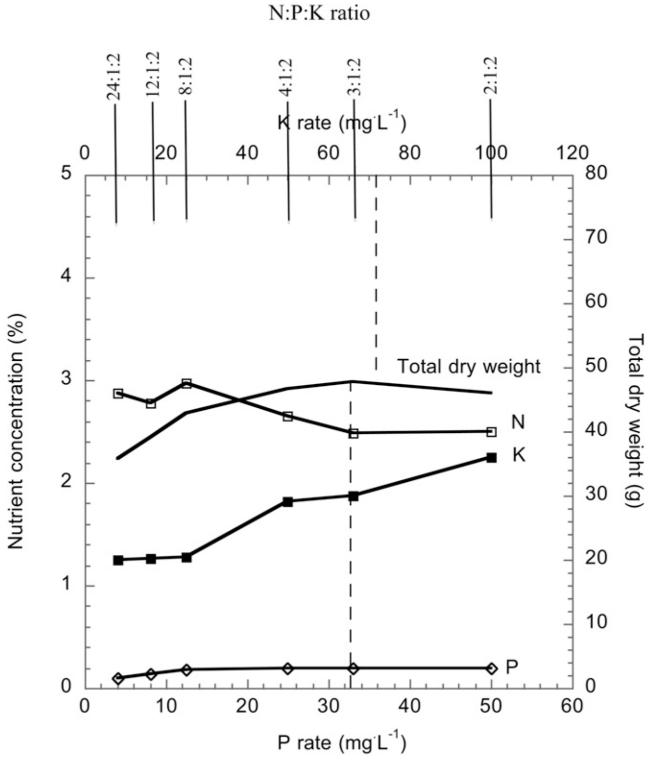

Fig. 5. Effects of phosphorus (P) and potassium (K) concentrations and nitrogen (N):P:K ratio on total plant dry weight of 'Goldsturm' rudbeckia (2006). N concentration held constant at 100 mg·L$^{-1}$. Vertical dashed lines represents the calculated P and K concentrations required to achieve maximum growth. Data are means of six observations.

Table 3. Effect of N:P:K ratio within each N concentration and N concentration within each N:P:K ratio on growth and foliar N concentration of 'Luna Red' hibiscus (2007).$^{z}$

| N:P:K ratios within N concn | Total dry wt (g) | N (%) | N concn within N:P:K ratio | Total dry wt (g) | N (%) |
|---|---|---|---|---|---|
| 50 (mg·L$^{-1}$) | | | 4:1:2 | | |
| 4:1:2 | 19.2*$^{y}$ | 2.6 | 50 | 19.2* | 2.6* |
| 8:1:2 | 25.9 ** | 2.5 | 100 | 36.6** | 2.8* |
| 12:1:2 | 27.1 ** | 2.5 | 200 | 57.5*** | 3.9** |
| ANOVA$^{x}$ | 0.002 | NS | | 0.0001 | 0.0001 |
| 100 (mg·L$^{-1}$) | | | 8:1:2 | | |
| 4:1:2 | 36.3* | 2.8** | 50 | 25.9* | 2.5* |
| 8:1:2 | 41.1** | 3.1* | 100 | 41.1** | 3.1** |
| 12:1:2 | 35.1* | 3.4* | 200 | 53.9*** | 3.9*** |
| ANOVA | 0.008 | 0.006 | | 0.0001 | 0.0001 |
| 200 (mg·L$^{-1}$) | | | 12:1:2 | | |
| 4:1:2 | 57.5* | 3.9* | 50 | 27.1* | 2.5* |
| 8:1:2 | 53.9* | 3.9* | 100 | 35.1** | 3.4** |
| 12:1:2 | 48.5** | 4.4** | 200 | 48.5*** | 4.4*** |
| ANOVA | 0.02 | 0.01 | | 0.0001 | 0.0001 |

$^{z}$Significant nutrient ratio × N concentration.

$^{y}$Data are means of six observations. Means followed by a different number of asterisks within a column are significantly different from each other based on single df linear contrasts.

$^{x}$Analysis of variance. NS (non-significant) at $P \leq 0.05$. $P$ value given otherwise.

N = nitrogen; P = phosphorus; K = potassium.

total dry weight of hibiscus was greatest when grown with 8:1:2 or 12:1:2, whereas total dry weight produced with 100 mg·L$^{-1}$ N was greatest with 8:1:2. When produced with 200 mg·L$^{-1}$ N, total dry weight was greatest with 4:1:2 and 8:1:2. Thus, at all three N concentrations, an 8:1:2 N:P:K ratio maximized growth. These data reinforce the hypothesis proposed by Harvey et al. (2004) and Soundy et al. (2001) that plant responses should be evaluated under a range of N concentrations.

The N concentration × N:P:K ratio interaction was significant for foliar N concentration of hibiscus (Table 3) but was nonsignificant for foliar P, K, Ca, Mg, and S concentrations (data not presented). At 50 mg·L$^{-1}$ N, foliar N concentration was unaffected by N:P:K ratio, whereas at 100 mg·L$^{-1}$ N, foliar N concentration was greatest with 8:1:2 and 12:1:2 and at 200 mg·L$^{-1}$, N foliar N was greatest with 12:1:2 (Table 3). In contrast, within each N:P:K ratio, foliar N concentration increased as N concentration increased to 200 mg·L$^{-1}$.

Foliar P concentration was unaffected by N concentration, whereas foliar P concentration decreased as the N:P:K ratio increased from 4:1:2 to 8:1:2 (Table 4). As growth was maximized at a ratio of 8:1:2, the elevated foliar P concentration at 4:1:2 may be indicating luxury consumption. As N concentration increased in the nutrient solution, foliar K, Ca, and Mg concentrations decreased most likely as a result of a dilution effect because plants were also larger with higher N concentrations. Similarly, Dubois et al. (2000) working with *Anemone ×hybrida* Paxton 'Margarete' (fall blooming anemone) reported foliar concentrations of K decreased linearly with increasing N concentration; however, in contrast to data here, foliar P increased to a plateau at 150 mg·L$^{-1}$ N in the fertilizer solution. Wright and Niemiera (1985) reported that 'Helleri' holly required higher N when P concentration in the fertilizer solution was greater than 40 mg·L$^{-1}$. In our N:P study (2005), hibiscus grew best with 50 mg·L$^{-1}$ P and a 2:1 N:P ratio.

Table 4. Effect of N concentration and N:P:K ratio on foliar mineral nutrient concentration of 'Luna Red' hibiscus (2007).[z]

| N concn (mg·L$^{-1}$) | P (%) | K (%) | Ca (%) | Mg (%) | S (%) |
|---|---|---|---|---|---|
| 50 | 0.3 | 1.4*[y] | 1.8* | 0.9* | 0.3* |
| 100 | 0.3 | 1.2** | 1.6** | 0.8* | 0.2** |
| 200 | 0.3 | 1.0** | 1.4*** | 0.7** | 0.3* |
| ANOVA[x] | NS | 0.0001 | 0.0001 | 0.0001 | 0.003 |
| N:P:K ratio | | | | | |
| 4:1:2 | 0.4* | 1.4* | 1.7 | 0.8 | 0.29* |
| 8:1:2 | 0.2** | 1.1** | 1.6 | 0.8 | 0.25** |
| 12:1:2 | 0.2** | 1.1** | 1.6 | 0.8 | 0.25** |
| ANOVA[x] | 0.0001 | 0.0009 | NS | NS | 0.002 |

[z] NS nutrient ratio × N concentration.

[y] Data are means of 12 observations. Means followed by a different number of asterisks within a column are significantly different from each other based on single df linear contrasts.

[x] Analysis of variance. NS (non-significant) at $P \leq 0.05$. $P$ value given otherwise.

N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; S = sulfur.

Similar to foliar P concentration, foliar concentrations of K were significantly higher when grown with the 4:1:2 ratio compared with 8:1:2 and 12:1:2. Because plants were largest with 200 mg·L$^{-1}$ N and the 8:1:2 ratio, the higher foliar P and K with the 4:1:2 ratio could be luxury consumption. Additionally, 200 mg·L$^{-1}$ N and 12:1:2 did not result in greater foliar P or K even with higher P (16.7 mg·L$^{-1}$ P) and K (33.3 mg·L$^{-1}$ K) in the fertilizer solution.

In contrast to hibiscus, the N concentration × N:P:K ratio interaction was nonsignificant for all measured parameters of rudbeckia (data not presented). Total dry weight of rudbeckia increased from 50 to 200 mg·L$^{-1}$ N, whereas total dry weight was unaffected by N:P:K (Table 5) indicating P and K were probably not limiting growth even at a ratio of 12:1:2.

Foliar N and P concentrations of rudbeckia increased as N concentration increased, whereas foliar Ca and Mg concentration decreased as N concentration increased from 100 to 200 mg·L$^{-1}$ (Table 6). Foliar K and S were unaffected by N concentration. Nutrient ratio affected foliar P and K concentration, which decreased as N:P:K ratio increased from 4:1:2 to 8:1:2 most likely as a result of decreasing concentration in the fertilizer solution. Rudbeckia responded similarly to hibiscus in that larger plants with higher foliar N were grown with higher N concentrations (200 mg·L$^{-1}$); however, foliar P in hibiscus and K in rudbeckia were unaffected by N concentration, whereas foliar P in rudbeckia increased and K in hibiscus decreased as N concentration increased.

Table 5. Effect of N concentration and N:P:K ratio on total dry weight of 'Goldstrum' rudbeckia (2007).[z]

| N concn (mg·L$^{-1}$) | Total dry wt (g) | N:P:K ratio | Total dry wt (g) |
|---|---|---|---|
| 50 | 25.3*[y] | 4:1:2 | 33.3 |
| 100 | 34.2** | 8:1:2 | 34.2 |
| 200 | 42.5*** | 12:1:2 | 34.4 |
| ANOVA[x] | 0.0001 | | NS |

[z] NS nutrient ratio × N concentration.

[y] Data are means of 12 observations. Means followed by a different number of asterisks within a column are significantly different from each other based on single df linear contrasts.

[x] Analysis of variance. NS (non-significant) at $P \leq 0.05$. $P$ value given otherwise.

N = nitrogen; P = phosphorus; K = potassium.

Based on data here, hibiscus growth can be maximized with 200 mg·L$^{-1}$ N and an 8:1:2 ratio, whereas rudbeckia grew best with 200 mg·L$^{-1}$ N and either an 8:1:2 or 12:1:2 N:P:K ratio. Both species required surprisingly high levels of P (25 mg·L$^{-1}$ P) and K (50 mg·L$^{-1}$ K) in fertilizer solutions when N concentration was also high. In concurrence with Scoggins (2005), plants in this study were larger with the highest concentrations of N (200 mg·L$^{-1}$) but hibiscus and rudbeckia were of acceptable visual quality although smaller with 100 mg·L$^{-1}$ N (personal observation). Additionally, hibiscus and rudbeckia grown with 100 mg·L$^{-1}$ N and an 8:1:2 N:P:K ratio had foliar N, P, and K concentrations similar to levels found with the optimal treatments in our experiments conducted in 2005 and 2006. Data here support Harvey et al. (2004) and Soundy et al. (2001) who recommended that fertilizer recommendations be developed based on evaluations of growth over a range of nutrient concentrations and ratios. Additionally, maximum growth may not always be a practical goal in production when shipping, environmental impacts, and fertilizer costs are considered against higher fertilizer concentration applications. Although plants grown with 200 mg·L$^{-1}$ N were larger and had more flower buds (hibiscus), they would have been more difficult to ship without breakage.

Similar results were reported by Adam and Sluzis (2005) who evaluated a variety of species of herbaceous perennials with increasing N concentration. These authors reported 136 mg·L$^{-1}$ N and foliar N levels of 2.1% N for hibiscus and 3.25% N for rudbeckia were sufficient for producing satisfactory growth and reported that luxury consumption was prevalent with many species. Adam and Sluzis (2005) advocated targeting fertilizer levels to attain 85% to 95% of maximum growth to avoid luxury consumption, reduce fertilizer waste and cost, and protect water quality. The optimal foliar N concentrations for hibiscus and rudbeckia reported by Adam and Sluzis (2005) are also similar to the foliar N concentration reported here for 100 mg·L$^{-1}$ N and the 8:1:2 N:P:K ratio.

In summary, when N was held constant at 100 mg·L$^{-1}$, 4:1 N:K (25 mg·L$^{-1}$ K) and 16:1

Table 6. Effect of N concentration and N:P:K ratio on foliar mineral nutrient concentration of 'Goldsturm' rudbeckia (2007).[z]

| N concn (mg·L$^{-1}$) | N (%) | P (%) | K (%) | Ca (%) | Mg (%) | S (%) |
|---|---|---|---|---|---|---|
| 50 | 2.29*[y] | 0.20* | 1.66 | 2.35* | 0.84* | 0.54 |
| 100 | 2.93** | 0.23* | 1.57 | 2.19* | 0.85* | 0.53 |
| 200 | 4.09*** | 0.30** | 1.65 | 1.87** | 0.75** | 0.62 |
| ANOVA[x] | 0.0001 | 0.0001 | NS | 0.0001 | 0.007 | NS |
| N:P:K ratio | | | | | | |
| 4:1:2 | 2.97 | 0.29* | 1.98* | 2.07 | 0.77 | 0.67* |
| 8:1:2 | 3.17 | 0.23** | 1.43** | 2.23 | 0.83 | 0.55** |
| 12:1:2 | 3.18 | 0.21** | 1.46** | 2.11 | 0.84 | 0.47*** |
| ANOVA | NS | 0.002 | 0.0001 | NS | NS | 0.0001 |

[z] NS nutrient ratio × N concentration.

[y] Data are means of 12 observations. Means followed by a different number of asterisks within a column are significantly different from each other based on single df linear contrasts.

[x] Analysis of variance. NS (non-significant) at $P \leq 0.05$. $P$ value given otherwise.

N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; S = sulfur.

N:P (6.3 mg·L$^{-1}$ P) were best for growing hibiscus, whereas higher K concentrations (1:2 N:K, 200 mg·L$^{-1}$ K) and lower P concentrations (32:1 N:P, 3.1 mg·L$^{-1}$ N) were required for growth of rudbeckia. However, when holding N constant at 100 mg·L$^{-1}$ N and varying both P and K in the fertilizer solutions, higher P and K concentrations and a 2:1:2 (50 mg·L$^{-1}$ P, 100 mg·L$^{-1}$) N:P:K ratio best supported hibiscus growth, whereas 3:1:2 (33 mg·L$^{-1}$ P, 66 mg·L$^{-1}$ K) N:P:K was needed for growth of rudbeckia. Finally, when both N concentration and N:P:K ratio were altered, optimum growth of both hibiscus and rudbeckia was achieved at lower and similar P and K concentrations (25 mg·L$^{-1}$ P and 50 mg·L$^{-1}$ K) and 200 mg·L$^{-1}$ N. An 8:1:2 N:P:K ratio was optimum for production of both hibiscus and rudbeckia, although 12:1:2 N:P:K (200 mg·L$^{-1}$ N, 17 mg·L$^{-1}$ P, 33 mg·L$^{-1}$ K) produced similar growth of rudbeckia. These two herbaceous perennials have N requirements similar to annual herbaceous plants and P and K requirements similar to woody perennial plants. Furthermore, our data indicate a higher ratio of N:P:K may be sufficient for herbaceous perennials compared with the current recommendations for annual or woody plants. Foliar concentrations of 2.2% N, 0.4% P, and 1.9% K should be sufficient for growth of hibiscus, whereas 2.4% N, 0.2% P, and 2.6% K are required to maximize growth of rudbeckia.

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