Nutrient Solution Concentration Affects Shoot : Root Ratio, Leaf Area Ratio, and Growth of Subirrigated Salvia (Salvia splendens)

Jong-Goo Kang
Department of Horticulture, Sunchon National University, 315 Meagok-dong, Sunchon, Chonnam, 540-742, South Korea

Marc W. van Iersel
Department of Horticulture, Plant Science Building, The University of Georgia, Athens, GA 30602-7273

Abstract. To evaluate the effects of nutrient concentration and pH of the fertilizer solution on growth and nutrient uptake of salvia (Salvia splendens F. Sellow ex Roem. & Schult. ‘Scarlet Sage’), we grew plants with five different concentrations of Hoagland nutrient solution [0.125, 0.25, 0.5, 1.0, and 2.0× full strength; electrical conductivity (EC) of 0.4, 0.7, 1.1, 2.0, and 3.7 dS·m⁻¹, respectively]. In a concurrent experiment, plants were subirrigated with modified Hoagland solution at 0.5x concentration and one of five solution pH values: 4.4, 5.4, 6.4, 7.2, and 8.0. Shoot and total dry weight and leaf area increased greatly with increasing nutrient solution concentrations from 0.125 to 1.0x, while leaf photosynthesis (Pn), transpiration, and stomatal conductance decreased with increasing nutrient solution concentrations. Treatment effects on growth apparently were caused by changes in carbon allocation within the plants. Shoot : root ratio and leaf area ratio increased with increasing fertilizer concentration. Plants flowered 8 days later at low concentrations of nutrient solution than at high concentrations. Shoot tissue concentrations of N, P, K, and B increased, while C, Al, Mo, and Na decreased with increasing concentration of the nutrient solution. The pH of the nutrient solution had no effect on the growth or gas exchange of the plants, while its effects on nutrient concentration in the shoot tissue generally were smaller than those of fertilizer concentration. These results indicate that 1.0 to 2.0x concentrations of Hoagland solution result in maximum growth, apparently because the plants produce leaf area more efficiently at high fertilizer concentrations.

Fertility probably is the most controllable cultural factor affecting the growth of greenhouse crops. Most greenhouse crops are grown in some type of soilless medium, which does not contribute a significant amount of nutrients. Instead, these kinds of media mainly function as substrates that can hold water and nutrients, thus making them available to the roots. An effective fertilization program has to take into account both the concentration of fertilizer to be applied, and its effect on the pH of the growing medium. Thus, fertilizer programs have to take into account both the concentration of fertilizer to be applied, and its effect on the pH of the growing medium.

Although there have been many research reports on optimal fertilizer concentrations for the production of floricultural greenhouse crops (e.g., James and van Iersel, 2001; Kang and van Iersel, 2002; Kent and Reed, 1996; Mak and Yeh, 2001; van Iersel, 1999), most of this research has been descriptive rather than explanatory. Although this research has yielded practical guidelines for the fertilization of greenhouse crops, it may not be universally applicable, since the optimal fertilizer concentration for plant growth may depend on the environmental conditions (Kang and van Iersel, 2001). Thus, to be able to predict fertilizer needs of plants under a range of conditions, it is essential to understand the mechanism by which different fertility treatments affect plant growth.

Photosynthesis is the physiological process responsible for almost all dry matter accumulation in plants (although accumulation of inorganic nutrients can account for up to 15% of dry matter). Therefore, to optimize plant growth, fertilization programs should aim to optimize plant photosynthesis. Whole-plant photosynthesis depends on both the photosynthesis per unit leaf area and the total leaf area of the plant. Although nutrition effects on leaf photosynthesis (Pn) are well understood (e.g. Marschner, 1995; Thornley, 1998; and references therein), nutrition effects on leaf area development have not been studied in as much detail.

The objective of this study was to determine the effects of nutrient solution concentration and pH on growth, Pn, and leaf area development of salvia.

Materials and Methods

Plant material. Salvia ’Scarlet Sage’ was seeded in plug flats (288 cells/flat) filled with soilless growing medium (Redi-Earth; The Scotts Co., Marysville, Ohio). The seeds were germinated in a growth chamber at 20 °C and continuous light. The seedlings were transplanted into cell packs (606 flats, volume 160 mL/cell) filled with an inert growing medium (diatomaceous earth; Isolite CG-2, Sun-dine Enterprises, Arvada, Colo.) at 12 d after seeding. All plants were placed on greenhouse benches in a double-layer polyethylene-covered greenhouse. The temperature set points for the greenhouse were 25 °C day/20 °C night.

Treatments. Two experiments were conducted simultaneously. In the first experiment, plants were subirrigated with different concentrations of modified Hoagland solution (Hoagland and Arnon, 1950), while plants were subirrigated with half-strength nutrient solution with different pH values in the second experiment. In the first experiment, the plants were watered with Hoagland solution at one of five concentrations: 0.125x (EC = 0.4 dS·m⁻¹, pH 6.8), 0.25x (EC = 0.7 dS·m⁻¹, pH 6.6), 0.5x (EC = 1.1 dS·m⁻¹, pH 6.4), 1.0x (EC = 2.0 dS·m⁻¹, pH 6.0) and 2.0x full strength (EC = 3.7 dS·m⁻¹, pH 5.3). These solutions contained 26, 52, 105, 210, and 420 mg·L⁻¹ N, respectively (6.7% NH₄⁺ and 93.3% NO₃⁻).

In the second experiment, the plants were watered with modified Hoagland solution at 0.5x concentration and one of five pH values: 4.4, 5.4, 6.4, 7.2, and 8.0. To make Hoagland solutions with differing pH values, HNO₃ or NH₄OH were used to adjust the pH of the 0.5x nutrient solution. These solutions may have differed slightly in N-content, although the total amount of N added for pH control was small compared to the 105 mg·L⁻¹ present in the 0.5x Hoagland solution.

Irrigation timing was based on a color change of the top layer of the diatomaceous earth, which becomes lighter as it dries out. Approximately every other day, the plants were subirrigated with nutrient solution by pouring 1 L of the solution into a watertight tray, and the solution was absorbed by the growing medium through holes in the bottom of the cell packs. The solution was left in the trays until all of it had been absorbed by the growing medium.

Measurements. Three plants were harvested at weekly intervals starting at 30 d after transplanting (DAT) to determine leaf area, shoot and root dry weight, and chlorophyll content. Shoots and roots were dried in a forced-air drying oven at 70 °C for a minimum of 3 d before dry weight was measured. Leaf area was determined using a LI-COR 3100 leaf area meter (LI-COR, Lincoln, Nebr.). Dry weight and leaf area data were used to determine the shoot : root ratio and the leaf area ratio, both on a whole plant (LARₜot, leaf area divided by total dry weight) and shoot basis (LARₜot,sh).
leaf area divided by shoot dry weight). Chlorophyll content of the leaves was measured with a SPAD-502 chlorophyll meter (Minolta, Ramsey, N.J.), which measures chlorophyll content in arbitrary units (here referred to as SPAD units). Leaf gas exchange parameters (P_\text{n}, stomatal conductance, transpiration, and leaf temperature) were measured with a portable photosynthesis system (CIRAS-1, PP Systems, Haverhill, Mass.) at 37, 48, and 56 DAT. Photosynthetic photon flux density was about 700, 350, and 415 µmol·m^{-2}·s^{-1} on these 3 d, respectively. Time to flowering was determined when 40% of the plants in an experimental unit were flowering, and length of the flower stalk was determined when all florets had opened. The shoots collected at the end of the experiment were analyzed for nutrient content. Tissue C, N, and S were determined with a CNS 2000 analyzer (LECO Corp., St. Joseph, Mich.) (Mills and Jones, 1996), while P, K, Ca, Mg, S, Al, B, Cu, Fe, Mn, Na, and Zn were determined by dry ashing and inductively coupled plasma spectrometry (Jones and Case, 1990).

Experimental design and data analysis. The experimental design for both experiments was a randomized complete block with four replications. The experimental unit was a flat with 36 plants. All data were analyzed by linear and quadratic regression, using Statistical Analysis Software (SAS Institute, Cary, N.C.). Correlations with P < 0.05 were considered to be statistically significant. Treatment effects on the relative growth rate (RGR) of the plants in both experiments were tested by fitting the following equation:

\[
\ln(DW) = a_0 + (a_1 \times \text{DAT}) + (a_2 \times C) + (a_3 \times \text{DAT} \times C) + (a_4 \times \text{DAT}^2 \times C) + (a_5 \times C^2) + (a_6 \times \text{DAT} \times C^2) + (a_7 \times \text{DAT}^2 \times C^2) + (a_8 \times \text{DAT} \times C) + (a_9 \times \text{DAT}^2) \quad \text{[Eq. 1]}
\]

where DW = plant dry weight; a_0, . . . , a_9 = regression coefficients; and C = concentration of the fertilizer solution. These regression coefficients have no implicit physiological meaning, and the equation was chosen simply because it resulted in a good description of the data. Hunt (1982) showed that RGR can be calculated as the first derivative with respect to time (DAT) of any function describing \(\ln(DW)\), so in this case:

\[
\text{RGR} = a_1 + (a_2 \times C) + (2 \times a_3 \times \text{DAT}) + (2 \times a_4 \times \text{DAT} \times C) + (a_5 \times C^2) + (2 \times a_6 \times \text{DAT} \times C^2) \quad \text{[Eq. 2]}
\]

These equations then were simplified by eliminating nonsignificant parameters using backward selection.

**Results and Discussion**

**Fertilizer concentrations and growth.** Regression analysis indicated a significant quadratic effect of nutrient solution concentration on salvia root dry weight at 44 and 51 DAT, while nutrient solution concentration had no effect on root dry weight at any other time (Fig. 1). Throughout the experiment, similar trends were seen in shoot and total dry weight. Shoot and total dry weight generally increased with increasing nutrient solution concentrations from 0.125 to 1.0×; however, there was little or no additional increase in dry weight from 1.0 to 2.0× concentrations (Fig. 1). The optimal fertilizer solution concentration of 1.0 to 2.0× correspond to N concentrations of 210 to 420 mg·L^{-1}. This is similar to the optimal N concentrations for subirrigated alypressum (\textit{Lobularia maritima} (L.) Desv., 210 mg·L^{-1}), \textit{dianthus} (\textit{Dianthus chinensis} L., 210 mg·L^{-1}), \textit{gompohrea} (\textit{Gomphrena globosa} L., 210–420 mg·L^{-1}), \textit{stock} (\textit{ Matthiola incana} (L.) R. Br., 210–20 mg·L^{-1}) (Kang and van Iersel, 2002), and pansy (\textit{Viola xwittrockiana} Gam., 164–256 mg·L^{-1}; van Iersel, 1999), but higher than that for New Guinea impatiens (\textit{Impatiens hawkeri} Bull.; 112 mg·L^{-1}; Kent and Reed, 1996), peace lily (\textit{Spathiphyllum} Schott.; 112–140 mg·L^{-1}; Kent and Reed, 1996, Mak and Yeh, 2001), and zinnia (\textit{Zinnia elegans} Jacq., 105 mg·L^{-1}; Kang and van Iersel, 2002). The results of this study suggest that salvia prefers relatively high fertilizer levels, but N concentrations >210 mg·L^{-1} do not further increase plant growth.

**Fertilizer concentrations in subirrigation systems.** Generally, it should be lower than in overhead irrigation systems (Elliott, 1990; Kent and Reed, 1996; Klock-Moore and Broschat, 1999), so higher N concentrations may be beneficial for salvia growth when overhead irrigation is used.

Chlorophyll content of the leaves increased with increasing nutrient solution concentrations from 0.125 to 1.0×, while there was little or no further increase from 1.0 to 2.0× concentrations in stomatal conductance with increasing fertilizer concentration (Fig. 2). The decrease in stomatal conductance and transpiration decreased with increasing fertilizer concentration (results not shown). Low fertilizer concentrations generally decrease chlorophyll content (Kang and van Iersel, 2002; Mak and Yeh, 2001), presumably due to lower nitrogen levels in the leaves.

Low chlorophyll concentrations in the leaves did not result in low P_\text{n}. There were no statistical differences on P_\text{n}, stomatal conductance, or transpiration at 37 DAT, but at 48 and 56 DAT, photosynthesis, stomatal conductance, and transpiration decreased with increasing fertilizer concentration (Fig. 2). The decrease in stomatal conductance with increasing fertilizer concentrations explains the decrease in transpiration. This in turn likely resulted in less overall photosynthesis.
evaporative cooling of the leaves and therefore higher leaf temperatures (Fig. 2).

The decrease in Pn and stomatal conductance with increasing fertilizer concentration was unexpected, because of the concurrent increase in dry weight. However, Mak and Yeh (2001) reported that the stomatal conductance of peace lily decreased gradually with increasing N above 56 mg·L−1, while dry weight was highest with N concentrations of 112 mg·L−1. These findings are consistent with the long-standing observation that there often is a poor correlation between Pn and crop yield (Elmore, 1980; Evans, 1975).

There are several factors which may contribute to this apparent paradox: the section of leaf that was measured may not have been representative for the entire canopy; there were both diurnal and seasonal changes in Pn; the respiratory CO2 flux from roots and stems were not measured (van Iersel and Bugbee, 2000); and, probably most importantly, differences in leaf area among treatments were not accounted for. Light interception probably is the most important factor determining plant growth, and light interception in turn depends on leaf area (Lawlor, 1995). Thus, treatment effects on leaf area development may be more important than effects on Pn. Generally, treatment effects on leaf area were similar to those on shoot or total dry weight and maximum leaf area generally was obtained when plants were fertilized with 1.0 to 2.0x concentrations of Hoagland solution (Fig. 3). However, the treatments greatly affected the shoot: root ratio (Fig. 3), indicating that partitioning in the plants was affected by the fertilizer concentrations. Shoot: root ratio increased with increasing fertilizer concentrations, and approximately doubled from 30 to 58 DAT. An increase in shoot: root ratio with increasing fertilizer concentration is common (Mak and Yeh, 2001; Sattelmacher et al., 1990; van Iersel and Kang, 2002). Since plants at higher fertilizer concentrations allocated a larger fraction of carbohydrates to shoot growth than those at lower concentrations, plants at high fertilizer concentration were able to produce more leaf area. This also is evident from the increase in LARplant with increasing fertilizer concentrations (up to 1x strength) (Fig. 3). Since LARplant indicates how much leaf area a plant produces per gram of dry matter, a high LARplant indicates that a plant is efficient at producing leaf area. Since leaf area determines light interception, which in turn is an important parameter affecting plant growth, a high LARplant would be expected to result in a high growth rate. Van Iersel and Kang (2002) did indeed report that fertilizer effects on growth of subirrigated pansy were closely correlated to effects on LARplant while Veneklaas et al. (2002) found that differences in growth among several woody species were related to the LAR of these species. Similarly, Nagel and Griffin (2001) found that species which produce leaf area in an energy-efficient way (i.e., use relatively little glucose) may have a competitive advantage over less efficient species.

In this experiment, treatment effects on LARplant were caused by effects on both the shoot: root ratio and LARshoot:

\[
\text{LAR}_{\text{plant}} = -29.6 + (7.65 \times \text{shoot: root ratio}) + (0.773 \times \text{LAR}_{\text{shoot}}), R^2 = 0.96, \]

based on all leaf area and dry weight data collected throughout this experiment. This is consistent with our previous findings concerning fertilizer effects on pansy (van Iersel and Kang, 2002). Fertilizer concentration may have affected LARshoot through its effect on nitrogen concentration in the shoot tissue. Leaf expansion is strongly affected by nitrogen nutrition (Radin and Boyer, 1982), and we did indeed find a close correlation between the shoot nitrogen concentration and both leaf area (r = 0.92) and LARshoot (r = 0.88) at the end of the experiment.

Changes in dry weight over time and in response to the fertilizer concentrations could be modeled accurately with Eq. 1 (R² = 0.93). There were no significant interactive effects of time and fertilizer concentration on dry weight (regression coefficients a3, a6, a7, and a8 were not statistically significant). Thus, the analysis did not indicate an effect of the fertilizer treatments on RGR (Eq. 2), which decreased throughout the experiment

\[
\text{RGR} = 0.212 - (0.0028 \times \text{DAT}) \]

Based on this analysis, the estimated RGR decreased from 0.128 d−¹ at 30 DAT to 0.050 d−¹ at 58 DAT. Previous research showed a similar linear decrease in RGR of salvia throughout the growing period (van Iersel, 1997) and this decrease in RGR is typical for plants (Kvét et al., 1971). Since RGR = LARplant × net assimilation ratio (NAR, the dry matter produced per unit leaf area per day, Kvét et al., 1971), and LAR generally increased with increasing fertilizer concentrations, this indicates that NAR decreased with increasing fertilizer concentrations. This is not
CROP PRODUCTION

surprising, since NAR decreases as intra- and interplant competition for light increases, and both types of competition increase as plants get larger (Květ et al., 1971).

Although we did not find statistically significant treatment effects on RGR, there must have been differences among treatments at some stage during the growing period, because the final dry weight of the plants differed, while the initial size of the seedlings was identical in all treatments. Thus, differences in RGR either occurred before the start of the destructive measurements (30 DAT), or treatment effects were too small to be detected using Eqs. 1 and 2. During early growth, competition for light is limited and any differences in NAR likely were small. Since the LAR data (Fig. 3) suggest that differences in \( \text{LAR}_{\text{plant}} \) started early in the experiment, early differences in \( \text{LAR}_{\text{plant}} \) may have resulted in differences in RGR as well.

Plants flowered later at low concentrations of nutrient solution than at high concentrations (Fig. 4). This delay in flowering was especially pronounced as fertilizer concentrations were decreased from 0.5 to 0.125×. The length of the flower stalk increased with increasing nutrient solution concentration from 0.125 to 1.0×, then decreased again in the 2.0× concentration (Fig. 4). Kang and van Iersel (2001) reported that fertilizer effects on the flower diameter of petunia were temperature dependent; at 35 °C day/27 °C night temperatures, flower diameter decreased with increasing EC of the fertilizer solution, while no effect was seen at

![Fig. 3. The effects of nutrient solution concentration on leaf area, shoot : root ratio, and leaf area ratio (LAR) of salvia. The plants were subirrigated with 0.125, 0.25, 0.5, 1.0 or 2.0 × full strength of Hoagland solution as needed. Data were collected at 30 (●), 37 (○), 44 (■), 51 (▲), and 58 (▲) d after transplanting. Lines indicates linear or quadratic significance within a sampling date; \( P \leq 0.05 \).](image)

![Fig. 4. The effects of nutrient solution concentration on time to flowering and flower length of salvia. The plants were subirrigated with 0.125, 0.25, 0.5, 1.0, or 2.0 × full strength of Hoagland solution as needed. Data collected at harvesting time (58 d after transplanting). Lines indicate significant quadratic effects; \( P \leq 0.05 \).](image)
lower temperatures. Devitt and Morris (1987) found that maximum flower diameter of seven of nine flowering annual species decreased as salinity levels increased. Kang and van Iersel (2002) reported that the flower diameter of zinnia also decreased with increasing nutrient concentration. Apparently salvia responds differently from these species, in that the length of its flower stalk was decreased by both higher and lower than optimal concentrations. Size of individual salvia flowers was not measured.

Tissue concentrations of N, P, K, and B in the shoot increased quadratically with increasing concentration of nutrient solution, while the C, Al, Mo, and Na concentrations decreased (Table 1). The decrease in C with increasing fertilizer concentrations was entirely due to dilution caused by the increases in other nutrients. When corrected for the concentrations of the other nutrients in Table 1, C accounted for 455 to 474 mg·g\(^{-1}\) of the remaining biomass (presumably almost entirely made up of C, H, and O).

All tissue nutrient concentrations were sufficient or in excess, according to the optimal ranges recommended by Mills and Jones (1996), which is consistent with the absence of any symptoms of nutrient deficiency. Although some of the nutrients were present at higher than recommended concentrations [e.g., N, K, and B at 1.0 and 2.0× concentrations, and Mo in all treatments (Mills and Jones, 1996)], there were no visible toxicity symptoms.

### Table 1. The effect of nutrient solution concentration (Hoagland solutions at different strengths) on the nutrient composition of salvia shoots. The plants were subirrigated as needed. Whole shoots were harvested at 58 d after transplanting.

| Concen x full strength | C  | N  | P  | K  | S  | Ca | Mg | Al  | B  | Cu | Fe | Mn | Mo | Na | Zn |
|------------------------|----|----|----|----|----|----|----|-----|----|----|----|----|----|----|----|
| 0.125×                 | 417| 34.8| 4.1| 34.9| 4.5| 17.9| 5.0| 81  | 54 | 10.3| 130| 128| 41 | 10539| 64 |
| 0.25×                  | 410| 37.7| 4.6| 35.0| 3.8| 19.1| 5.6| 87  | 56 | 7.9 | 111| 107| 25 | 6432 | 47 |
| 0.5×                   | 404| 53.4| 6.5| 55.4| 3.4| 22.0| 6.7| 38  | 70 | 7.9 | 115| 123| 27 | 4180 | 22 |
| 1.0×                   | 385| 58.4| 7.3| 67.4| 2.5| 21.3| 6.7| 29  | 90 | 7.9 | 122| 155| 17 | 1912 | 28 |
| 2.0×                   | 379| 62.8| 6.7| 74.9| 2.4| 18.6| 5.8| 34  | 143| 10.3| 123| 152| 13 | 13245| 45 |
| Significance           | Q  | Q  | Q  | Q  | L  | Q  | L  | L   | L  | L  | L  | L  | L  | L  | L  |

*Non-significant at \( P \leq 0.05; \) L = linear; Q = quadratic.

### Table 2. The effect of nutrient solution pH on the plant growth at 58 d after transplanting of salvia. The plants were watered as needed with modified Hoagland solution at 0.5× concentration and one of five solution pH values: 4.4, 5.4, 6.4, 7.2 and 8.0.

| Solution pH | Root Dry wt (g) | Shoot Dry wt (g) | Total Dry wt (g) | Leaf area (cm\(^2\)/plant) | Chlorophyll content (SPAD units) | Time to flower (d) | Flower stalk length (cm) |
|-------------|-----------------|------------------|------------------|-----------------------------|-------------------------------|--------------------|-------------------------|
| 4.4         | 0.42            | 2.77             | 2.79             | 457                        | 41.0                          | 48.5               | 15.4                    |
| 5.4         | 0.43            | 2.48             | 2.91             | 543                        | 41.4                          | 49.3               | 13.9                    |
| 6.4         | 0.48            | 2.64             | 3.12             | 510                        | 40.4                          | 49.0               | 14.5                    |
| 7.2         | 0.45            | 2.65             | 3.10             | 523                        | 40.9                          | 49.5               | 14.5                    |
| 8.0         | 0.46            | 2.21             | 2.67             | 423                        | 38.9                          | 50.0               | 13.1                    |
| Significance | NS             | NS               | NS               | NS                         | NS                           | NS                 | NS                      |

*Non-significant at \( P \leq 0.05; \) L = linear; Q = quadratic.

### Table 3. The effect of nutrient solution pH on the nutrient composition of salvia shoots. The plants were subirrigated with 0.5× Hoagland solution as needed.

| Solution pH | C  | N  | P  | K  | S  | Ca | Mg | Al  | B  | Cu | Fe | Mn | Mo | Na | Zn  |
|-------------|----|----|----|----|----|----|----|-----|----|----|----|----|----|----|-----|
| 4.4         | 407| 54.0| 6.1| 53.3| 2.8| 21.3| 6.5| 65  | 65 | 7.5 | 125| 130| 23 | 4003 | 29 |
| 5.4         | 400| 55.0| 6.5| 57.4| 2.9| 20.1| 6.6| 36  | 69 | 7.7 | 133| 131| 25 | 4170 | 26 |
| 6.4         | 404| 53.4| 6.5| 55.4| 3.4| 22.0| 6.7| 38  | 70 | 7.9 | 115| 123| 27 | 4180 | 22 |
| 7.2         | 389| 54.9| 6.9| 57.4| 3.0| 22.6| 6.8| 42  | 72 | 8.6 | 194| 125| 32 | 4186 | 28 |
| 8.0         | 398| 56.1| 4.7| 57.0| 2.6| 21.4| 6.8| 43  | 75 | 7.7 | 276| 84 | 33 | 4001 | 22 |
| Significance | NS | Q   | NS   | NS | NS | NS | NS | NS  | NS | NS | NS | NS | NS | NS | NS  |

*Non-significant at \( P \leq 0.05; \) L = linear; Q = quadratic.

### Conclusions

Increasing fertilizer concentrations from 0.125× to 1× increased growth of salvia. Neither treatment effects on leaf photosynthesis, which generally declined with increasing fertilizer concentrations, nor on RGR, which was not affected by the fertility treatments, could explain the fertilizer effects on the growth of the plants. Instead, the increased growth with higher fertilizer concentrations appears to have been the result of changes in carbon allocation in the plants. Shoot : root ratio increased with increasing fertilizer concentration, while LAR : plant increased up to 1× concentrations. Because of these changes in allocation, plants grown with higher fertilizer concentrations produced a larger leaf area, resulting in more light interception and increased growth. Unlike fertilizer concentration, fertilizer pH had no effect on the growth of the plants.

### Literature Cited

Devitt, D.A. and R.L. Morris. 1987. Morphological response of flowering annuals to salinity. J. Amer. Soc. Hort. Sci. 112:951–955.
Elliott, G. 1990. Reduce water and fertilizer with ebb and flow. Greenhouse Grower 8(6):70–75.
Elmore, C.D. 1980. The paradox of no correlation between leaf photosynthetic rates and crop yields, p. 155–167. In: J.D. Hesketh and J.W. Jones (eds.). Predicting photosynthesis for ecosystem models. Vol. II. CRC Press, Boca Raton, Fla.
Evans, L.T. 1975. The physiological basis of crop yield, p. 327–335. In: L.T. Evans (ed.). Crop physiology. Cambridge Univ. Press, Cambridge, U.K.
Hoagland, D.R. and D.I. Arnon. 1950. The water culture method for growing plants without soil. Circ. 347. California Agr. Expt. Stn., Univ. of California, Berkeley.
Hunt, R. 1982. Plant growth curves. The functional approach to plant growth analysis. Univ. Park Press, Baltimore.
James, E.C. and M.W. van Iersel. 2001. Fertilizer concentration affects growth and flowering of subirrigated petunias and begonias. HortScience 36:40–44.
Jones, J.B. and V.W. Case. 1990. Sampling, handling, and analyzing plant tissue samples, p. 389–427. In: R.L. Westerman (ed.). Soil testing and plant analysis. Soil Sci. Soc. Amer.
Kang, J.G. and M.W. van Iersel. 2001. Nutrient solution concentration affects growth of subirrigated bedding plants. J. Plant Nutr. 25:387–403.
Kent, M.W. and D.W. Reed. 1996. Nitrogen nutrition of New Guinea impatiens ‘Barbados’ and Spathiphylum ‘Petite’ in a subirrigation system. J. Amer. Soc. Hort. Sci. 121:816–819.
Klock-Moore, K.A. and T.K. Broschat. 1999. Differences in bedding plant growth and nitrate loss with a controlled-release fertilizer and two irrigation systems. HortTechnology 9:206–209.
Květ, J., J. P. Ondok, J. Nečas, and P.G. Jarvis. 1971. Methods of growth analysis, p. 343–391. In: Z. Šesták, J. Čásky, and P.G. Jarvis (eds.). Plant photosynthetic production. Manual of methods. Dr. W. Junk N.V., Publ., The Hague.
Lawlor, D.W. 1995. Photosynthesis, productivity and environment. J. Expt. Bot. 46:1449–1461.
Mak, A.T.Y. and D.M. Yeh. 2001. Nitrogen nutrition of Spathiphyllum ‘Sensation’ grown in sphagnum peat- and coir-based media with two irrigation methods. HortScience 36:645-649.
Marschner, H. 1995. Mineral nutrition of higher plants. 2nd ed. Academic Press, San Diego.
Mills, H.A. and J.B. Jones. 1996. Plant analysis handbook II. A practical sampling, preparation, analysis, and interpretation guide. MicroMacro Publ., Athens, Ga.
Nagel, J.M. and K.L. Griffin. 2001. Construction cost and invasive potential: Comparing Lythrum salicaria (Lythraceae) with co-occurring native species along pond banks. Amer. J. Bot. 88:2252–2258.
Radin, J.W. and J.S. Boyer. 1982. Control of leaf area expansion by nitrogen nutrition in sunflower. Plant Physiol. 69:771–775.
Sattelmacher, B., F. Klotz, and H. Marschner. 1990. Influence of the nitrogen level on the root growth and morphology of two potato varieties differing in nitrogen acquisition. Plant Soil 123:131–137.
Thornley, J.H.M. 1998. Dynamic model of leaf photosynthesis with acclimation to light and temperature. Ann. Bot. 81:421–430.
van Iersel, M.W. 1999. Fertilizer concentration affects growth and nutrient composition of subirrigated pansies. HortScience 34:660–663.
van Iersel, M.W. 1997. Root restriction effects on growth and development of salvia (Salvia splendens). HortScience 32:1186–1190.
van Iersel, M.W. and B. Bugbee. 2000. A semi-continuous, multi-chamber, crop CO2-exchange system: Design, calibration, and data interpretation. J. Amer. Soc. Hort. Sci. 125:86–92.
van Iersel, M.W. and J.-G. Kang. 2002. Nutrient solution concentration affects whole-plant CO2 exchange of subirrigated pansy. J. Amer. Soc. Hort. Sci. 127:423–429.
Veneklaas, E.J., M.P.R.M. Santos Silva, and F. den Ouden. 2002. Determinants of growth rate in Ficus benjamina L. compared to related faster-growing woody and herbaceous species. Scientia Hort. 93:75–84.