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ROOT-ZONE MANAGEMENT OF CONTAINER-GROWN HERBACEOUS PERENNIALS

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ROOT-ZONE MANAGEMENT OF CONTAINER-GROWN HERBACEOUS PERENNIALS

By

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ABSTRACT

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By

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Media moisture levels, fertilizer concentrations, and nutrient-solution reactions were evaluated for the effect on plant growth and development during the forcing into flower of 15 different container-grown herbaceous perennial species in a greenhouse. There were no treatment effects on floral initiation and development. In general, both shoot fresh weight and plant height increased with increasing water availability, while percent dry weight was affected minimally. Both low and high fertilizer rates generally decreased shoot fresh weight and only the high fertilizer rate decreased the height. An acidic nutrient solution had less effect on lowering medium pH than an basic nutrient solution had on raising medium pH. Both nutrient solutions had minimal effect on plant growth and appearance.

Shoot and leaf tissue macronutrient and micronutrient concentrations were determined for 15 container-grown herbaceous perennial species forced into flower in a greenhouse. Averaged over all species, the six NS produced a range of values for each macronutrient that varied by ≤ 0.5, 1.0, or ≥ 1.5 % for P and Mg^{2+}, N and Ca^{2+}, or K, respectively. In general, N and P showed minimal differences while K concentrations increased with increasing fertilizer rate. The ranges of Fe, Mn, Zn, B, and Cu concentration over all treatments were 33 to 1515, 40 to 483, 21 to 244, 16 to 205, and 1 to 10 $\mu g \cdot g^{-1}$, respectively.

To all the FINE people out there seeking the truth.

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EFFECT OF MEDIA MOISTURE AND NUTRIENT SOLUTION ON THE GROWTH AND FLOWERING OF FIFTEEN CONTAINER-GROWN HERBACEOUS PERENNIALS

Effect of Media Moisture and Nutrient Solution on the Growth and Flowering of Fifteen Container-grown Herbaceous Perennials

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Abbreviations: ANS, acidic nutrient solution; BNS, basic nutrient solution; BR, bareroot; CC, container capacity; CLF, constant liquid fertilizer; EC, electrical conductivity; FC, fertilizer concentration; HPS, high pressure sodium; ML, moisture level; MSU, Michigan State University; NS, nutrient solution; NSR, nutrient-solution reaction; RO, reverse osmosis; SME, saturated media extract; WSF, water-soluble fertilizer.

Effect of Media Moisture and Nutrient Solution on the Growth and Flowering of Fifteen Container-grown Herbaceous Perennials

Additional index words. fertilizer concentration, nitrogen form, root-medium pH, soilless media, water

Abstract. Media moisture levels, fertilizer concentrations, and nutrient-solution reactions were evaluated for the effect on plant growth and development during the forcing into flower of 15 container-grown herbaceous perennial species in a greenhouse. There were no treatment effects on floral initiation and development. Water availability was evaluated by both irrigation frequency with three different moisture levels, >50% container capacity (CC), <60% CC, and >75% CC, and with three different root media, 70% sphagnum peat 30% perlite, 100% sphagnum peat, and 50% bark, 30% sphagnum peat, and 20% perlite. *Echinacea*, *Heuchera*, and *Lavandula* had the greatest increase in shoot fresh weight, and *C. grandiflora*, *Echinacea*, and *Salvia* had the greatest increase in height with increasing moisture availability. In general, both shoot fresh weight and plant height increased with increasing water availability, while percent dry weight was affected minimally. Nutrient availability was altered by three different macronutrient fertilizer concentrations of water-soluble fertilizer, 125N-20P-125K, 31N-11P-31K, 250N-32P-250K, while micronutrients remained constant. Root-medium electrical conductivity ranged from 0.9 to 1.7 $dS \cdot m^{-1}$ (1:2 method) at harvest in a non-leaching system with a preplant fertilizer. Both low and high fertilizer rates generally

decreased shoot fresh weight and only the high fertilizer rate decreased the height. Root-medium pH was altered by drenching the root medium with an acidic or basic solution to alter the initial pH to <5.0 or >7.0, respectively, but the drenches were phytotoxic to most species. An acidic nutrient solution (50% NH_4-N, 15 Ca^{2+}, 5 Mg^{2+}, and 20 mg $CaCO_3 \bullet L^{-1}$) had less effect on lowering medium pH than an basic nutrient solution (5% NH_4-N, 167 Ca^{2+}, 60 Mg^{2+}, and 320 mg $CaCO_3 \bullet L^{-1}$) had on raising medium pH. Both nutrient solutions had minimal effect on plant growth and appearance. Root-media pH ranged from 5.0 to 8.0 at harvest based on nutrient-solution reaction treatment.

Introduction

The interest of gardeners in herbaceous perennials since the 1980's has prompted researcher's and grower's involvement in production of container-grown herbaceous perennials. Most herbaceous perennial research has focused on acquiring knowledge for species-specific flowering requirements relating to vernalization, photoperiod and temperature on development (Inversen, 1994; Heins et al, 1997). In conjunction with adequate knowledge of aerial conditions to grow herbaceous perennials in a greenhouse, a grower needs to understand the root-zone conditions of container-grown herbaceous perennials, especially when many species are grown in a common environment. To our knowledge, limited information exists on how root-zone management effects the growth and development of container-grown herbaceous perennials forced into flower in a greenhouse (Armitage, 1994).

Traditionally, production of herbaceous perennials took place in the field, but high labor costs limited potential profitability (Locklear, 1981). With the ease of container production and potential profitability, the trend shifted to container-growing. In field production, most fertilizer recommendations vary considerably by soil type and fertility. Fertilizer rate with both granular and controlled-release fertilizer was evaluated on growth and development of some field-grown herbaceous perennials by Duarte and Perry (1988). Root-zone conditions in outdoor container production of herbaceous perennials were addressed including both interactions between nutrient concentration and media components, in addition to obtaining optimum nitrogen fertility for *Hemerocallis* L. 'Stella de Oro' (Perry and Adam, 1990), and interactions of irrigation and controlled-release fertilizers on plant growth and substrate solution for *Rudbeckia fulgida* Ait. 'Goldsturm' (Groves et al, 1998a and 1998b). In the greenhouse, nutrient deficiencies effect on growth and development were evaluated for *Achillea filipendulina* Lam. 'Cloth of Gold', *Aquilegia* hybrid L. 'Dragonfly Mixture', *Coreopsis grandiflora* Hogg ex Sweet 'Sunray', *Dendranthemum* x*grandiflorum* Kitam 'Ginger', *Dianthus plumarius* L. 'Double Mix', *Lythrum virgatum L.* 'Morden Gleam', and *Veronica incana* L. 'Red Fox' (Schouten and Agnew, 1994). Root-zone cultural requirements for perennial production have also been discussed by Peterson (1985), Smith (1985), Pealer (1985), Perry (1998), and Elliot (1990). However, there is limited peer-review literature on how these cultural recommendations apply directly to herbaceous perennials forced into flower under greenhouse conditions.

In a greenhouse, one fertilizer concentration applied to one root medium designed to maintain a desired pH and electrical conductivity (EC) can be used to grow a wide variety of container-grown ornamental crops in common light and temperature conditions. General fertilization of container-grown crops, concerning water, media, and fertilizer, for ornamental greenhouse crops has been reviewed by Joiner et al (1983). However, when problems arise other than those induced by temperature and light, the problems are usually related to either one or more of three different factors: 1) water and air proportions in the medium caused by over or under watering and the medium's physical condition; 2) quantity of fertilizer being too high or too low or some unique nutrient deficiency that is species-specific; or 3) sensitivity to pH extremes causing a nutrient toxicity, e.g. seed geranium (*Pelargonium xhortorum* Bailey) and marigold (*Tagetes erecta* L.) response to low pH, or a nutrient deficiency, e.g. petunia (*Petunia xhybrida* **????**) chlorosis due to high pH.

A method of comparison between species is necessary to identify potential problems related to water and nutrient availability, and root-medium pH. The primary objective of this research was to assess the effect of water, fertilizer, and pH relations on the growth, development, and nutrient status of 15 container-grown herbaceous perennials. A second objective was to develop a simple method of screening container-grown ornamental crops for the response to a range of water, fertility and root-medium pH conditions.

Materials and Methods

Design setup. The experiment included 12 treatments composed of a standard and two types of media, five nutrient solution (NS), two irrigation frequencies, and two root-medium pH. The treatments were selected to compare a range of root-zone conditions in moisture level (ML), media components, N-P-K-Ca concentration, water-soluble P availability, nutrient-solution reaction (NSR), and initial root-medium pH to one standard root-zone regime, comprising a standard level for all six factors. A completely randomized design was used with 8 replications (plants) for each treatment.

The effect of each factor on growth and development was statistically analyzed as a comparison between low, standard, and high levels using SAS (SAS Institute, Cary, NC.) general linear models procedure (PROC GLM) for analysis of variance and trends, and Duncan's Multiple Range Test for mean separation (MEANS / DUNCANS).

Media Preparation. All root media consisted of at least one or more of the following components: select Canadian sphagnum peat (Fisons professional black bale peat, Sun Gro Horticulture, Bellevue, WA) with long fibers and little dust (Von Post scale 1-2; Puustjarvi and Robertson 1975), composted pine bark (Stronglite, Arkansas), and perlite. The standard medium was a blend (by volume) of 70% peat with 30% perlite (standard). The alterations in media component treatments consisted of 100% screened (0.65 cm mesh) peat (peat) and a blend of 50% composted unscreened pine bark, 20% sphagnum peat, and 30% perlite (bark).

Sufficient amounts of dolomitic hydrated lime ($Ca(OH)_2$ and $Mg(OH)_2$ with 34% Ca^{2+} and 20% Mg^{2+}) were added to increase the pH of the medium to 5.8 to 6.2. The amount of hydrated lime added per cubic meter (yard) was (in kg) 1.5 (2.5 lbs.) standard, 2.1 (3.5 lbs.) peat, and 0.6 (1 lbs.) bark. Hydrated lime was selected over carbonate lime so little or no residual lime would be present in the medium to buffer future pH changes (Argo and Biernbaum, 1996).

In addition to the lime, a preplant nutrient charge consisting of 0.6kg (1 $lb \cdot yd^{-3}$) KNO_3, 0.3 kg (0.5 $lb \cdot yd^{-3}$) triple superphosphate (0N-19.8P-0K), and 0.9 kg (1.5 $lb \cdot yd^{-3}$) gypsum; 0.07 kg (0.1 $lb \cdot yd^{-3}$) fritted trace elements; 0.3 kg (0.5 $lb \cdot yd^{-3}$) wetting agent (Aquagro "G", Aquatrols, Pennsaulken, NJ) per m^3 of medium were incorporated into all media at mixing. Sufficient reverse osmosis (RO) purified water was added at mixing to bring the moisture content of the medium to 40-50% of container capacity. At planting, the three media had an average pH of 5.9, an EC of 1.7 $dS \cdot m^{-1}$, and (in $mg \cdot L^{-1}$) 130 NO_3-N, 39 PO_4-P, 180K^+, 105 Ca^{2+}, and 60 Mg^{2+}, as measured with a saturated media extract (SME) analysis with RO water as the extractant (Warncke, 1986).

After planting, the root-medium pH was altered with an acidic and basic drench, 2.0 $ml \cdot L^{-1}$ H_2SO_4 (93%) and 4.8 $g \cdot L^{-1}$ $KHCO_3$, respectively, to create a range of initial root-medium pH. Drenches were applied at 250 ml intervals until desired pH reached for an acidic and basic root medium, $\leq$5.0 and $\geq$7.0, respectively.

Nutrient solutions. NS-1, standard, was a water-soluble fertilizer (WSF) made of $Ca(NO_3)_2$, KNO_3, NH_4NO_3, and $NH_4H_2PO_4$ that contained ($mg \cdot L^{-1}$) 125N-20P-125K-33Ca-0Mg-0SO_4 mixed with acidified well water, produced by adding

H_2SO_4 (93%) to the well water which provided a pH 5.8, an EC of 0.7 $dS{\bullet}m^{-1}$, concentrations of 100 Ca^{2+}, 30 Mg^{2+}, and 91 SO_4-S ($mg{\bullet}L^{-1}$), and a titratable alkalinity to pH 4.5 of 120 mg $CaCO_3{\bullet}L^{-1}$. NS-1, NS-2, NS-3, and NS-4 remained constant at 25% NH_4-N, 30 Mg^{2+}, 12 Na^+, and 91 SO_4-S ($mg{\bullet}L^{-1}$), whereas NS-2 and NS-3 varied in concentration of N-P-K-Ca $mg{\bullet}L^{-1}$, 62N-14P-62K-116Ca and 250N-32P-250K-166Ca, respectively. NS-2 and NS-3 were made with the same fertilizer salts and water as NS-1. The fertilizer concentration (FC) of NS-1 was cut in half to create a low FC, NS-2, and doubled to create a high FC, NS-3. After five weeks into the experiment, N-P-K-Ca rate of NS-2 was halved from 62N-14P-62K-16Ca to 31N-11P-31K-8Ca, because the root-medium EC reading was similar to NS-1, not lower as desired. For NS-4, low P, $NH_4H_2PO_4$ was substituted with urea to create an intended zero P WSF. A zero level was not maintained due to an unlabeled component in the micronutrient source, as explained later.

A basic NS (BNS), NS-5, and an acidic NS (ANS), NS-6, were developed to create NSR on the root-medium pH. For NS-5 and NS-6, concentration of N-P-K was maintained at a constant 125N-20P-125K, but %NH_4-N, Ca^{2+}, Mg^{2+}, and SO_4-S were varied. NS-5 was a WSF made from $Ca(NO_3)_2$, $Mg(NO_3)_2$, KNO_3, and KH_2PO_4 that contained 5% NH_4-N with 67 Ca^{2+}, 30 Mg^{2+}, and 0 SO_4-S ($mg{\bullet}L^{-1}$) mixed with well water that had a pH of 7.8, an EC of 0.6 $dS{\bullet}m^{-1}$, concentrations of Ca^{2+}, Mg^{2+}, and Na^+ similar to that of the well water in NS-1, and a titratable alkalinity to pH 4.5 of 320 mg $CaCO_3{\bullet}L^{-1}$. NS-6 was a WSF made from NH_4NO_3, urea, KNO_3, K_2S0_4, and $NH_4H_2PO_4$ that contained 50% NH_4-N, with 0 Ca^{2+}, 0 Mg^{2+}, and 27 SO_4-S ($mg{\bullet}L^{-1}$) mixed with RO purified well water that had a pH 5.5, an EC of 0.1 $dS{\bullet}m^{-1}$, and 15

Ca^{2+}, 5 Mg^{2+}, 27 Na+, and 1 SO_4-S, and a titratable alkalinity to pH 4.5 of <20 mg $CaCO_3$•L^{-1}.

Micronutrients (Fe, Mn, Zn, Cu, B, and Mo) were added to all NS with a commercially available blended chelated material [Compound 111 (1.50Fe-0.12Mn-0.08Zn-0.11Cu-0.23B-0.11Mo) Scotts, Marysville, Ohio] at a constant 50 mg•L^{-1}. This rate is higher than usually incorporated in preblended WSF used at a rate of 125 mg•L^{-1} N. Typically, when WSF rates are diluted or concentrated, micronutrient levels are simultaneously diminished or elevated, respectively. However, in an attempt to eliminate potential trace element deficiencies with low FC or toxicities with high FC, micronutrient levels were maintained constant for all NS.

Water Availability. The eight plants in each treatment were irrigated at the same time independent of other treatments. Time for irrigation was determined gravimetrically when four or more of the eight pots within a single treatment reached a target weight of 500 g (except for bark, low ML, and high ML), based on predetermined weight of the pot, plant, and medium. Pots were checked daily for target weight at which point 250 ml was applied by top watering.

Both physical and chemical properties of the medium can be altered to evaluate potential differences in plant growth. Physical properties of a medium determine how much water and oxygen are supplied to the plant roots, whereas the chemical properties of a medium alter nutrient availability. To focus on how different media components affect water availability, our intent was that only the physical properties were altered while the chemical properties of the different media were adjusted to be equivalent. Saturation or excess drying of the three different media were also prevented by gravitational measurements prior to irrigation. The bark based medium had a greater bulk density (0.21 g•cm^{-1}) than the standard or peat (0.11 and 0.10 g•cm^{-1}, respectively), and required irrigation at an elevated target weight, 600 g per pot.

Standard, low, and high ML, >50%, <60% and >75% CC, respectively were based on CC of standard root medium, 1030 g , and assigned target weights (in g), 500, 400, and 800, respectively. Initial low and high ML were established, and then maintained with small irrigation volumes, 125 ml. As plant growth increased, irrigation frequencies increased for high ML beyond convenience, and irrigation volumes were increased, 250 ml, to decrease the irrigation frequency. Based on prior media moisture studies (unpublished), severe drying to the point of wilt followed by thorough watering with leaching was not as effective a method for using low medium moisture to control plant size as frequent low volume applications at regular intervals.

Plant culture. During Oct.1, 1997 to June 1, 1998 plants were forced into flower at different times, based on forcing schedules developed at Michigan State University (MSU), E. Lansing, MI. Plugs and bare root plants (Table 1) were received from commercial growers, and upon arrival were given the appropriate species-specific cold treatment recommended by MSU herbaceous perennial research (Table 1). For cooling, plants were placed in a cooler at 5 ±0.5 °C and illuminated for 9 h•d^{-1} with cool-white flourescent lamps (VHOF96T12; Phillips, Bloomfield, N.J.) at ≈10 μmol•m^{-2}•s^{-1}. While in the cooler, plants were watered with acidified (93% H_2SO_4) well water (340 mg $CaCO_3 \cdot L^{-1}$) to a titratable alkalinity of 120 mg $CaCO_3 \cdot L^{-1}$.

After cold treatment, 96 plants of each species plus approximately 16 plants for guard rows were transplanted into 14-cm (1.5 L) square plastic containers, containing one of the three medium formulated at MSU. Eight pots in each treatment were placed on water-catcher trays (Landmark Plastic, Akron, OH), providing a non-leaching system. The greenhouse heating and cooling setpoints were 20 °C and 23 °C. Supplemental lighting was provided with high pressure sodium lamps (HPS) from 0700 to 2200 HR at ≈90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at plant level, in two glass greenhouse sections at MSU in East Lansing, MI. Due to the sun sensitivity of *Hosta*, a 50% aluminum shade cloth (LS Americas, Charlotte, NC) covered the plants during production.

Data collection. Dates of visible bud and first open flower were recorded for each plant, and days to visible bud and flowering were calculated. At flowering, total visible flower buds and total nodes were counted, and total height was measured from top of medium in container. Shoot fresh and dry weight were determined when majority of all treatments for a particular species were in flower. Root-medium pH and EC were monitored every three weeks and at the end of experiment by a 1:2 dilution method. Samples were removed from the lower half of the pot, and consisted of approximately 25 ml per pot from four of the eight pots per treatment. Replication for the final samples was made by sampling from both sets of four pots per treatment. Nutrient content in the root medium from the standard treatment of each species was tested using SME method with RO purified water as extractant.

Data presentation. To allow easier comparison of treatment effects compared to the standard and across species varying in plant size, data were normalized by dividing the treatment means by the standard treatment mean. Both leaf tissue and whole shoot tissue from plants receiving the six NS and the standard NS, respectively, were collected at flower and analyzed for elemental content, but are reported separately (Morrison and Biernbaum, 1999).

Results and Discussion

Overview. Time to flower for the 15 species ranged from 38 days for *Salvia* to 94 days for *Hibiscus* (Table 1). A few species exhibited statistical differences in days to flower due to moisture level and fertilizer concentration, however for any species days to flower did not vary by more than 5-7 days. Days to flower, flower number per plant, and final node count for the standard treatment are found in Table 1. Flowering is primarily controlled by temperature and/or photoperiod. With similar greenhouse light and temperature conditions, developmental differences were not expected from water and nutrient management, and in general were not observed.

Shoot fresh weight ranged from about 20 to 200 g across species with standard root-zone conditions or a 10-fold difference in shoot growth, whereas shoot growth rate, adjusted for crop time, ranged from 0.06 to 0.39 g dry wt•day^{-1}, only a 6.5 fold difference (data not shown). Visual differences in plant growth usually required a 20 to 30% difference in fresh weight, even though statistical significance occurred below these percentages (Figure 1).

Herbaceous, leafy perennials like *Gaillardia*, *Leucanthemum*, and *Sedum* ranged from 7.7 to 11.3% dry matter, while woody plants like *C. verticillata*, *Lavandula*, and *Perovskia,* ranged from 22.1 to 24.5% with standard root-zone conditions. In general, percent dry weight differences of 10% ± 5% were required for statistical significance (Figure 2).

With standard root-zone conditions plant height ranged from 71 to 81 cm for taller plants, like *Echinacea*, *Hibiscus*, and *Perovskia* to 15 to 27 cm for shorter species, like *Gaillardia*, *Leucanthemum*, and *Sedum*. Statistical significance generally required a difference between treatments within a species greater than 15% (Figure 3), however, visually a difference of 25 to 30% or greater was noticeable. It is unclear why the standard for *Leucanthemum*, *Salvia*, and *Scabiosa* was different enough to offset all the remaining treatments.

Media. Pore space characteristics in unplanted pots of the standard, peat, and bark medium, after saturated and drained , were 23, 17, and 23% for air and 56, 71, and 50% for water, respectively. Greater differences in air and water porosity were expected between the different medium component. Air space did not decrease as much as expected in the 100% peat medium, most likely because the peat quality, in terms of particle size, was still acceptable even after screening. Air space was not increased and water space decreased in the bark medium presumably because the pine bark contained a high percentage of smaller particles. Probably because of the smaller differences in air and water space than intended, there were few statistical differences in growth due to media, however, the differences were small and the data are not reported. Another explanation why differences in growth were small between the three different media components is because water availability was carefully managed gravimetrically to prevent saturation or excess drying. For outdoor container production rain becomes an issue because water application is less controlled and excessive saturation may occur. Plants grown in potentially saturating outdoor conditions may benefit from a more porous root medium containing bark or from taller containers.

Our goal was to have similar chemical properties in the media. There was no apparent effect of the composted pine bark on nitrogen availability at our standard FC. In this experiment, the low overall pH of the bark media, 5.8, 5.7, and 5.0 for standard, peat, and bark, respectively, at harvest over the 15 species might be attributed to the hydrated lime, which provided no residual buffer. Acidification of the bark media over time was not expected, but maybe merited to the lower lime addition in medium.

Low P. There were no differences in growth between the standard and low P nutrient solution, and the data are not reported. During the course of the experiment, a nutrient analysis of the low P nutrient solution revealed a P level of 8 $mg \cdot L^{-1}$. From fertilizer nutrient analysis, the source of P was determined to be an unlabeled component in the commercial micronutrient blend, Compound 111. The corrected P values for the FC nutrient solutions would be 8, 11, 20, and 32 $mg \cdot L^{-1}$ P as opposed to the intended concentration of 0, 3, 12, and 24 $mg \cdot L^{-1}$ P. The comparison of the low P and standard NS, therefore was a comparison of 8 $mg \cdot L^{-1}$

P and 20 mg•L^{-1} P, respectively. The overall P delivery to root zone was relatively close, thus similar growth responses are not surprising. It has been proposed that as low as 10 mg•L^{-1} P constant application of P was adequate for most ornamental container-grown plants (Argo and Biernbaum, 1996). While there were no apparent visual symptoms of P deficiency in this study and based on tissue concentrations of 0.20 and 0.30% P with the lowest applied concentrations (Morrison and Biernbaum, 1999), we recommend 20 mg•L^{-1} P for production of herbaceous perennials to meet plant requirements with an adequate safety margin in case of leaching. It is important to note that the medium contained 0.3 kg•m^{-3} triple superphosphate (0N-19.8P-0K) and P in superphosphate is readily leachable (Argo and Biernbaum, 1995). Since there was no leaching in our system, all this P would also have been available to the plant.

Moisture Level. Generally, shoot fresh weight and plant height had an increasing linear trend with increasing moisture, and flower number increased with increasing ML. Height was influenced the greatest by ML, especially for *Echinacea* with a 35% increase at the high ML, and for *Hemerocallis* with a 35% decrease with the low ML relative to the standard. Percent dry weight increased as ML decreased. Compared with the mean standard ML for 15 species, the mean low ML decreased by 41% and the mean high ML increased by 45% in total water volume applied (Table 2). Our original goal was to apply similar amounts of water while keeping plants dry or moist, so that differences in fertilizer applied were minimized. The extreme moisture levels were initially established and were to be maintained by adding small aliquots of water, 125 ml, at appropriate frequencies. Differences in plant size soon resulted in water being applied less frequently to the dry treatment, and a need to increase the quantity of water applied (250 ml) each day to the moist treatment. This increase in constant liquid fertilizer (CLF) application tends to confound ML and FC treatments. To separate water and fertilizer treatments in the future, fertilizer application could be administered weekly, while irrigation frequency would be managed independently based on demand. However, with differences in plant size due to medium moisture level, a uniform fertilizer quantity applied would seemingly result in excess for smaller plants or inadequate levels for a larger plants.

Total amount of applied N in g•pot^{-1} N was calculated by multiplying water use by concentration (0.125 g•L^{-1} N) and averaged 0.37, 0.63, and 0.91 g•pot^{-1} N over all species for the three ML. The differences between low and high FC were greater, 0.19 and 1.04 g•pot^{-1} N for low and high, respectively (Table 2). The mean water use for a species as ML increased was 50, 80, and 120 ml•day^{-1}, respectively, per pot. However, *Gaillardia* and *Rudbeckia* received 48% more water, and *Hosta* and *Sedum* 35% less than the mean amount of total applied water. The decrease in water use by *Hosta* was probably due to a 50% aluminum shade cloth covering the plants, decreasing light levels and evapotranspiration.

As ML increased, mean growth rate (based on shoot growth only) was 0.16, 0.22, and 0.29 g dry wt•day^{-1} (averaged over entire crop cycle), respectively, for the dry, standard, and wet treatment (data not shown). *Echinacea*, *Heuchera*, *Lavandula,* and *Perovskia* maintained similar growth rates at low and standard ML, yet had greatest growth rates, 40% over the standard, at high ML. Low above ground growth rates were observed for *Hosta* and *Hemerocallis*, possibly suggesting a greater tendency to partition available resources to roots. Growth rates decreased by 50% or greater at low ML for *Hemerocallis* and *Rudbeckia*, hence the more than 40% decrease in shoot fresh weight (Figure 1).

Mean water use efficiencies for all species as ML increased were 3.25, 2.57, and 2.35 g shoot dry wt•L^{-1} H_2O per pot (data not shown). Based on shoot growth only and not root growth, *C. grandiflora* and *Sedum* had greatest water use efficiencies overall, especially at low ML, 5.61 and 5.65 g dry wt•L^{-1} H_2O, respectively, per pot with only minimal differences between standard and high ML. Contrastingly, *Hemerocallis* and *Hosta* had overall below mean water use efficiencies. Both of these species appeared to increase in root mass more than other species (personal observation only).

Fertilizer. No differences were observed in flower number with FC. Generally, high FC decreased plant height and shoot fresh weight. The latter also decreased with low FC, although percent dry weight generally increased and by over 20% for *Echinacea*, *Gaillardia*, and *Leucanthemum*. A quadratic trend in shoot fresh weight with increasing FC was most notable by a 40% or greater decrease with both low and high FC for *Rudbeckia*. The FC effect on plant height was most prominent with *Echinacea*, increasing by 21% with low FC, and with *Hemerocallis*, *Lavandula*, and *Rudbeckia*, decreasing by about 20% with high FC. Water use, growth rate, and water use efficiencies at all three FC were similar.

Compared to standard root-zone conditions, both low and high FC decreased or increased in total applied N by 70% or 66%, respectively (Table 2). Even though the difference in fertilizer rate of the low FC, 31 mg•L^{-1} N, to the standard FC, 125 mg•L^{-1} N, was a 4 fold increase, the mean soluble salt level in the root medium at harvest was only 24% lower, 0.99 and 1.30 dS•m^{-1}, respectively (Table 2). The EC increased and pH decreased from standard FC to high FC, 1.27 to 1.74 dS•m^{-1}, and 5.73 to 5.25, respectively. *Hibiscus* and *Perovskia* had higher than mean soluble salts at all three FC, while both *Salvia* and *Sedum* had lower soluble salts for only the standard and high FC. *Hibiscus*, *Perovskia*, and *Sedum* had elevated total applied N at low FC because these species received 62 mg•L^{-1} N for initial five weeks of production compared to 31 mg•L^{-1} N for all other species. Low and high FC received, 8% and 17%, less total applied water, respectively, than standard root-zone conditions.

Root-medium pH drench and % NH_4-N. The method of adjusting medium pH with an acidic or basic drench resulted in symptoms that could not reliably be attributed to pH alone. Therefore, plant growth data are not reported. The reason plant material was not planted directly into pH adjusted media was to allow some plant establishment prior to altering root-medium pH of the plant. The drench technique had been successful with pot plant and bedding plant crops, where medium pH was moved from low or high pH for acceptable root-zone conditions (5.5-6.5) back toward a standard level (unpublished). In this study, the drench technique appeared to not inhibit growth for some species, yet, for many species the rapid pH change in the opposite direction, from an acceptable to an unacceptable pH (low or high), inhibited growth and development. From our observations, it was difficult to separate the effect of the pH change from the application method on plant or root damage. Our recommendation for future experiments would be to gradually change the pH over a longer time period or to plant into pH modified media.

Differences in shoot fresh weight, percent dry weight, and plant height due to differing %NH_4-N were minimal. There was no affect on visual appearance (data not shown). Typically detrimental effects on plant growth due to ammonium-based fertilizers would be observed during low light or low soil temperature conditions, or rates of greater than 50% NH_4-N. In this experiment, with ≈90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ supplemental lighting from HPS lamps for 16 hours a day, average daily temperatures about 20 °C, and nitrogen of 50% NH_4-N or less, no differences were expected.

Argo and Biernbaum (1996, 1997) demonstrated root-medium pH effects with acidic and basic nutrient solution over a fifteen week crop time on hybrid Impatiens (*Impatiens wallerana* Hook. F.), but minimal differences in shoot dry weight. In this experiment, the mean root-zone pH for basic, standard, acidic NS was 7.2, 5.8, and 6.0, respectively. Both nutrient solution and plant species affected root-medium pH (Table 2). Plants grown with BNS had the highest medium pH for all species, while only *Gaillardia*, *Hemerocallis*, and *Hibiscus* decreased in medium pH with ANS. On the other hand, all plant species with the standard NS, medium pH remained within a range of 5.7 to 6.3, except for *Heuchera*, *Lavandula*, and *Rudbeckia* where the media pH decreased, 5.5, 4.8, and 5.2, respectively. A lack of pH decrease in root media with ANS contrasts with Argo and Biernbaum (1996) findings that pH fell by 0.5 after 8 weeks at 200 $mg \cdot L^{-1}$ N, a rate higher than required for normal Impatiens growth. The pH effect of a NS depends not only on the % NH_4-N of the WSF, but also on amount delivered to the container and the duration of production (Argo and Biernbaum, 1997). In this experiment, the range of bench time for the 15 perennials was between 6 to 14 weeks and the fertilizer concentration was about half the rate, 125 vs 200 mg•L^{-1} N. In a time frame of ten weeks and a reduced FC, one would not expect a major influence as opposed to growing long term and at a higher FC.

In this study, the final pH decreased significantly more at a high FC (5.25) than with the ANS (6.03). The high FC provided 86 to 100% as much NH_4-N as the ANS for eleven perennials except for *C. grandiflora*, *Echinacea*, *Hibiscus*, and *Rudbeckia,* where high FC supplied only 69 to 78% of NH_4-N applied by ANS. Differences in root-medium pH observed between high FC and ANS could be attributed to an increase in application rate more than % NH_4-N in WSF.

The target pH range for most greenhouse crops is 5.8 to 6.2, however, in this study, herbaceous perennials produced acceptable growth with a pH range of 5.2 to 7.1, except for *Rudbeckia* (Morrison and Biernbaum, 1999). Though it may appear herbaceous perennials have a wider acceptable pH range, it is likely that the acceptable range is actually broader than the 0.5 pH unit target mentioned above frequently given for greenhouse crops (Nelson, 1998). Research on annuals had identified a few exceptions, like seed geranium and marigold, requiring a narrower pH range (Argo, 1996; Biernbaum et al, 1988). As herbaceous perennial production expands some exceptions could be detected requiring a narrower pH range, such as *Rudbeckia.* When root-medium pH fell below 5.5, purple tissue developed on the underside of foliage and leaf tissue Fe concentrations were 2900 μg•g^{-1}, indicating Fe toxicity .

General Response to Water and Fertilizer. Maintenance of adequate water and nutrient levels is essential for production of containerized greenhouse crops. Severe reduction of water availability indirectly affects plant growth and development by first reducing expansive growth and then reducing photosynthesis. Growth response to irrigation depends on how much and how often water is delivered, air and water-holding capacity of the substrate material, plant species, and rate of fertilization. Many differences occurred in shoot fresh and dry weights due to ML for most of the 15 herbaceous perennials. However, percent dry weight, a measure of the plant tissue water content, was altered in response to media ML for only a few species from standard ML. In general, fresh and dry weight had linear trends with increasing moisture, but horticulturally significant differences were expressed most resoundingly at only either low or high ML. Typically, growth was affected by ML at one extreme, and the other extreme differed minimally from the standard. Species tolerant of dry conditions in the garden had similar growth and development regimes with dry and standard ML, such as *Echinacea*, *Lavandula*, and *Perovskia*. When water availability was high for all species shoot fresh weight increased, except for *Salvia* and *Sedum.*

Water availability can limit nutrient availability. Water availability relates to nutrient solubilization in a root medium, and how available these nutrients potentially are to the roots. Overall, the mean root-medium EC for 15 herbaceous perennials from the means of three moisture levels was similar, 1.28 $dS \cdot m^{-1}$. As moisture level increased, the amount of fertilizer applied also increased, which would typically lead to higher soluble salts in a non-leaching method. A relative similar EC for all ML could be interpreted as evidence that nutrients accumulated in the dry treatment faster than in the standard or wet, or could also be that nutrients were removed faster from the wet treatment. If EC value increased as moisture increases then water was probably not limiting nutrient availability.

Plant species' response to different levels of water and nutrient availability differed also. Root-medium EC values for *Gaillardia*, *Hemerocallis*, *Hibiscus*, and *Salvia* decreased as ML increased, which could indicate low ML can inhibit mass flow of nutrients to the plant roots and decrease growth. *Coreopsis verticillata*, *Rudbeckia*, and *Sedum* at a high ML led to elevated soluble salts, probably due to accumulation of fertilizer nutrients.

The relationship between irrigation volume and amount of fertilizer applied with CLF is important in minimal and non-leaching regimes (Yelanich and Biernbaum, 1994). With the high ML, not only does the amount of water applied increase, but also, the quantity of nutrients applied to the root zone increases. Eventually, high soluble salts in root medium can potentially reduce availability of water to the plants, and thus reduce growth. In this experiment, the high moisture level had a 73 % increase in total applied water over the high FC, but the high FC only had 14 % increase in total applied N over the high ML. With high FC, fresh weight decreased and was more likely due to increased root-medium soluble salts (1.74 vs. 1.27 $dS \bullet m^{-1}$) than decreased water applied (4.17 vs. 7.25 L) or increased applied N (1.04 vs 0.91 g). In comparison, high ML soluble salts, 1.27 $dS \bullet m^{-1}$, remained in an acceptable range and plant growth was not inhibited. Warncke (1990) assigned soluble salt values between 0.5 to 0.99 $dS \bullet m^{-1}$ as suitable for most established plants. Further, values between 1.00 to 1.49 $dS \bullet m^{-1}$ are considered higher than desired, but reduced growth is typically observed at values of 1.50 to 1.99 $dS \bullet m^{-1}$. Overall, high FC produced acceptable plant quality and no visible signs of toxicity, however, high soluble salts in root zone could create unpredictable plant quality in post production environments. A linear increase in inflorescence and shoot fresh weight with increasing water availability and not increasing fertilizer, can be interpreted as an indication of the relative importance of how water availability can have a greater influence on growth, in both dry matter and cellular enlargement, over fertilizer concentration.

Low FC plants demonstrated acceptable growth and development, and no visible deficiency symptoms were evident. Preplant charges can last up to 2-3 weeks if minimal leaching occurs or longer in non-leaching systems (Argo and Biernbaum, 1995). Additionally, the amount of applied N for low FC was 50 % less than applied with low ML, yet in 14 out of 15 species, shoot fresh weight of low FC was either the same or greater than low ML. Minimal or non-leaching regimes allows growers to focus on the amount (in grams of N) of fertilizer applied to the root zone. Low FC plants grew normally as long as fertilizer was applied at each irrigation, evident by the low FC final mean EC measurement of 0.99 $dS \bullet m^{-1}$. In constant liquid fertilization, as more water is applied more fertilizer is applied, so as irrigation is increased more fertilizer is automatically applied (Yelanich, 1991). There is no need to change fertilizer concentration. The low FC might not work as well when leaching is occurring (Yelanich and Biernbaum, 1994). Acceptable growth with higher than normally recommended media EC can also be explained based on the higher Ca and Mg of our irrigation water, which accumulate under a non-leaching system and contribute significantly to root-medium EC.

A decrease in shoot growth may be attributed to low nutrient levels in the root medium, but root:shoot ratio must be considered. The roots of *Echinacea*, *Hosta*, and *Hemerocallis* were washed and visually observed for all eight pots from the three FC treatments. The three species had increased root mass with decreasing fertilizer rates (observation only). In a separate study, at low FC *Hydrastis canadensis* L. increased by 41% in root mass compared to high FC (unpublished data). Higher soluble salts in the media due to increasing FC possibly could have limited root growth, and resulted in a decreased root mass within the pot. The low root:shoot ratio limits the plant's potential to acquire both water and nutrients, reducing the plant's adaptability to survive abrupt changes to root-zone conditions, and enhancing susceptibility to excess drying, saturation, or disease infestation. Root mass production is important to consider for herbaceous perennial production in addition to post production purposes. Future studies should monitor root mass response to water and nutrient availability.

Post Production and Fertilizer Runoff. Most herbaceous perennial species are directly cultivated from the wild, where tolerances for low water and nutrient availability and pH extremes may be developed for survival. Differences in the nature of crop responses to nutrient stress have been compared between agricultural crops selected for greater productivity and reproductive output and species that have evolved in nature, particularly under low-nutrient conditions (Chapin, 1980). From the growth and development responses of these15 herbaceous perennials over a range of water and nutrient availability and root-medium pH, acceptable growth appeared with adequate ML and relatively low FC, and a pH tolerance ranging from 5.0 to 7.1. High fertilization practices not only can lead to excess nutrient runoff with leaching practices and produce more lush shoot growth, but also could decrease root mass, increasing the crops sensitivity to cultural management problems, such as sunburn damage or insect damage. Consideration of plant quality after production through marketing and in the garden is important. Beyond differences due to plant morphology, percent dry weight may be useful to evaluate plant stress during production. An increase in percent dry weight could reflect a water or nutrient availability limitation possibly from either low moisture or high soluble salts in the root medium, which could affect expansive growth in plant tissue. Good shoot growth with poor root growth may cause problems when a plant is placed in the retail store or garden. Roots are what keep herbaceous perennials and ultimately the customer coming back.

In general, herbaceous perennials can be successfully grown with irrigation and fertilization techniques similar to those used for annual bedding plants. As with bedding plants, the risk of fertilizer runoff can be very low as long as the nutrient solution is applied directly to the media.

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Table 1. The growth and development of 15 herbaceous perennials grown under standard root-zone conditions and forced into flower in the greenhouse environment, including initial plant material size and weeks of cold treatment. Growth and development data were measured at first open flower and represent the mean of eight values for the standard treatment plants. BR=Bareroot.

Species	Plant material	Weeks at 5 °C	Plant date	Days to flower	Flower[z] number	Final[y] node	Plant ht (cm)	Shoot fresh wt	% Shoot dry wt
Coreopsis grandiflora Hogg ex Sweet 'Sunray'	BR	10	12/28	51	27	6	52	143	11.0
Coreopsis verticillata L. 'Moonbeam'	125 cell	0	12/12	56	173	9	54	38	24.5
Echinacea purpurea (L.) Moench 'Magnus'	70 cell	10	12/28	70	5	13	71	93	18.9
Gaillardia x *grandiflora* Van Houtte 'Goblin'	70 cell	13	2/23	46	35	15	22	180	9.9
Hemerocallis L. 'Stella de Oro'	BR	15	2/23	51	10	6	35	22	19.3
Heuchera sanguinea Engelm 'Firefly'	BR	10	12/28	51	2	10	34	47	19.6
Hibiscus moscheutos L. 'Disco Belle Hybrid'	305 cell	0	11/3	94	32	27	75	127	19.8
Hosta (Otto & Dietr.) L. H. Bail. 'undulata variegata'	BR	15	1/27	73	15	11	58	23	19.0
Lavandula angustifolia Mill. 'Munstead'	70 cell	15	3/30	47	15	23	33	45	22.1
Leucanthemum x *superbum* Bergman ex J. Ingram 'Snow Cap'	2 1/2"	6	12/15	57	12	18	15	98	11.3
Perovskia atriplicfolia Benth	BR	5	11/25	69	46	21	81	52	24.0
Rudbeckia fulgida Ait. 'Goldsturm'	2 1/2"	12	1/29	72	30	9	39	146	17.9
Salvia x *superba* Stapf. 'Blue Queen'	125 cell	9	3/2	38	15	5	32	31	15.8
Scabiosa caucasica Bieb 'Butterfly Blue'	70 cell	10	1/12	43	26	10	36	62	18.2
Sedum H. Ohba 'Autumn Joy'	70 cell	0	11/3	92	4263	20	27	269	7.7

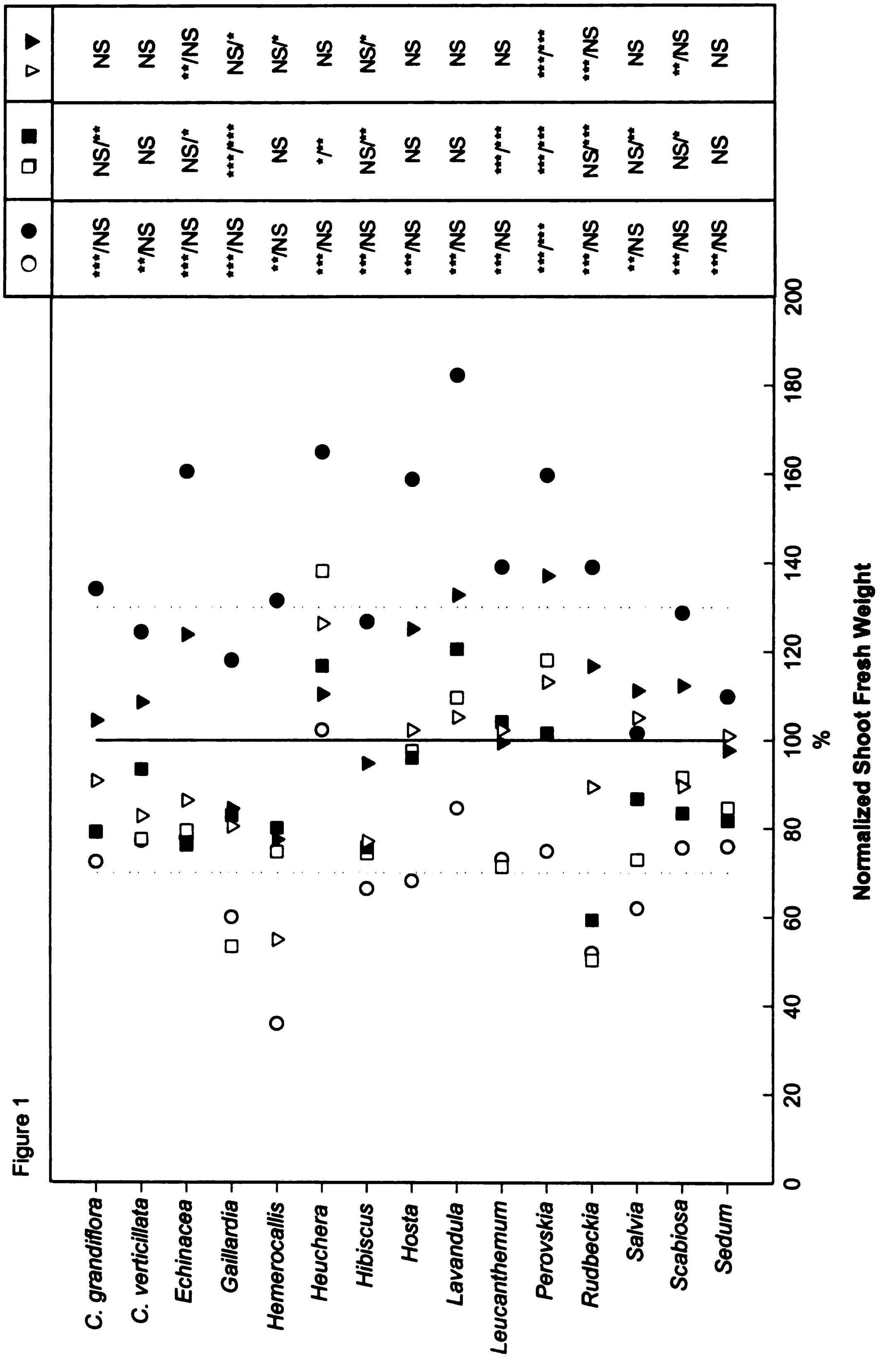
[z]Number of visible flower buds or inflorescences on the plant.
[y]Number of nodes on the stem to the first flower.

Table 2. Low, standard, and high values of total applied water for moisture levels (ML), total applied water-soluble fertilizer (WSF)-N and final root-medium electrical conductivity (EC) (1:2 dilution) for fertilizer concentrations (FC), and final root-medium pH for N-form nutrient solution (NS) for media used in growing 15 herbaceous perennials.

	Applied water (liters)			Total applied WSF-N (g/pot)			Medium EC (dS•m^{-1})			Medium pH		
	Low	Standard	High	Low	Standard	High	Low	Standard	High	Basic	Standard	Acidic
Species		ML			FC			FC			NSR	
Coreopsis grandiflora 'Sunray'	2.38	4.25	6.63	0.12	0.53	0.88	1.25	1.71	1.86	7.1	5.7	6.5
Coreopsis verticillata 'Moonbeam'	2.50	3.75	6.25	0.22	0.47	0.94	1.08	1.55	1.92	7.0	6.0	6.1
Echinacea purpurea 'Magnus'	3.50	5.50	9.63	0.16	0.69	1.13	1.00	1.16	1.92	7.3	6.0	6.8
Gaillardia x *grandiflora* 'Goblin'	3.50	5.75	7.00	0.14	0.72	1.06	0.84	1.01	1.53	7.1	6.5	6.0
Hemerocallis 'Stella de Oro'	2.50	4.00	7.63	0.12	0.50	0.94	0.57	1.08	1.49	6.4	5.7	5.2
Heuchera sanguinea 'Firefly'	2.38	3.75	7.25	0.14	0.47	0.88	0.99	1.39	1.67	6.9	5.5	6.1
Hibiscus moscheutos 'Disco Belle Hybrid'	4.38	7.50	9.13	0.40	0.94	1.50	1.31	1.69	2.23	7.9	6.3	5.8
Hosta 'undulata variegata'	2.25	4.50	6.13	0.13	0.56	0.94	0.86	1.12	1.50	6.9	5.8	5.9
Lavandula angustifolia 'Munstead'	2.75	4.25	6.63	0.13	0.53	0.94	1.10	1.50	2.09	6.0	4.8	5.0
Leucanthemum x *superbum* 'Snow Cap'	2.88	4.00	6.38	0.12	0.50	0.94	0.85	0.99	1.57	7.6	6.1	6.7
Perovskia atriplicfolia	3.38	6.00	8.00	0.40	0.75	1.25	1.42	1.67	2.39	7.0	5.6	5.7
Rudbeckia fulgida 'Goldsturm'	5.13	10.00	13.75	0.22	1.25	1.69	1.16	1.67	2.17	8.0	5.2	5.6
Salvia x *superba* 'Blue Queen'	1.75	2.75	3.88	0.08	0.34	0.63	0.80	1.01	1.30	7.2	6.0	6.4
Scabiosa caucasica 'Butterfly Blue'	2.38	3.75	4.63	0.11	0.47	0.81	0.79	1.09	1.39	7.1	5.5	6.6
Sedum 'Autumn Joy'	2.88	5.50	5.88	0.31	0.69	1.13	0.85	0.87	1.00	7.7	5.7	6.0
Low	1.75	2.75	3.88	0.08	0.34	0.63	0.57	0.87	1.00	6.0	4.8	5.0
High	5.13	10.00	13.75	0.40	1.25	1.69	1.42	1.71	2.39	8.0	6.5	6.8
Mean	2.97	5.02	7.25	0.19	0.63	1.04	0.99	1.30	1.74	7.2	5.8	6.0

Figure 1. Normalized shoot fresh weight at flower. The low and high moisture levels (ML) (○ and ●), fertilizer concentrations (FC) (❑ and ■), and nutrient-solution reactions (NSR) (∇ and ▼) of root-zone conditions were divided by standard root-zone conditions and percentage differences calculated. Hollowed symbols represent low treatments and filled symbols represent high treatments. Data represents the mean of eight values. Significant trends (Linear/Quadratic). NS, *,**,*** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, for three treatments.

Figure 1


C. grandiflora
C. verticillata
Echinacea
Gaillardia
Hemerocallis
Heuchera
Hibiscus
Hosta
Lavandula
Leucanthemum
Perovskia
Rudbeckia
Salvia
Scabiosa
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Normalized Shoot Fresh Weight
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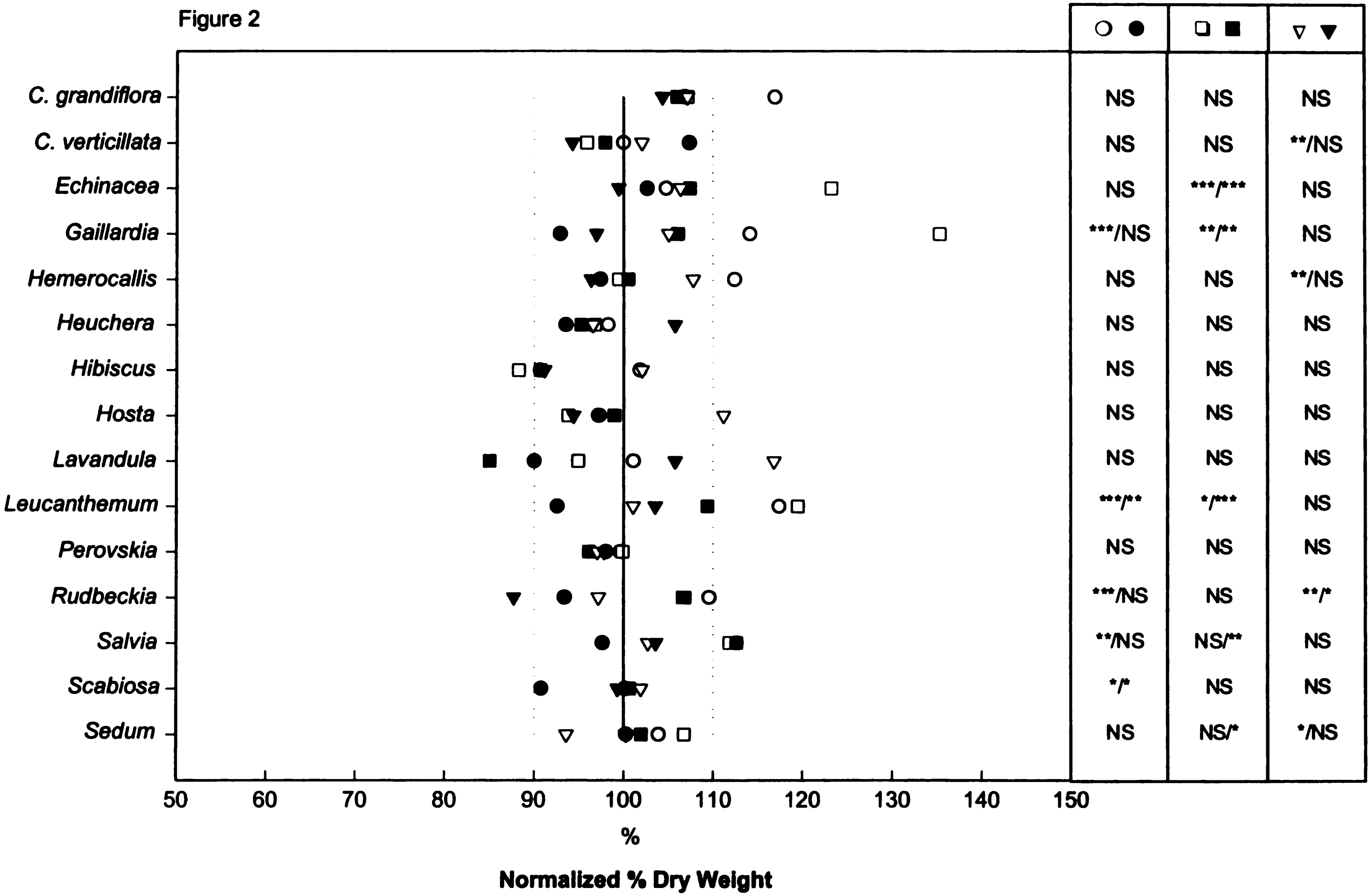
Figure 2. Normalized % dry weight at flower. The low and high moisture levels (ML) (○ and ●), fertilizer concentrations (FC) (□ and ■), and nutrient-solution reactions (NSR) (∇ and ▼) of root-zone conditions were divided by standard root-zone conditions and percentage differences calculated. Hollowed symbols represent low treatments and filled symbols represent high treatments. Data represents the mean of eight values. Significant trends (Linear/Quadratic). NS, *,**,*** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, the three treatments.

Figure 2


C. grandiflora
C. verticillata
Echinacea
Gaillardia
Hemerocallis
Heuchera
Hibiscus
Hosta
Lavandula
Leucanthemum
Perovskia
Rudbeckia
Salvia
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Normalized % Dry Weight
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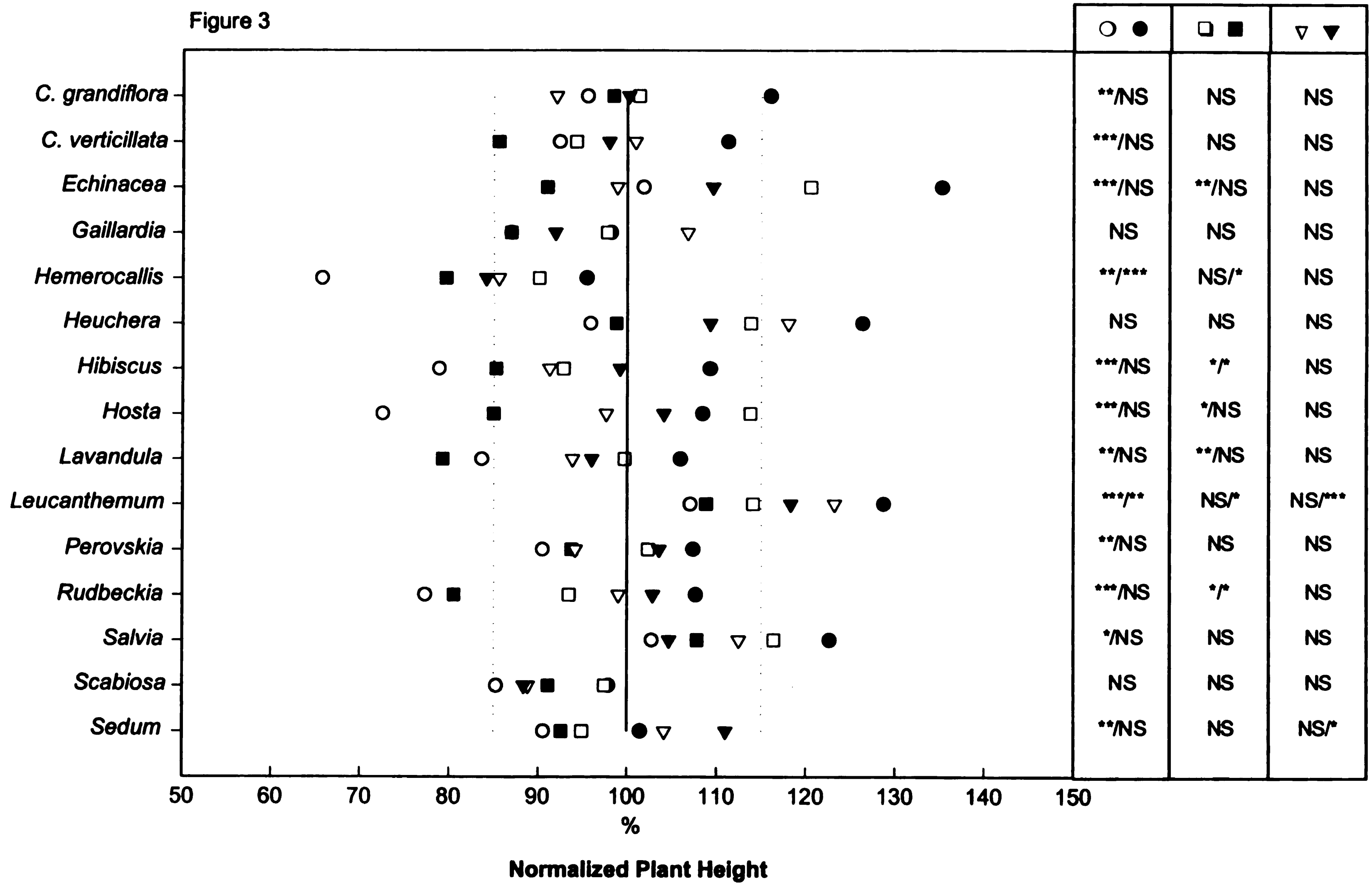
Figure 3. Normalized plant height at flower. The low and high moisture levels (ML) (○ and ●), fertilizer concentrations (FC) (□ and ■), and nutrient-solution reactions (NSR) (▽ and ▼) of root-zone conditions were divided by standard root-zone conditions and percentage differences calculated. Hollowed symbols represent low treatments and filled symbols represent high treatments. Data represents the mean of eight values. Significant trends (Linear/Quadratic). NS, *,**,*** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, the three treatments.

Figure 3



C. grandiflora
C. verticillata
Echinacea
Gaillardia
Hemerocallis
Heuchera
Hibiscus
Hosta
Lavandula
Leucanthemum
Perovskia
Rudbeckia
Salvia
Scabiosa
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Normalized Plant Height
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CHAPTER II

FOLIAR NUTRIENT CONCENTRATIONS OF FIFTEEN CONTAINER-GROWN HERBACEOUS PERENNIALS IRRIGATED WITH SIX NUTRIENT SOLUTIONS

Foliar Nutrient Concentrations of Fifteen Container-grown Herbaceous Perennials Irrigated with Six Nutrient Solutions

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Abbreviations: ANS, acidic nutrient solution; BNS, basic nutrient solution; EC, electrical conductivity; FC, fertilizer concentration; HPS, high pressure sodium; ML, moisture level; MSU, Michigan State University; NS, nutrient solution; NSR, nutrient-solution reaction; RO, reverse osmosis; SME, saturated media extract; WSF, water-soluble fertilizer.

Foliar Nutrient Concentrations of Fifteen Container-grown Herbaceous Perennials Irrigated with Six Nutrient Solutions

Additional index words. Ammonium, macronutrients, micronutrients, nutrition phosphorus, root-medium pH, soilless media,

Abstract. Shoot and leaf tissue macronutrient and micronutrient concentrations were determined for 15 container-grown herbaceous perennial species forced into flower in a greenhouse. Nutrient solution concentrations were altered by three different macronutrient fertilizer concentrations of water-soluble fertilizer, 125N-20P-125K, 31N-11P-31K, and 250N-32P-250K, while micronutrient concentrations remained constant. Averaged over all species, the six nutrient solutions produced a range of values for each macronutrient that varied by $\leq$0.5, 1.0, or $\geq$1.5 % for P and Mg^{2+}, N and Ca^{2+}, or K, respectively. In general, N and P showed minimal differences while K concentrations increased with increasing fertilizer rate. The ranges of Fe, Mn, Zn, B, and Cu concentration over all treatments were 33 to 1515, 40 to 483, 21 to 244, 16 to 205, and 1 to 10 $\mu g \cdot g^{-1}$, respectively. Micronutrients were minimally affected for most species, but some species accumulated a particular trace element at low fertilizer concentration or low medium pH. Nutrient solutions differing in %NH_4-N, Ca^{2+}, and Mg^{2+} and irrigation water source were applied to create a basic (5% NH_4-N, 167 Ca^{2+}, 60 Mg^{2+}, 320 $CaCO_3$ ($mg \cdot L^{-1}$)), neutral (25% NH_4-N, 133 Ca^{2+}, 30 Mg^{2+}, 120 $CaCO_3$ ($mg \cdot L^{-1}$)), or acidic (50% NH_4-N, 15 Ca^{2+}, 5 Mg^{2+}, 20 $CaCO_3$ ($mg \cdot L^{-1}$)) reaction with the root-medium pH to evaluate

the effect of water-soluble fertilizer and irrigation water source on nutrient tissue concentrations. Generally, P increased and Ca^{2+} and Mg^{2+} decreased with increasing % NH_4-N.

Introduction

Mills and Jones (1996) reported nutrient levels in dried foliar tissue for over 100 herbaceous perennial species mostly from container production in a nursery or from the landscape. These values provide nutrient tissue averages, or in some cases sufficiency ranges, based on outdoor production, but further evaluations are necessary to establish nutrient ranges of herbaceous perennials grown over a range of root zone conditions in a greenhouse. In a greenhouse, one fertilizer concentration applied to one root medium designed to maintain a desired pH and electrical conductivity (EC) can be used to grow a wide variety of container-grown ornamental crops in common light and temperature conditions. However, when problems arise other than those induced by temperature and light, the problems are usually related to either one or more of three different factors: 1) water and air proportions in the medium caused by over or under watering and the medium's physical condition; 2) quantity of fertilizer being too high or too low or some unique nutrient deficiency that is species-specific; or 3) sensitivity to pH extremes causing a nutrient toxicity, e.g. seed geranium (*Pelargonium xhortorum* Bailey) and marigold (*Tagetes erecta* L.) response to low pH, or a nutrient deficiency, e.g. petunia (*Petunia xhybrida* hort. Viim.-Andr.) chlorosis due to high pH.

General fertilization requirements and nutrient management of greenhouse container-grown floricultural crops has been addressed in Bunt (1988), Hanan (1998), Joiner et al. (1983), Reed (1996), and Nelson (1998). Argo and Biernbaum (1996) reported tissue concentrations for Impatiens (*Impatiens wallerana* Hook. F.) grown with 12 nutrient solutions formulated from 4 water sources and 3 water-soluble fertilizers. Argo (1996) then screened a range of bedding plant species with acidic, neutral, and alkaline nutrient solution (NS) with low and high Ca^{2+} and Mg^{2+} produced over seven weeks. Tissue concentrations among species showed similar increasing trends of Ca^{2+} and Mg^{2+} uptake, but each species had different ranges of concentration. Impatiens consistently had 0.6% and 0.2% greater Ca^{2+} and Mg^{2+} tissue level than eight and six other bedding plants, respectively, with all NS. A method of comparison between species is necessary to identify potential problems related to nutrient availability and root-medium pH. Based on the fact that many herbaceous perennial plants have not undergone intensive genetic selection under greenhouse container production performance, one could hypothesize the nutrient requirements might generally be lower compared to flowering potted plants, selected for performance under higher rates of fertilization common in container plant production. Differences in the nature of crop responses to nutrient stress have been compared between agricultural crops selected for greater productivity and reproductive output and species that have evolved in nature, particularly under low-nutrient conditions (Chapin, 1980). As more herbaceous perennials are forced in greenhouse production, nutrient related management problems could become more common.

Strategies, such as minimal leaching, have been developed to reduce greenhouse fertilizer and water use along with minimizing fertilizer runoff (Biernbaum, 1992). As fertilization rates become lower to meet actual fertilizer requirements, the proper selection of fertilizer solutions becomes more critical. A major concern in minimal leaching systems is the accumulation of soluble salts in the root medium that could be detrimental to plant growth. Typically, as applied fertilizer rates increase, foliar concentrations of macronutrients increase. Nutrient antagonisms can occur at high concentrations. For instance, if plants are supplied with a high concentration of one cation, e.g. NH_4^+, then other cations, particularly Ca^{2+}, Mg^{2+}, and K^+ concentrations could be lower (Bunt, 1988). Lang and Pannkuk (1998) found foliar N-P-K concentrations to be highest in New Guinea impatiens 'Barbados' (*Impatiens xhawkeri* Bull) treated with 250 $mg•L^{-1}$ N in a minimal leaching system, while Ca^{2+} and Mg^{2+} concentrations were highest at lower fertilizer concentrations, 84 $mg•L^{-1}$ N, and both had a final pH of 5.5. Argo and Biernbaum (1996) concluded at a fertilizer rate of 200 $mg•L^{-1}$ N, Ca^{2+} availability was not reduced by a low pH in peat-based media or higher NH_4-N, but availability was from a lack of sources applied to the medium. Generally, the lower the Ca^{2+} and Mg^{2+} concentration applied in the NS, the lower the Ca^{2+} and Mg^{2+} tissue values.

Media based on mineral soils typically contain sufficient amounts of micronutrients and do not require additional sources, unlike peat-based media which can be deficient in B, Cu, and Fe (Bunt, 1988). Peterson (1981) addressed the availability of micronutrients in peat-based media for greenhouse crops based on nutrient concentrations in fresh, unplanted root media, and found an inverse relationship existed between pH and availability of micronutrients except Mo. In addition to micronutrient's presence in root media components and possibly in the irrigation water source (Bunt, 1988), Argo and Biernbaum (1995) looked at the relationship between root-medium pH and tissue concentration of micronutrients (Fe, Mn, Zn, Cu, and B) on Impatiens. They found foliar tissue levels of Fe, Zn, and B decreased with increasing pH, Cu was unaffected by pH, and Mn concentration increased as the pH decreased or increased from pH 6.

The primary objective of this research was to assess macronutrient and micronutrient concentration in foliar tissue from container-grown herbaceous perennials under a range of root-zone conditions. A second objective was to develop a simple method of screening container-grown ornamental crops for their nutrient concentration responses to nutrient solutions varying in concentration and reaction.

Materials and Methods

Design setup. The experiment included 12 treatments composed of a standard and two types of media, five NS, two irrigation frequencies, and two root-medium pH. The treatments were selected to compare a range of root-zone conditions in moisture level (ML), media components, N-P-K-Ca concentration, water-soluble P availability, nutrient-solution reaction (NSR), and initial root-medium pH to one standard root-zone regime, comprising a standard level for all six factors. A completely randomized design was used with 8 replications (plants) for each treatment. Water, media, and root-medium pH treatments are reported in Morrison and Biernbaum (1999). Only six treatments were sampled for plant nutrient concentrations.

To evaluate the effect of each factor on species nutrient concentration, each factor was statistically analyzed as a comparison between low, standard, and high levels, except phosphorus treatment with just a low and standard level, using SAS (SAS Institute, Cary, NC.) general linear models procedure (PROC GLM) for analysis of variance and Duncan's Multiple Range Test for mean separation (MEANS / DUNCANS).

Media Preparation. Root medium consisted of the following components: select Canadian sphagnum peat (Fisons professional black bale peat, Sun Gro Horticulture, Bellevue, WA) with long fibers and little dust (Von Post scale 1-2; Puustjarvi and Robertson 1975), and perlite. Sufficient amounts of dolomitic hydrated lime ($Ca(OH)_2$ and $Mg(OH)_2$ with 34% Ca^{2+} and 20% Mg^{2+}) were added to increase the pH of the medium to 5.8 to 6.2. The amount of hydrated lime added per cubic meter (yard) was 1.5 kg (2.5 lbs.). Hydrated lime was selected over carbonate lime so little or no residual lime would be present in the medium to buffer future pH changes (Argo and Biernbaum, 1996). In addition to the lime, a preplant charge consisting of 0.6 kg (1 $lb•yd^{-3}$) KNO_3, 0.3 kg (0.5 $lb•yd^{-3}$) triple superphosphate (0N-19.8P-0K), and 0.9 kg (1.5 $lb•yd^{-3}$) gypsum; 0.07 kg (0.1 $lb•yd^{-3}$) fritted trace elements; 0.3 kg (0.5 $lb•yd^{-3}$) wetting agent (Aquagro "G", Aquatrols, Pennsaulken, NJ) per m^3 of medium were incorporated into the medium at mixing. Sufficient reverse osmosis (RO) water was added at mixing to bring the moisture content of the medium to 40-50% of container capacity. At planting, the medium had pH of 5.9, an EC of 1.7 $dS \cdot m^{-1}$, and (in $mg \cdot L^{-1}$) 130 NO_3-N, 39 PO_4-P, 180 K^+, 105 Ca^{2+}, and 60 Mg^{2+}, as measured with a saturated media extract (SME) analysis with RO water as the extractant (Warncke, 1986).

Nutrient solutions. NS-1, standard, was a water-soluble fertilizer (WSF) made of $Ca(NO_3)_2$, KNO_3, NH_4NO_3, and $NH_4H_2PO_4$ that contained ($mg \cdot L^{-1}$) 125N-20P-125K-33Ca-0Mg-0SO_4 mixed with acidified well water, produced by adding H_2SO_4 (93%) to the well water which provided a pH 5.8, an EC of 0.7 $dS \cdot m^{-1}$, concentrations of 100 Ca^{2+}, 30 Mg^{2+}, and 91 SO_4-S ($mg \cdot L^{-1}$), and a titratable alkalinity to pH 4.5 of 120 mg $CaCO_3 \cdot L^{-1}$. NS-1, NS-2, NS-3, and NS-4 remained constant at 25% NH_4-N, 30 Mg^{2+}, 12 Na^+, and 91 SO_4-S ($mg \cdot L^{-1}$), but NS-2 and NS-3 varied in concentration of N-P-K-Ca $mg \cdot L^{-1}$, 62N-14P-62K-116Ca and 250N-32P-250K-166Ca, respectively. NS-2 and NS-3 were made with the same fertilizer salts and water as NS-1. The fertilizer concentration (FC) of NS-1 was cut in half to create a low FC, NS-2, and doubled to create a high FC, NS-3. After five weeks into the experiment, N-P-K-Ca rate of NS-2 was halved from 62N-14P-62K-16Ca to 31N-11P-31K-8Ca, because the root-medium EC reading was similar to NS-1, not lower as desired. For NS-4, low P, $NH_4H_2PO_4$ was substituted with urea to create an intended zero P WSF. A zero level was not maintained due to an unlabeled component in the micronutrient source, as explained later.

A basic NS (BNS), NS-5, and an acidic NS (ANS), NS-6, were developed to create NSR on the root-medium pH. For NS-5 and NS-6, concentration of N-P-K was maintained at a constant 125N-20P-125K, but % NH_4-N, Ca^{2+}, Mg^{2+}, and SO_4-S was varied. NS-5 was a WSF made from $Ca(NO_3)_2$, $Mg(NO_3)_2$, KNO_3, and KH_2PO_4

that contained 5% NH_4-N, with 67 Ca^{2+}, 30 Mg^{2+}, and 0 SO_4-S ($mg \cdot L^{-1}$) mixed with well water that had a pH of 7.8, an EC of 0.6 $dS \cdot m^{-1}$, concentrations of Ca^{2+}, Mg^{2+}, and Na^+ similar to that of the well water in NS-1, and a titratable alkalinity to pH 4.5 of 320 mg $CaCO_3 \cdot L^{-1}$. NS-6 was a WSF made from NH_4NO_3, urea, KNO_3, K_2SO_4, and $NH_4H_2PO_4$ that contained 50% NH_4-N with 0 Ca^{2+}, 0 Mg^{2+}, and 27 SO_4-S ($mg \cdot L^{-1}$) mixed with RO purified well water that had a pH 5.5, an EC of 0.1 $dS \cdot m^{-1}$, and concentrations of 15 Ca^{2+}, 5 Mg^{2+}, 27 Na^+, and 1 SO_4-S ($mg \cdot L^{-1}$), and a titratable alkalinity to pH 4.5 with <20 mg $CaCO_3 \cdot L^{-1}$.

Micronutrients (Fe, Mn, Zn, Cu, B, and Mo) were added to all NS with a commercially available blended chelated material [Compound 111 (1.50Fe-0.12Mn-0.08Zn-0.11Cu-0.23B-0.11Mo) Scotts, Marysville, Ohio] at a constant 50 $mg \cdot L^{-1}$. This rate is higher than usually incorporated in preblended WSF used at a rate of 125 mg $N \cdot L^{-1}$. Typically, when WSF rates are diluted or concentrated, micronutrient levels are simultaneously diminished or elevated, respectively. However, in an attempt to eliminate potential trace element deficiencies with low FC or toxicities with high FC, micronutrient levels were maintained constant for all NS.

Irrigation. The eight plants in each treatment were irrigated at the same time independent of other treatments. Time for irrigation was determined gravimetrically when four or more of eight pots within a single treatment reached a target weight of 500 g, based on predetermined weight of the pot, plant, and medium. Pots were checked daily for target weight at which point 250 ml was applied by top watering.

Plant culture. During Oct.1, 1997 to June 1, 1998 each species was forced into flower at different times, based on forcing schedules developed at Michigan

State University (MSU), E. Lansing, MI. The species studied were received from commercial growers, and upon arrival were given the appropriate species-specific cold treatment (Morrison and Biernbaum, 1999) recommended by MSU herbaceous perennial research. After cold treatment, 96 plants of each species plus approximately 16 plants for guard rows were transplanted into 14-cm (1.5 L) square plastic containers, containing one of the three medium formulated at MSU. Eight pots in each treatment were placed on water-catcher trays (Landmark Plastic, Akron, OH), providing a non-leaching system. The greenhouse heating and cooling setpoints were 20 °C and 23 °C. Supplemental lighting was provided with high pressure sodium lamps (HPS) from 0700 to 2200 HR at ≈90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at plant level, in two glass greenhouse sections at MSU in East Lansing, MI. Due to the sun sensitivity of *Hosta*, a 50% aluminum shade cloth (LS Americas, Charlotte, NC) covered the plants during production.

Data collection and presentation. Shoot fresh and dry weight were determined when majority of all treatments for a particular species were in flower. Root-medium pH and EC were monitored every three weeks and at the end of experiment by a 1:2 dilution method. Samples were removed from the lower half of the pot, and consisted of approximately 25 ml per pot from four of the eight pots per treatment. Replication for the final samples was made by sampling from both sets of four pots per treatment. Nutrient content in the root medium from the standard treatment of each species was tested using SME method with RO purified water as extractant.

Leaf tissue samples were collected at flower and analyzed for the six NS. Each sample came from four plants within a treatment, providing 2 samples for each of the six treatments. Mature leaves were collected from the upper part of the plant at flower. Usually leaf samples are collected prior to anthesis, however this was not considered feasible since flowering and plant size data were collected from the same plant. Leaf samples were washed in 0.1 N HCl for 1 minute and rinsed in RO purified water for 1 minute prior to drying at 60 °C in a forced air drying oven. Dried samples were ground and sent to a commercial plant testing laboratory (MicroMacro Inc., Athens, GA), where they were analyzed for nitrogen after Kjehldahl digestion and for other nutrients by inductively coupled plasma spectrometry. In addition, a sample, from the whole above ground biomass used for dry weights, was combined and ground for nutrient analysis from the standard treatment only.

Recommended tissue analysis guidelines, consisting of minimum and maximum critical levels and standard desired levels or sufficiency ranges, based on a wide range of floriculture crops, are incorporated into Figures 1A-E and 2A-E (Hanan, 1998, Reed, 1996, and Nelson, 1998).

Results and Discussion

Whole shoot growth. At flowering, all plants appeared healthy and were of marketable quality and size. Plant growth and flowering results are reported in Morrison and Biernbaum (1999). Shoot dry weights ranged from 4.3 g for *Hemerocallis* to 26.1 g for *Rudbeckia* (Table 1). The standard FC had the greatest dry weight, while both low and high FC overall mean decreased by 16% and 15%, respectively, and minimal differences were observed with low P and NSR treatments. Overall differences in percent dry weight for all treatments was minimal. There were no obvious signs of nutrient deficiencies or toxicities for most species, the exception being *Rudbeckia* and *Hibiscus*.

Media analysis. The final root-medium pH averaged over 15 species was similar for low P, low FC, standard, and ANS, 5.61, 5.73, 5.74, and 6.03, respectively. High FC pH decreased to 5.25 and BNS pH increased to 7.03, both out of target range, 5.8 to 6.2 (Warncke and Krauskopf, 1983). Soluble salt levels at flower increased with increasing fertilizer 0.99, 1.30, and 1.74 $dS \bullet m^{-1}$, respectively, and decreased with both ANS and BNS, 1.08 and 0.90 $dS \bullet m^{-1}$. Low P EC was similar to the standard, 1.31 $dS \bullet m^{-1}$. The target range for EC values from a 1:2 dilution method is 0.5 to 0.99 $dS \bullet m^{-1}$ (Warncke, 1990). Further, values between 1.00 to 1.49 $dS \bullet m^{-1}$ are considered higher than desired, but reduced growth is typically observed at values of 1.50 to 1.99 $dS \bullet m^{-1}$.

Macronutrient tissue analysis. Averaged over all species, the six NS produced a range of values for each macronutrient that varied by $\leq$0.5, 1.0, or $\geq$1.5 % for P and Mg^{2+}, N and Ca^{2+}, or K, respectively.

Nitrogen values were consistently between 5.0 to 6.0%, even for the FC at 31 mg $N \bullet L^{-1}$ (Figure 1A). Argo and Biernbaum (1997a) found N tissue concentrations in Impatiens higher with increasing NH_4-N:NO_3-N at a fertilizer rate of 200 $mg \bullet L^{-1}$ N after four weeks, accompanied by a decreasing media pH. In this experiment, the ratio of NH_4-N:NO_3-N had minimal effect on shoot dry weight and tissue N (Figure 1A).

Nitrogen levels were higher than expected and expressed little to no differences among all treatments. In comparison, Mills and Jones (1996) had N levels for the 15 herbaceous perennials ranging from 1.3 to 3.7% for mature leaves from new growth. Their samples were from container production in the nursery or from botanical gardens or arboretums. One explanation for the high levels of N could be attributed to the age of the tissue sample, which were taken at flower or shortly after from mature leaves. At this stage of growth, nitrogen may have accumulated to higher levels than normally found in recently mature leaves. Differences in N concentration that may have influenced plant size early in development, may have disappeared once final plant size was determined by flower bud initiation. Dole and Wilkins (1991) found N concentrations highest in upper leaves of vegetative poinsettia (*Euphorbia pulcherrima* Willd. 'Gutbier V-14 Glory') plants consistently at 3, 6, and 9 weeks, and also found the highest N concentration values from the first five apical leaves per plant at 6 weeks with only a 0.1% decrease in the tissue of an older plant sampled 3 weeks later.

Phosphorus values ranged from 0.2 to 1.2%, approximately a 6 fold difference (Figure 1B), and showed the most differences of all macronutrients and micronutrients for the comparison of low P and the standard treatment. P concentrations increased and minimally decreased with ANS and BNS, respectively, where the pH of the latter treatment increased to a mean of 7.1. Our results are similar to Argo and Biernbaum (1996), where as the pH increased, levels of available water-soluble P in the root medium decreased, but the effect on shoot tissue concentration was minimal until the pH increased above 7.6.

Many P values were between 0.2 and 0.4%. Based on experience with many greenhouse flower crops P deficiency symptoms are unlikely until 0.2% or below. Phosphorus deficient symptoms or tissue levels (<0.2 %) were not observed. During the course of the experiment, a unlabeled P component in the commercially available micronutrient blend was revealed in a nutrient analysis, and led to the overall P delivery to root zone of 8 mg•L^{-1} P and not the intended 0 mg•L^{-1} P. The corrected P values for the FC nutrient solutions would be 11, 20, and 32 mg•L^{-1} P as opposed to the intended concentration of 3, 12, and 24 mg•L^{-1} P. Minimal differences may also be due to the preplant P incorporated in the medium and the zero level of leaching. Since *Hemerocallis*, *Heuchera*, *Hosta*, and *Rudbeckia* maintained P levels near the critical minimum, 0.2 %, and all species lacked deficiency symptoms, possibly low levels of P fertilization (20 mg•L^{-1}) could be suggested for herbaceous perennial production with minimal leaching methods, provided root medium was initially amended with at least 0.3 kg•m^{-3} (0.5 lb•yd^{-3}) triple superphosphate (0N-19.8P-0K).

Potassium values ranged from 1.5 to 8.8% depending on species and NS, approximately a 6 fold difference (Figure 1C). Potassium differences between species were greater than the differences between FC. The desired range for K in floricultural crops is 3.5 to 5.0 %. A few species consistently had K values below 3.0%, but showed no apparent deficiency symptoms. *Coreopsis verticillata* and *Heuchera* ranged from 1.7 to 2.0 % and 1.5 to 2.5 % K, respectively. Other species tended to accumulate higher concentrations of K than the maximum critical, particularly *Leucanthemum*, which accumulated from 6.9 to 8.8%, and *Gaillardia*, from 5.5 to 8.5%. With such a range across 15 species, adjustments to the typical desired K range may need to be defined by plant species.

Calcium and Mg^{2+} ranged from 0.5 to 5.0% and from 0.3 to 1.8%, respectively, with a 10 and 6 fold range, respectively (Figure 1D-E). Several species had higher Mg^{2+} values than the recommended desired range (>0.7%). Mg^{2+} levels in MSU water, 30 mg•L^{-1}, can lead to problems particularly when not leached. Usually the container root medium is leached once a month to remove Mg or to prevent antagonism with Fe and Mn. The elevated tissue Mg levels, however, appeared to not cause any obvious nutrient problems.

In a majority of the species, Mg^{2+} concentrations declined as FC increased from low to high, particularly for *Echinacea* where Mg^{2+} concentrations decreased from 1.8 to 1.0 %. Our results agree with Lang and Pannkuk (1998) who noted Mg^{2+} values were significantly higher in New Guinea impatiens irrigated with low concentrations of N-P-K in a minimal leaching system. Calcium showed no consistent differences with varying FC. At low nutrient concentrations ion absorption is very selective and little interference is encountered, unlike at higher nutrient concentrations where ion absorption is competitive (Barker and Mills 1980). Decreased Ca^{2+} concentrations in the foliar tissue could be contributed to similar cation competition at the higher fertilizer rates. Plant uptake of Ca^{2+} and Mg^{2+} can be depressed by applications of high concentrations of other major cations, such as NH_4^+ and K^+ (Marschner, 1995).

At our standard fertilizer rate, 125 mg•L^{-1} N, but lower % NH_4-N and higher Ca^{2+} and Mg^{2+} levels, the BNS treatment, Ca^{2+} and Mg^{2+} values increased slightly. Argo and Biernbaum (1996) reported that as applied concentrations of nutrient solutions increased from 18 to 210 mg•L^{-1} Ca^{2+} and 7 to 90 mg•L^{-1} Mg^{2+}, Impatiens tissue Ca^{2+} and Mg^{2+} increased linearly by 1.4 and 0.4%, respectively, after 12 weeks growth in a medium amended with hydrated lime. The NSR was designed to produce an acidic, neutral, and basic reaction in the root medium based on water-soluble fertilizer and irrigation water source. Nutrient solubility and uptake are influenced by pH management (Peterson, 1981). In media containing hydrated lime, the NS was found to control the root-medium pH after four weeks (Argo and Biernbaum, 1997). Argo and Biernbaum (1996) concluded that Ca^{2+} availability was not reduced by low pH in peat-based media, but a lack of Ca^{2+} applied to the root medium did reduce uptake. In this study, generally, the lower the Ca^{2+} and Mg^{2+} concentration applied with NS, the lower was the tissue Ca^{2+} and Mg^{2+} values.

Differences in NS SO_4-S concentrations, ranging from 0 to 91 mg•L^{-1} SO_4-S, had no effect on foliar tissue S values.

Micronutrient tissue analysis. The ranges of Fe, Mn, Zn, B, and Cu concentration over all treatments were 33 to 1515, 40 to 483, 21 to 244, 16 to 205, and 1 to 10 μg•g^{-1}, respectively (Figure 2A-E). A few species had significant accumulations of certain trace elements outside of normal acceptable ranges. At low FC, *Echinacea*, *Hibiscus*, and *Rudbeckia* accumulated B, Zn, and Fe, respectively, at the following values, 205, 244, and 1516 μg•g^{-1} dry weight, respectively. Boron and Mo induced foliar toxicity on seed geranium at tissue levels of 337 $\mu g \cdot g^{-1}$ B and 485 $\mu g \cdot g^{-1}$ Mo (Lee et al, 1996), whereas acute B toxicity developed on begonia (*Begonia xhiemalis* Fotsch) at tissue concentrations of 125 to 258 $\mu g \cdot g^{-1}$ B (Elliot and Nelson, 1981). At lower root-medium pH, foliar tissue from Impatiens tended to accumulate higher amounts of trace elements except for Cu and Mo (Biernbaum and Argo, 1995). Iron and Zn levels were generally higher in *Hibiscus*, whereas *Lavandula* had higher levels of Fe and Mn, and *Rudbeckia* had higher levels of Fe. Accumulation of trace elements could lead to potential problems if plant material is maintained for an extended period of time. Conversely, Cu levels consistently were below recommended lower desired range of 10 $\mu g \cdot g^{-1}$ without deficiency symptoms. Many greenhouse tissue samples reviewed over the past years have been between 1 and 10 $\mu g \cdot g^{-1}$, so the critical levels may need adjustment. Lower levels are acceptable, yet need to be considered as a warning to not go too low, or problems will likely occur.

Some herbaceous perennials had Fe and Mn values considered to be deficient, while other species accumulated levels assumed toxic. The Fe values between standard and low P for *Hibiscus* doubled from 596 to 1174 $\mu g \cdot g^{-1}$ (Fig 2A), respectively, and root-medium pH decreased from 6.2 to 5.7, respectively. For most species, ANS consistently increased Fe, Mn, Zn, B, and Cu concentration in leaf tissue, yet the magnitude of the increase and its significance was strictly species-specific. Differences in root-medium pH would be expected to have the greatest effect on Fe and Mn. Higher Fe and Mn tissue levels in marigolds and seed geraniums have been attributed to low root-medium pH (Biernbaum et al, 1988) or to increasing concentrations of applied Fe in the root medium (Albano et al, 1996;

Lee et al, 1996). With *Rudbeckia*, when the root-medium pH fell below 5.5, Fe reached levels associated with toxicity, above 500 $\mu g \bullet g^{-1}$. Leaf size was reduced and leaf color was dark green with purplish tissue on the underside of the foliage. In seed geraniums Lee et al. (1996) noted reduced leaf size and production of purplish-black spots on some leaves at tissue levels of 951 $\mu g \bullet g^{-1}$ Fe. In a treatment not reported here, the root medium of *Rudbeckia* was drenched with an acidic solution, and Fe levels reached 2918 $\mu g \bullet g^{-1}$ at a pH of 4.6. Growth was inhibited, possibly due to application method, but the foliage still developed purplish tissue, which eventually led to necrosis of older foliar tissue. In a follow up study, *Rudbeckia* were grown with different liming rates and sources, 1.5 $kg \bullet m^{-3}$ (2.5 $lb \bullet yd^{-3}$) of hydrated lime and 12 $kg \bullet m^{-3}$ (20.0 $lb \bullet yd^{-3}$) of carbonated lime. Fe, Mn and Zn values were 1737, 363, and 118 $\mu g \bullet g^{-1}$, or 397, 182, and 72 $\mu g \bullet g^{-1}$, for the low and high lime treatment, respectively. Plant appearance at the high lime rate was lush with fully expanded leaves and lacked purplish blemishes, unlike the low lime rate which developed small and brittle leaves with purplish tissue on older leaves. A standard recommendation for the prevention of iron toxicity in *Rudbeckia* is to maintain a root-medium pH of 6.0 or above.

Hibiscus developed periodic marginal white leaf tissue and leaf crinkling on new growth regardless of nutrient solutions at 20 °C with HPS lamps on a bright sunny day immediately following a few days of Michigan winter cloudy weather. The cause of this symptom is unclear. In a separate study at temperatures of 23 °C or greater with similar light conditions, no marginal white tissue developed. Based on previous MSU studies with *Hibiscus*, we recommend 23 °C for a minimum temperature to force (Wang et al. 1998). From tissue samples taken at 20, 23, 26, and 29 °C with HPS lamps, Ca and Fe values decreased with decreasing temperatures. Also, at 23 °C in a comparison between HPS lamps and no lamps, Ca values slightly increased and Fe levels decreased from 761 to 342 $\mu g \cdot g^{-1}$, respectively. Marginal white leaf tissue was analyzed separately from the interior green leaf blade of the same leaf, and found Fe values were similar at 154 and 187 $\mu g \cdot g^{-1}$, respectively. The symptoms would remain for a 24 to 48 hour period depending on light levels, and then margins would green up, but never to the extent of the unaffected interior portion of the leaf blade. The leaf distortion damage to the tissue, as a result of inhibiting expansive growth, was temporary and did not reduce plant quality. Furthermore, regardless of the temperature, an interveinal chlorosis developed occasionally during production more commonly at higher temperatures. Comparing green leaves to interveinal chlorotic leaves, Fe and Mn levels were lower in interveinal chlorosis leaf tissue, 90 and 43 $\mu g \cdot g^{-1}$, respectively (based on one sample). *Hibiscus* had higher Fe, Mn, and Zn levels in general compared to other herbaceous perennials in this study. Desired values may need to be evaluated further for this species.

Whole shoot tissue analysis. Whole shoot tissue analysis for the standard treatment is found in Table 1. Total plant nutrient concentrations were normally less than foliar concentrations, except for P. Most species had similar or higher P values. Macronutrient, N, P, K, Ca, and Mg, mean values for whole shoot concentration between all fifteen species were 5.3, 0.5, 3.8, 1.2, and 0.5 %. Micronutrient, Fe, Mn, Zn, B, and Cu, mean values were 141, 92, 57, 35, and 5

$\mu g \cdot g^{-1}$ dry weight. Typically, whole shoot tissue values are not recommended to evaluate the nutrient status of a crop. However, the combination of the dry weight and tissue concentrations could be used as an estimate of the above ground biomass nutrient removal per pot during production. This information is useful for estimating fertilizer requirement in non-leaching systems. The estimation would not account for root mass and root nutrient content, which must be considered to calculate total nutrient removal from the medium.

Critical levels have not been firmly established for every element for standard floriculture crops, and could be quite different for herbaceous perennials. Minimum critical levels usually indicate a need for additional fertilizer or a possible growth limiting situation, but would likely vary depending on plant species. Maximum critical levels usually indicate over fertilization, and possible accumulation of some elements, like Fe, Mn, Zn, and B, to toxic levels, which could lead to growth reductions. Potassium can accumulate as much as 10% dry matter without detrimental effects, other than possibly inducing deficiencies of other elements such as Ca^{2+} and Mg^{2+}. *Hibiscus*, *Rudbeckia*, and *Sedum* appeared to contain higher than normal concentrations of Ca^{2+} and Mg^{2+}. Calcium and Mg^{2+} are not expected to be toxic, but can lead to induced deficiencies of other elements, particularly Fe and Mn if Mg^{2+} is in excess.

Most tissue samples are taken from the most recently mature leaves on new growth. In this experiment due to the constraints of collecting flowering data, the tissue samples were not collected until flowering or shortly after on the most recently mature leave. All plants were treated consistently so no differences between species would be attributed to different sampling times. In most cases the plants were not showing any damage or signs of loss of color. Based on these results, we can determine how certain species have the potential to accumulate particular nutrients, in general, over other herbaceous perennial species, or with certain NS regimes during production in a greenhouse. We would recommend collecting leaf samples earlier in future studies, perhaps at first visible bud. Also, due to the constraints of collecting growth and development data, only two tissue samples per treatment per species were able to be taken, but at least three are recommended in future experiments.

In general, nutrient values of many species did not conform to published desired ranges for floriculture crops, nevertheless all species produced healthy plants. Some of the factors affecting plant nutrient concentrations are elemental concentration in medium, capacity of medium to supply nutrients, moisture level of medium, total solution concentration, aeration, temperature, plant age, part of plant sampled, plant species and cultivar, transpiration, nutrient interactions, and nutrient sources (Hanan, 1998). Altering any one of the above can contribute to a difference in the breadth of sufficiency ranges for a particular element. In a controlled environment the main factors to consider are plant age, part of plant sampled, and plant species. Nutrient solution concentration or reaction would have the most effect on nutrient levels in leaf tissue in a greenhouse, if all other sampling factors were treated as consistently as feasible.

Literally hundreds of herbaceous perennials are available for greenhouse forcing and pot culture. We believe a screening method that provides a range of fertilizer concentrations and nutrient solutions similar to the ones used in this study will help establish critical nutrient ranges. However, due to the close proximity of an elemental range for a species, it is difficult to suggest a protocol for evaluation of the six nutrient solutions on nutrient concentration. In future experiments, samples should be collected earlier to evaluate nutrient levels, particularly N, at visible bud or prior to first open flower. Also, establishing a lower fertilizer concentration or altering the root medium nutrient charge would be useful to evaluate low N and P levels.

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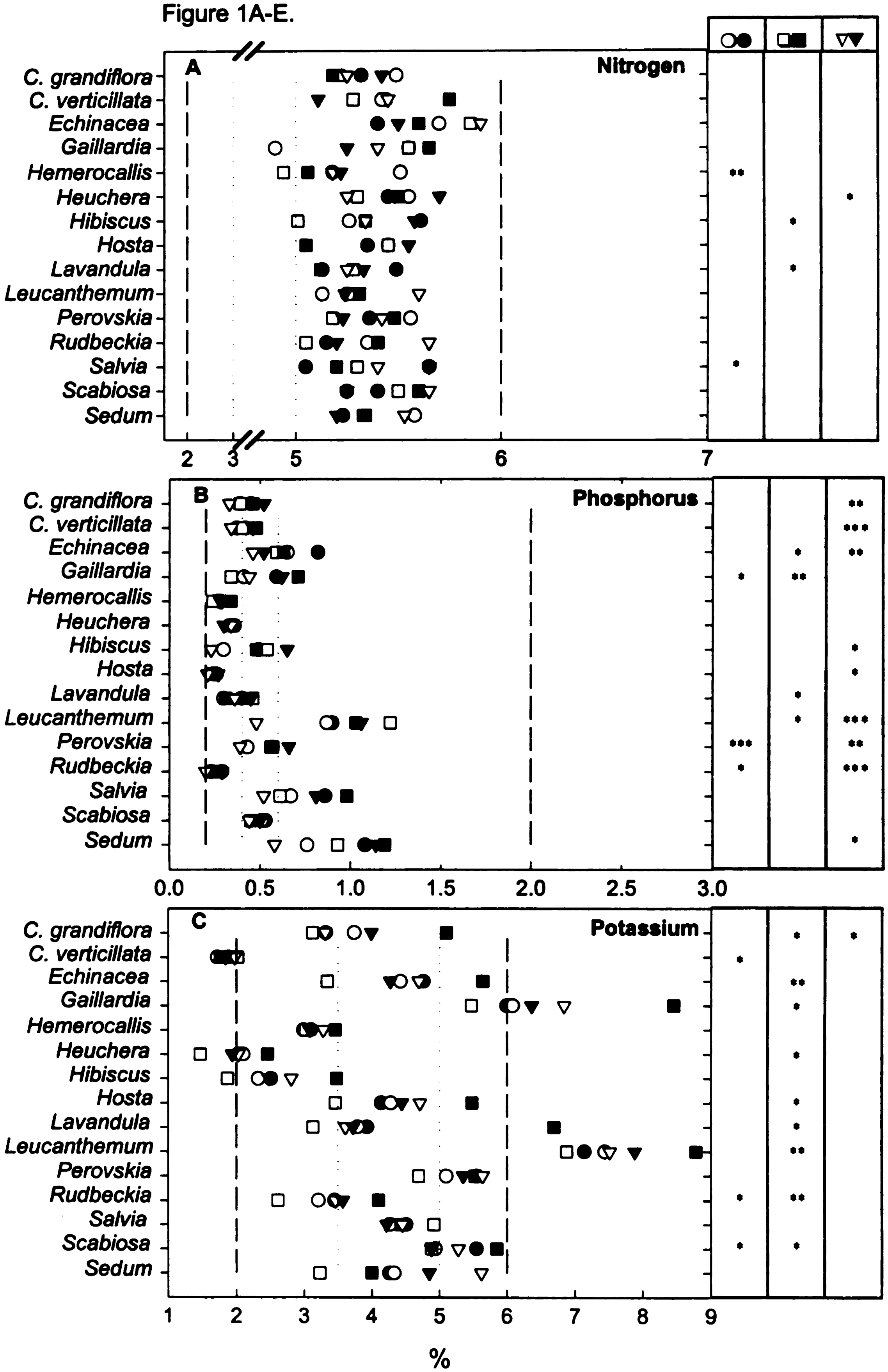
Table 1. Nutrient values and dry weight from whole shoot tissue of 15 herbaceous perennials grown under standard root-zone conditions. Dry weight data represent the mean of eight measurements. Tissue data represent one composite sample from eight plants.

Species	Dry Weight	Nutrients									
		N	P	K	Ca	Mg	Fe	Mn	Zn	B	Cu
	g	(% dry weight)					($\mu g \cdot g^{-1}$ dry weight)				
Coreopsis grandiflora Hogg ex Sweet 'Sunray'	15.59	5.4	0.5	4.6	1.1	0.7	129	95	58	36	4
Coreopsis verticillata L. 'Moonbeam'	9.37	5.2	0.5	2.4	0.5	0.3	45	89	46	27	2
Echinacea purpurea (L.) Moench 'Magnus'	17.66	5.3	0.5	4.7	0.8	0.7	65	65	28	49	4
Gaillardia x *grandiflora* Van Houtte 'Goblin'	17.82	5.3	0.6	5.0	1.6	0.6	88	50	49	44	5
Hemerocallis L. 'Stella de Oro'	4.25	5.5	0.3	2.9	0.5	0.2	70	52	22	41	2
Heuchera sanguinea Engelm 'Firefly'	9.30	5.5	0.4	3.2	1.2	0.5	46	65	44	34	5
Hibiscus moscheutos L. 'Disco Belle Hybrid'	25.11	5.2	0.6	3.3	1.7	0.9	282	108	85	37	5
Hosta (Otto & Dietr.) L. H. Bail. 'undulata variegata'	4.38	5.2	0.3	3.1	0.7	0.4	116	67	25	20	3
Lavandula angustifolia Mill. 'Munstead'	9.77	5.5	0.4	3.3	1.1	0.6	422	178	56	31	4
Leucanthemum x *superbum* Bergman ex J. Ingram 'Snow Cap'	11.10	5.3	0.8	6.0	0.9	0.7	59	90	104	31	7
Perovskia atriplicfolia Benth	12.37	5.3	0.4	3.2	0.7	0.3	58	58	55	30	5
Rudbeckia fulgida Ait. 'Goldsturm'	26.10	5.4	0.4	4.0	2.2	0.8	516	157	81	41	6
Salvia x *superba* Stapf. 'Blue Queen'	4.87	5.2	0.6	4.1	1.0	0.6	69	113	56	31	5
Scabiosa caucasica Bieb 'Butterfly Blue'	11.17	5.4	0.5	3.8	0.9	0.3	82	86	51	34	5
Sedum H. Ohba 'Autumn Joy'	20.72	5.5	0.7	3.4	2.5	0.6	62	111	92	42	7

Fig 1A-E. Effect of fertilizer concentrations and N form on foliar tissue macronutrient concentrations of 15 herbaceous perennials forced into flower in a greenhouse. Low phosphorus (○), fertilizer concentrations (❑ and ■), and nutrient-solution reaction (∇ and ▼) were compared to standard (●). Hollowed symbols represent low treatments and filled symbols represent high treatments. Tissue data represent the mean of two samples, each sample represents four plants. Vertical dotted lines (··········) indicate the recommended desired range and the dashed lines (—) indicate the minimum and maximum critical values. *,**,*** Significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Figure 1A-E.



A
Nitrogen
B
Phosphorus
C
Potassium
C. grandiflora
C. verticillata
Echinacea
Gaillardia
Hemerocallis
Heuchera
Hibiscus
Hosta
Lavandula
Leucanthemum
Perovskia
Rudbeckia
Salvia
Scabiosa
Sedum
2
3
5
6
7
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1
2
3
4
5
6
7
8
9
%

Figure 1A-E. (cont'd)

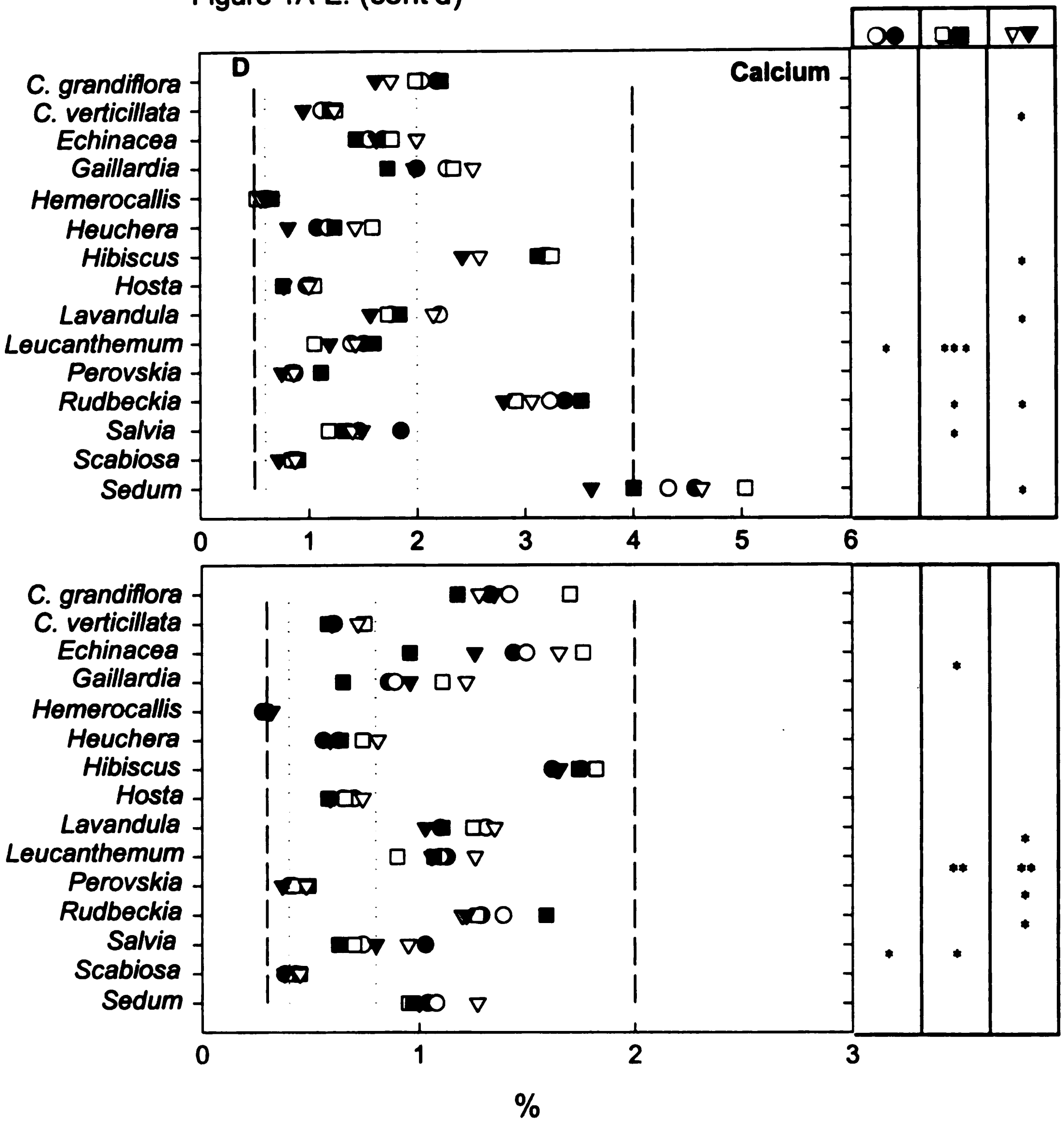
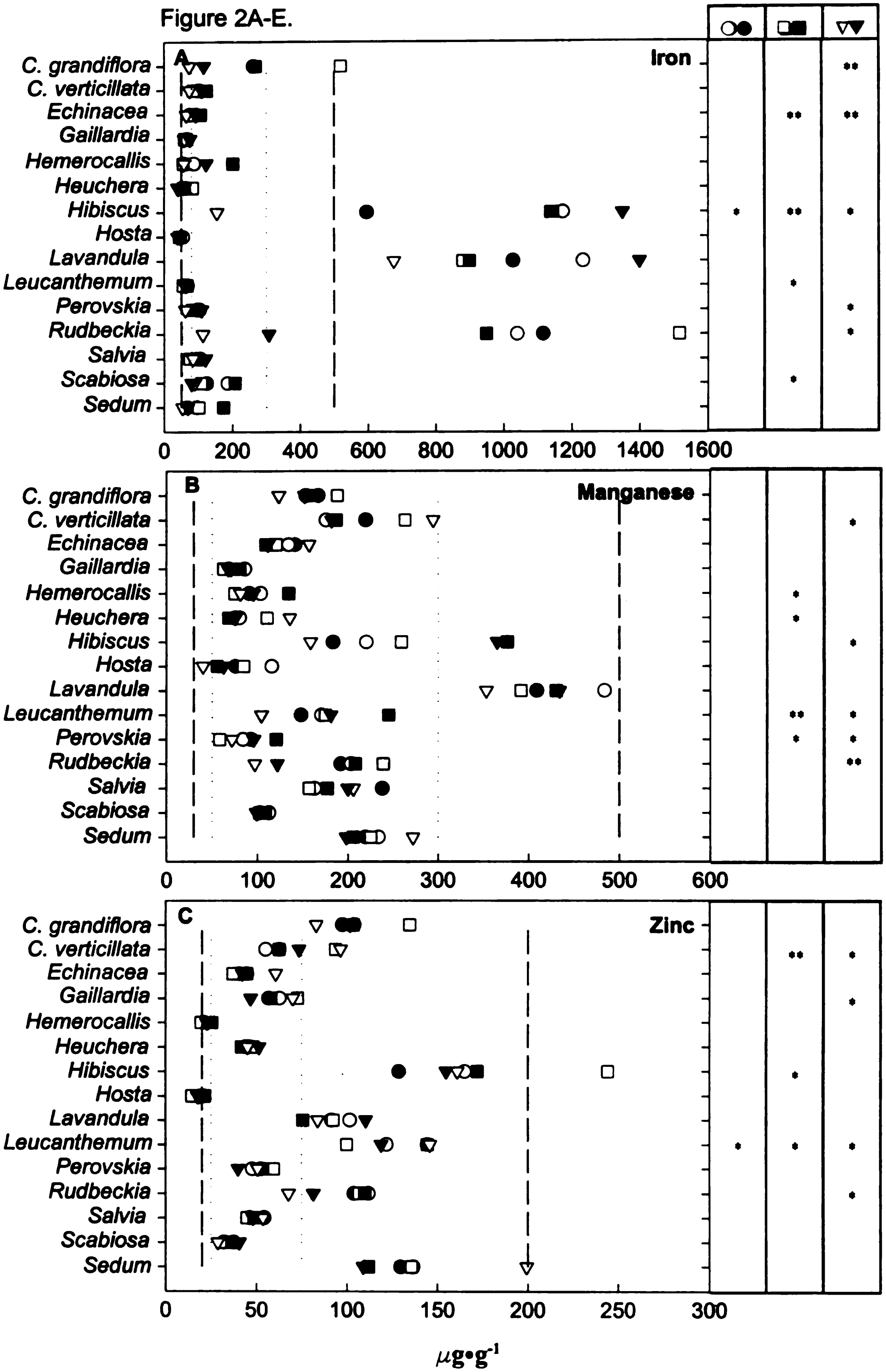


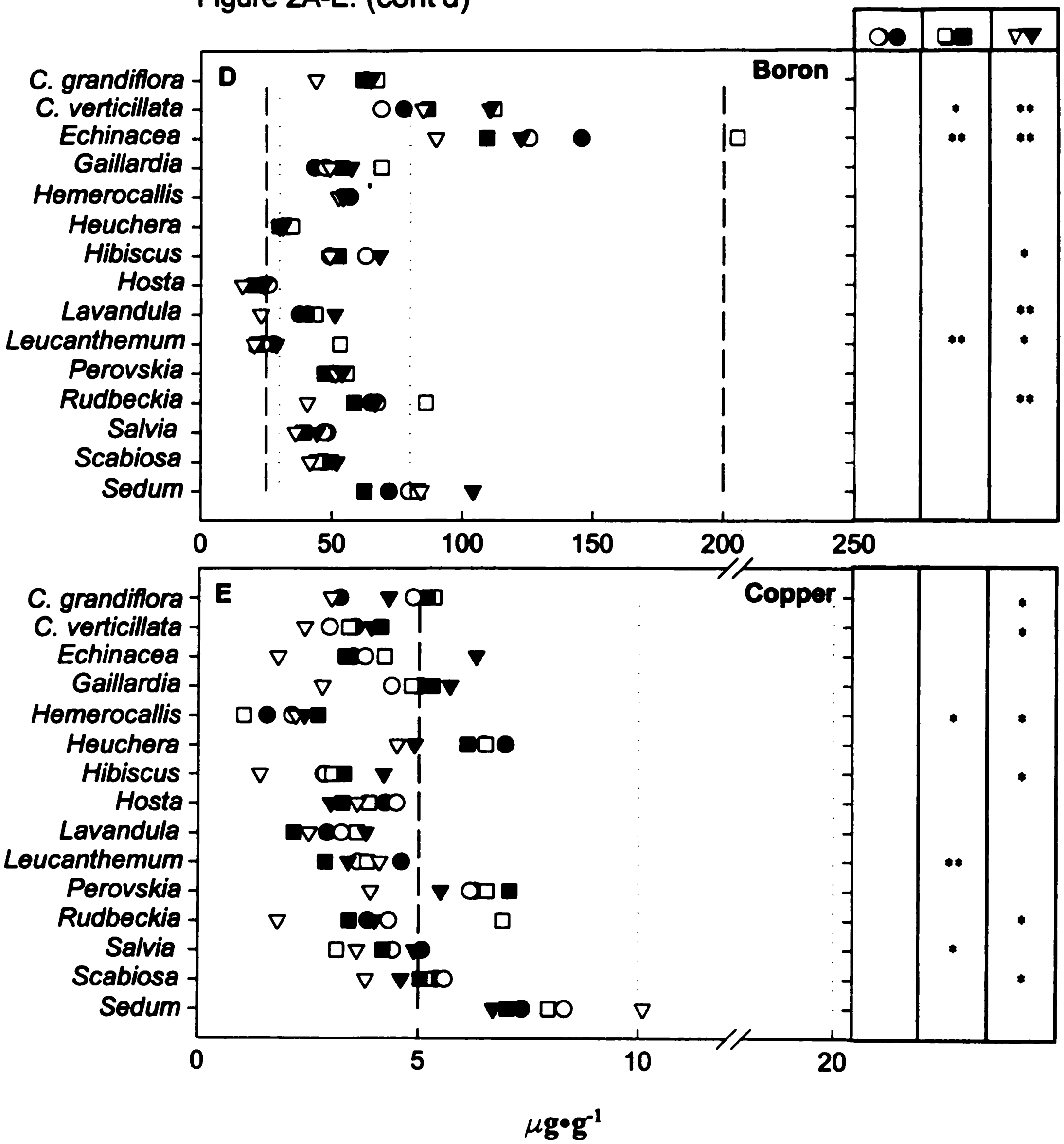
Fig 2A-E. Effect of fertilizer concentrations and N form on foliar tissue micronutrient concentrations of 15 herbaceous perennials forced into flower in a greenhouse. Low phosphorus (○), fertilizer concentrations (□ and ■), and nutrient-solution reaction (▽ and ▼) were compared to standard (●). Hollowed symbols represent low treatments and filled symbols represent high treatments. Tissue data represent the mean of two samples, each sample represents four plants. Vertical dotted lines (··········) indicate the recommended desired range and the dashed lines (---) indicate the minimum and maximum critical values. *,**,*** significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Figure 2A-E.



A
Iron
B
Manganese
C
Zinc
C. grandiflora
C. verticillata
Echinacea
Gaillardia
Hemerocallis
Heuchera
Hibiscus
Hosta
Lavandula
Leucanthemum
Perovskia
Rudbeckia
Salvia
Scabiosa
Sedum
0 200 400 600 800 1000 1200 1400 1600
0 100 200 300 400 500 600
0 50 100 150 200 250 300
μg•g-1

Figure 2A-E. (cont'd)



APPENDIX

Table 1. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Astilbe chinensis*. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	84	3	28.9	8	31.8	9.1	28.9	4.13	0.5	5.7	1.3
>50% CC	88	2	27.1	8	33.0	8.6	25.8	6.00	0.8	5.5	1.3
>75% CC	91	1	36.2	7	69.9	16.5	23.6	11.25	1.4	5.8	1.1
Significance	NS	NS	NS	NS	**	**	***				
Trends (Linear/Quadratic)											
Media											
Peat	98	1	29.2	8	26.3	6.4	24.4	5.00	0.6	5.7	1.3
Peat/Perlite	88	2	27.1	8	33.0	8.6	25.8	6.00	0.8	5.5	1.3
Bark	86	2	31.2	7	41.9	11.1	26.6	6.75	0.8	5.3	1.2
Significance	*	NS	NS	NS	NS	*	NS				
WSF Rate (ppm)											
31N-3P-31K	96	1	40.4	8	30.9	8.0	25.9	5.25	0.2	6.4	0.7
125N-12P-125K	88	2	27.1	8	33.0	8.6	25.8	6.00	0.8	5.5	1.3
250N-24P-250K								5.25	1.3	4.3	1.8
Significance	NS	NS	NS	NS	**	**	***				
Trends (Linear/Quadratic)											
Low P WSF (ppm)											
125N-8P-125K	87	1	30.6	7	36.9	9.6	26.1	5.50	0.7	5.3	1.4
125N-12P-125K	88	2	27.1	8	33.0	8.6	25.8	6.00	0.8	5.5	1.3
Significance	NS	NS	NS	NS	NS	NS	NS				
pH Drench											
ph<5.5	93	1	26.5	7	39.5	10.3	26.1	4.75	0.6	5.3	0.8
5.8<pH<6.2	88	2	27.1	8	33.0	8.6	25.8	6.00	0.8	5.5	1.3
pH>6.5											
Significance	NS	NS	NS	NS	NS	NS	NS				
Nutrient Solution											
5% NH4/320 ALK	91	1	28.8	7	25.5	7.0	27.5	5.50	0.7	7.5	1.3
25% NH4/120 ALK	88	2	27.1	8	33.0	8.6	25.8	6.00	0.8	5.5	1.3
50% NH4/20ALK	91	2	28.6	7	43.8	13.6	34.4	6.00	0.8	4.8	0.7
Significance	NS	NS	NS	NS	NS	*	NS				
Trends (Linear/Quadratic)											

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

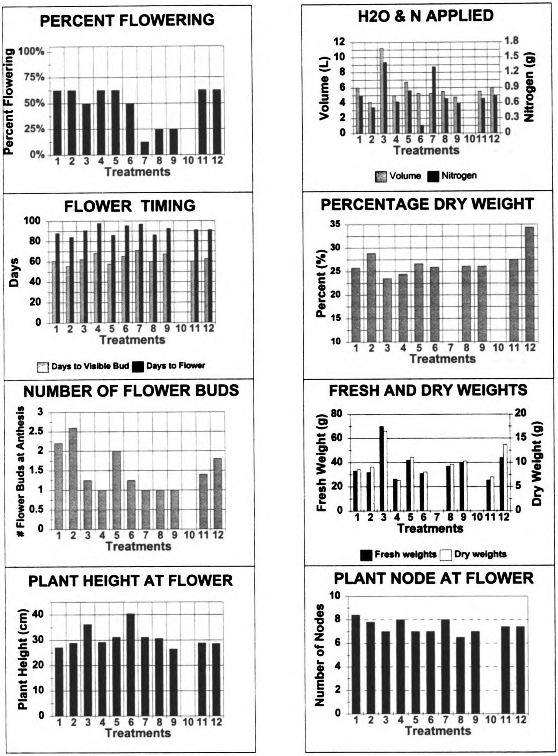


Figure 1. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Astilbe chinensis*. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1} , 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 2. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Campanula carpatica* 'White Clips'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	54	34	10.1	17	19.2	3.5	18.0	1.50	0.2	5.6	0.8
>50% CC	52	24	10.0	17	19.8	3.3	16.7	1.75	0.2	5.8	0.8
>75% CC	51	42	10.3	15	25.9	4.6	18.6	2.00	0.3	5.5	0.9
Significance	NS	NS	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)											
Media											
Peat	53	40	12.5	17	26.1	4.6	17.7	2.25	0.3	5.7	1.3
Peat/Perlite	52	24	10.0	17	19.8	3.3	16.7	1.75	0.2	5.8	0.8
Bark	51	43	10.2	19	27.6	5.0	18.5	1.75	0.2	4.9	0.7
Significance	NS	*	NS	NS	NS	*	NS				
WSF Rate (ppm)											
31N-3P-31K	50	36	9.9	17	24.2	4.2	17.2	1.75	0.1	5.6	0.6
125N-12P-125K	52	24	10.0	17	19.8	3.3	16.7	1.75	0.2	5.8	0.8
250N-24P-250K	53	48	11.7	17	25.6	4.6	17.8	2.00	0.5	5.2	1.1
Significance	NS	**	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)		NS/***									
Low P WSF (ppm)											
125N-8P-125K	53	29	10.0	15	21.8	3.7	16.9	2.25	0.3	5.5	0.9
125N-12P-125K	52	24	9.7	17	19.8	3.3	16.7	1.75	0.2	5.8	0.8
Significance	NS	NS	NS	NS	NS	NS	NS				
pH Drench											
ph<5.5	54	36	11.0	17	26.5	4.7	18.0	2.25	0.3	5.9	1.0
5.8<pH<6.2	52	24	10.0	17	19.8	3.3	16.7	1.75	0.2	5.8	0.8
pH>6.5	54	33	10.9	15	23.9	4.2	17.3	2.25	0.3	5.7	0.8
Significance	NS	NS	NS	NS	NS	NS	NS				
Nutrient Solution											
5% NH4/320 ALK	52	27	9.1	16	15.1	2.7	17.6	2.50	0.3	6.3	0.7
25% NH4/120 ALK	52	24	10.0	17	19.8	3.3	16.7	1.75	0.2	5.8	0.8
50% NH4/20ALK	48	36	11.3	15	25.2	4.8	19.0	2.50	0.3	5.4	0.7
Significance	NS	NS	NS	NS	**	**	***				
Trends (Linear/Quadratic)					*/**	**/**	***/NS				

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

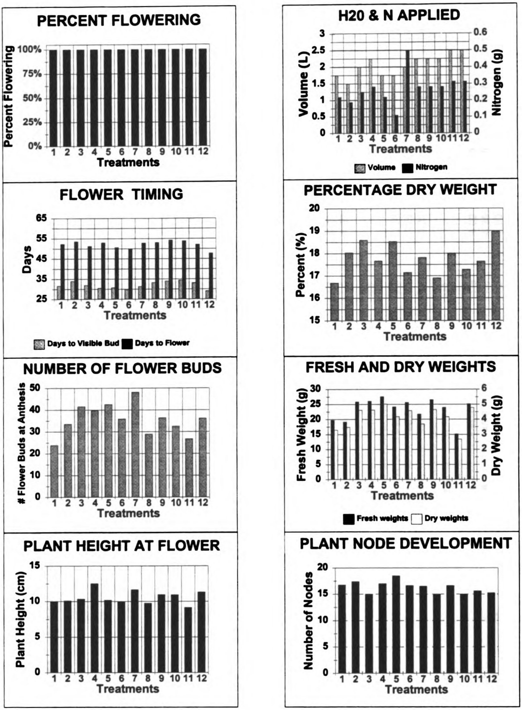


Figure 2. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Campanula carpatica* 'White Clips'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 3. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Coreopsis grandiflora* 'Sunray'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3$ •L^{-1}).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	51	22	49.4	5	104.0	13.4	12.9	2.38	0.3	5.7	1.3
>50% CC	51	27	51.7	6	143.3	15.6	11.0	4.25	0.5	5.7	1.7
>75% CC	55	34	60.0	6	192.3	21.3	11.8	6.63	0.8	5.7	1.4
Significance	*	NS	**	NS	***	***	NS				
Trends (Linear/Quadratic)	*/NS		**/NS		***/NS	***/NS					
Media											
Peat	51	34	52.2	6	160.2	19.0	11.9	5.00	0.6	6.1	1.4
Peat/Perlite	51	27	51.7	6	143.3	15.6	11.0	4.25	0.5	5.7	1.7
Bark	51	22	44.3	6	128.2	15.2	12.0	4.00	0.5	4.5	1.4
Significance	NS	*	*	NS	NS	*	NS				
WSF Rate (ppm)											
31N-3P-31K	53	26	52.4	6	113.5	13.5	11.8	4.00	0.1	5.3	1.3
125N-12P-125K	51	27	51.7	6	143.3	15.6	11.0	4.25	0.5	5.7	1.7
250N-24P-250K	53	26	50.9	6	113.7	13.1	11.7	3.50	0.9	5.3	1.9
Significance	NS	NS	NS	NS	*	NS	NS				
Trends (Linear/Quadratic)					NS/**						
Low P WSF (ppm)											
125N-8P-125K	48	32	50.0	6	145.1	18.0	12.4	5.00	0.6	5.6	1.8
125N-12P-125K	51	27	51.7	6	143.3	15.6	11.0	4.25	0.5	5.7	1.7
Significance	NS	NS	NS	NS	NS	NS	NS				
pH Drench											
ph<5.5	52	15	41.4	5	69.9	8.6	12.6	2.00	0.3	4.6	1.5
5.8<pH<6.2	51	27	51.7	6	143.3	15.6	11.0	4.25	0.5	5.7	1.7
pH>6.5	54	29	51.4	6	99.9	12.1	12.1	3.25	0.4	7.1	1.4
Significance	NS	**	**	NS	***	***	NS				
Nutrient Solution											
5% NH4/320 ALK	50	23	47.6	6	130.2	15.3	11.8	4.00	0.5	7.1	1.0
25% NH4/120 ALK	51	27	51.7	6	143.3	15.6	11.0	4.25	0.5	5.7	1.7
50% NH4/20ALK	51	35	51.8	5	149.8	17.2	11.5	4.50	0.6	6.5	0.7
Significance	NS	NS	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)											

NS, *, **, *** Nonsignificant or significant at $P < 0.05, 0.01, 0.001$, respectively.

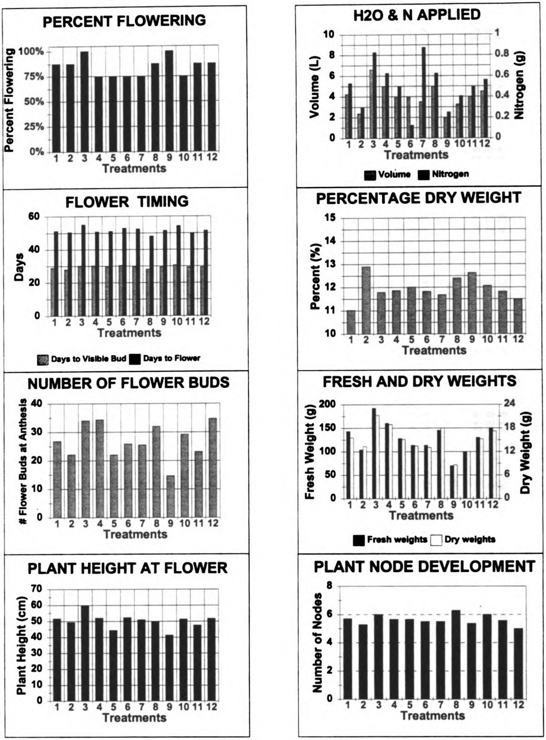


Figure 3. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Coreopsis grandiflora* 'Sunray'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 4. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Coreopsis verticillata* 'Moonbeam'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	58	148	49.9	11	29.4	7.2	24.5	2.50	0.3	6.2	1.5
>50% CC	56	173	54.0	9	38.0	9.4	24.5	3.75	0.5	6.0	1.6
>75% CC	57	226	60.1	11	47.3	12.1	26.3	6.25	0.8	6.4	1.7
Significance	NS	*	***	**	**	***	NS				
Trends (Linear/Quadratic)		**/NS	***/NS	NS/**	**/NS	***/NS					
Media											
Peat	58	216	57.6	10	44.6	10.8	24.2	4.25	0.5	6.0	1.6
Peat/Perlite	56	173	54.0	9	38.0	9.4	24.5	3.75	0.5	6.0	1.6
Bark	54	193	55.0	9	51.9	12.9	24.9	4.75	0.6	5.2	1.2
Significance	NS	NS	NS	NS	**	**	NS				
WSF Rate (ppm)											
31N-3P-31K	58	123	50.9	12	29.5	7.0	23.5	3.50	0.2	6.5	1.1
125N-12P-125K	56	173	54.0	9	38.0	9.4	24.5	3.75	0.5	6.0	1.6
250N-24P-250K	55	175	46.2	11	35.5	8.5	24.0	3.75	0.9	5.4	1.9
Significance	NS	NS	NS	*	NS	NS	NS				
Trends (Linear/Quadratic)				NS/**							
Low P WSF (ppm)											
125N-8P-125K	54	168	51.1	10	39.8	6.6	16.7	4.25	0.5	5.9	1.5
125N-12P-125K	56	173	54.0	9	38.0	9.4	24.5	3.75	0.5	6.0	1.6
Significance	NS	NS	NS	NS	NS	*	***				
pH Drench											
ph<5.5								2.50	0.3	3.8	1.3
5.8<pH<6.2	56	173	54.0	9	38.0	9.4	24.5	3.75	0.5	6.0	1.6
pH>6.5	58	118	53.5	10	26.4	7.0	26.4	3.25	0.4	7.3	1.4
Significance	NS	*	NS	NS	**	*	NS				
Nutrient Solution											
5% NH4/320 ALK	54	133	54.5	11	31.5	7.8	25.0	3.75	0.5	7.0	1.2
25% NH4/120 ALK	56	173	54.0	9	38.0	9.4	24.5	3.75	0.5	6.0	1.6
50% NH4/20ALK	58	187	52.9	10	41.3	9.5	23.0	4.25	0.5	6.1	1.5
Significance	NS	NS	NS	NS	NS	NS	*				
Trends (Linear/Quadratic)							**/NS				

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

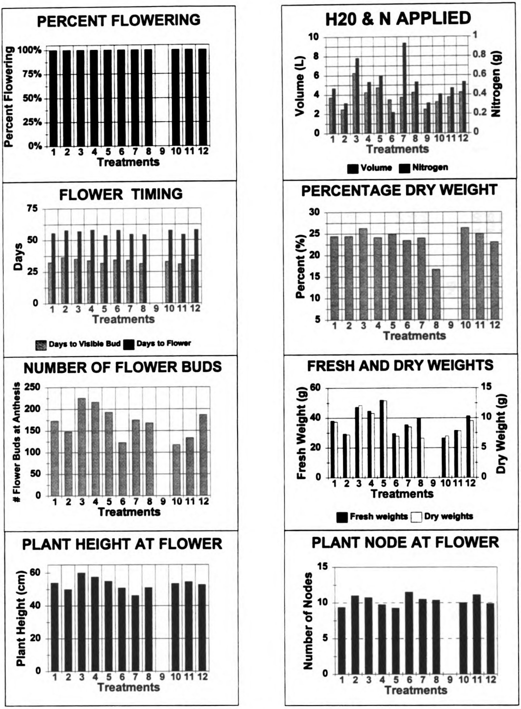


Figure 4. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Coreopsis verticillata* 'Moonbeam'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 5. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Delphinium grandiflorum* 'Blue Mirror'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	61	78	38.7	8	23.8	5.2	21.9	3.25	0.4	5.7	1.3
>50% CC	59	62	44.4	8	25.9	5.6	22.0	4.25	0.5	6.1	0.8
>75% CC	60	51	41.2	8	26.3	5.0	20.6	5.25	1.1	6.1	0.6
Significance	NS	NS	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)											
Media											
Peat	62	68	43.2	8	25.8	5.1	20.1	4.25	0.5	5.5	1.2
Peat/Perlite	59	62	44.4	8	25.9	5.6	22.0	4.25	0.5	6.1	0.8
Bark	61	96	47.5	9	36.1	7.6	21.0	5.25	0.7	5.1	1.1
Significance	NS	NS	NS	NS	*	*	*				
WSF Rate (ppm)											
31N-3P-31K	60	72	46.3	9	30.6	7.0	23.4	4.50	0.1	6.3	0.5
125N-12P-125K	59	62	44.4	8	25.9	5.6	22.0	4.25	0.5	6.1	0.8
250N-24P-250K	61	76	42.4	9	23.3	5.0	21.9	4.00	1.0	5.7	1.4
Significance	NS	NS	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)											
Low P WSF (ppm)											
125N-8P-125K	61	89	47.1	9	32.5	9.9	30.5	4.75	0.6	5.8	1.1
125N-12P-125K	59	62	44.4	8	25.9	5.6	22.0	4.25	0.5	6.1	0.8
Significance	NS	*	NS	*	NS	*	*				
pH Drench											
ph<5.5	65	4	16.0	6				2.50	0.3	4.0	0.7
5.8<pH<6.2	59	62	44.4	8	25.9	5.6	22.0	4.25	0.5	6.1	0.8
pH>6.5	64	47	43.7	9	15.2	3.3	20.8	3.25	0.4	7.3	0.7
Significance	*	NS	**	*	NS	NS	NS				
Nutrient Solution											
5% NH4/320 ALK	60	68	46.9	9	26.2	5.9	22.5	4.50	0.6	7.1	0.9
25% NH4/120 ALK	59	62	44.4	8	25.9	5.6	22.0	4.25	0.5	6.1	0.8
50% NH4/20ALK	60	102	45.7	9	31.9	7.0	21.9	4.50	0.6	6.6	0.7
Significance	NS	NS	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)											

NS, *, **, *** Nonsignificant or significant at $P < 0.05, 0.01, 0.001$, respectively.

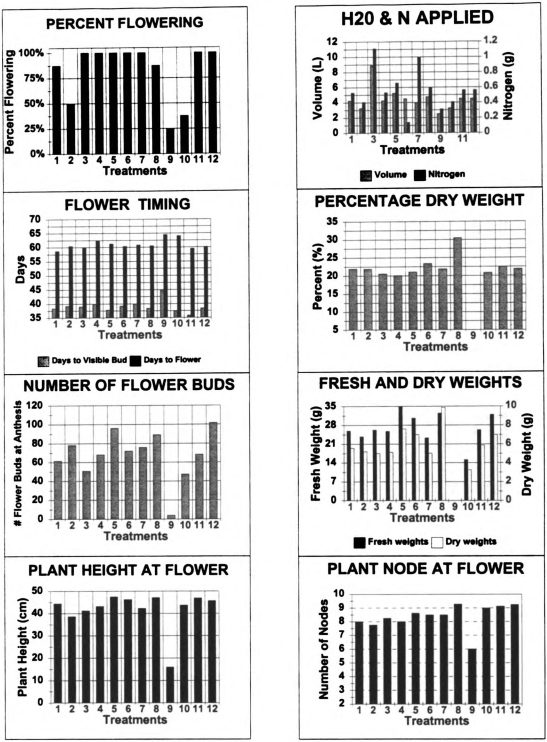


Figure 5. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Delphinium grandiflorum* 'Blue Mirror'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 6. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Echinacea purpurea* 'Magnus'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	75	6	72.4	14	72.1	14.2	19.8	3.50	0.4	5.8	1.5
>50% CC	70	5	71.1	13	92.5	17.7	18.9	5.50	0.7	6.0	1.2
>75% CC	70	8	96.2	13	148.6	28.9	19.4	9.63	1.2	5.7	1.3
Significance	NS	NS	***	NS	***	***	NS				
Trends (Linear/Quadratic)			***/NS		***/NS	***/NS					
Media											
Peat	72	6	80.2	13	102.2	20.3	20.0	6.00	0.8	5.5	1.4
Peat/Perlite	70	5	71.1	13	92.5	17.7	18.9	5.50	0.7	6.0	1.2
Bark	74	8	72.6	15	101.2	19.6	19.5	5.25	0.7	5.1	1.0
Significance	NS	**	NS	NS	NS	NS	NS				
WSF Rate (ppm)											
31N-3P-31K	69	5	85.7	12	73.6	17.2	23.4	5.25	0.2	5.4	1.0
125N-12P-125K	70	5	71.1	13	92.5	17.7	18.9	5.50	0.7	6.0	1.2
250N-24P-250K	72	6	64.7	13	70.6	14.3	20.2	4.50	1.1	5.4	1.9
Significance	NS	NS	*	NS	*	NS	***				
Trends (Linear/Quadratic)			**/NS		NS/*		***/***				
Low P WSF (ppm)											
125N-8P-125K	73	7	72.0	12	116.8	23.4	20.2	7.00	0.9	5.7	1.5
125N-12P-125K	70	5	71.1	13	92.5	17.7	18.9	5.50	0.7	6.0	1.2
Significance	NS	NS	NS	NS	NS	*	NS				
pH Drench											
ph<5.5	66	8	65.1	14	74.0	15.9	21.7	5.00	0.6	4.2	1.2
5.8<pH<6.2	70	5	71.1	13	92.5	17.7	18.9	5.50	0.7	6.0	1.2
pH>6.5	76	5	68.0	13	58.0	13.1	23.4	5.00	0.6	7.1	1.4
Significance	NS	*	NS	NS	**	NS	NS				
Nutrient Solution											
5% NH4/320 ALK	72	7	70.3	12	79.9	15.9	20.1	4.75	0.6	7.3	1.0
25% NH4/120 ALK	70	5	71.1	13	92.5	17.7	18.9	5.50	0.7	6.0	1.2
50% NH4/20ALK	73	7	77.9	14	114.6	21.5	18.8	6.25	0.8	6.8	1.1
Significance	NS	NS	NS	NS	**	*	NS				
Trends (Linear/Quadratic)					**/NS	**/NS					

NS, *, **, *** Nonsignificant or significant at $P < 0.05, 0.01, 0.001$, respectively.

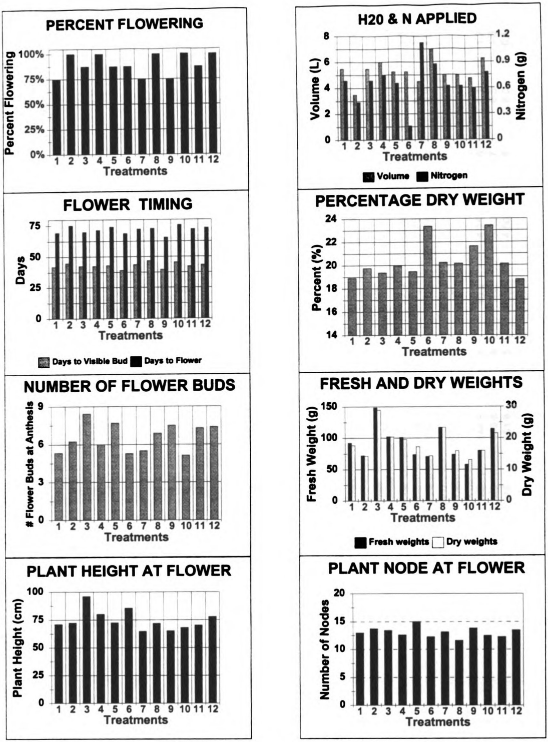


Figure 6. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Echinacea purpurea* ' Magnus'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 7. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Gaillardia* x *grandiflora* 'Goblin'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	40	18	19.3	12	107.9	12.1	11.3	3.50	0.4	6.1	1.1
>50% CC	46	35	22.2	15	179.6	17.8	9.9	5.75	0.7	6.5	1.0
>75% CC	47	34	21.8	18	212.2	19.6	9.2	7.00	0.9	6.5	0.8
Significance	NS	NS	NS	NS	***	***	**				
Trends (Linear/Quadratic)					***/NS	***/NS	***/NS				
Media											
Peat	44	35	22.7	15	171.8	17.4	10.1	5.75	0.7	6.2	1.1
Peat/Perlite	46	35	22.2	15	179.6	17.8	9.9	5.75	0.7	6.5	1.0
Bark	46	32	26.2	17	174.4	18.3	10.6	6.50	0.8	5.6	0.9
Significance	NS	NS	NS	NS	NS	NS	NS				
WSF Rate (ppm)											
31N-3P-31K	44	29	21.7	15	96.0	13.0	13.4	4.50	0.1	6.1	0.8
125N-12P-125K	46	35	22.2	15	179.6	17.8	9.9	5.75	0.7	6.5	1.0
250N-24P-250K	45	37	19.3	13	149.1	15.6	10.5	4.25	1.1	5.6	1.5
Significance	NS	NS	NS	NS	***	*	***				
Trends (Linear/Quadratic)					***/***	NS/*	**/**				
Low P WSF (ppm)											
125N-8P-125K	48	26	19.7	19	143.9	14.8	10.3	5.50	0.7	6.5	1.1
125N-12P-125K	46	35	22.2	15	179.6	17.8	9.9	5.75	0.7	6.5	1.0
Significance	NS	NS	NS	NS	***	**	NS				
pH Drench											
ph<5.5	50	8	16.6	13	47.7	9.9	22.9	3.75	0.5	4.7	1.3
5.8<pH<6.2	46	32	22.2	15	179.6	17.8	9.9	5.75	0.7	6.5	1.0
pH>6.5	47	24	24.1	18	137.5	14.9	10.9	4.75	0.6	7.5	1.0
Significance	NS	*	NS	NS	***	***	***				
Nutrient Solution											
5% NH4/320 ALK	46	25	23.7	16	144.6	14.8	10.4	4.75	0.6	7.1	1.2
25% NH4/120 ALK	46	35	22.2	15	179.6	17.8	9.9	5.75	0.7	6.5	1.0
50% NH4/20ALK	49	24	20.4	16	151.8	14.5	9.6	4.50	0.6	6.0	0.5
Significance	NS	NS	NS	NS	*	NS	NS				
Trends (Linear/Quadratic)					NS/*						

NS, *, **, *** Nonsignificant or significant at $P < 0.05, 0.01, 0.001$, respectively.

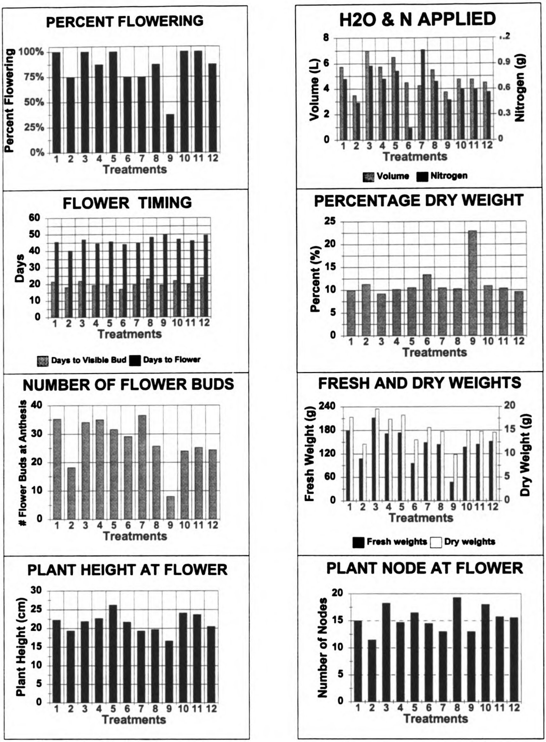


Figure 7. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Gaillardia xgrandiflora* 'Goblin'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 8. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Hemerocallis* 'Stella de Oro'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	67	7	23.2	6	8.0	1.8	21.7	2.50	0.3	5.5	1.2
>50% CC	51	10	35.3	6	22.2	4.2	19.3	4.00	0.5	5.7	1.1
>75% CC	55	14	33.7	7	29.2	5.3	18.8	7.63	1.0	5.6	1.0
Significance	*	*	***	NS	**	**	NS				
Trends (Linear/Quadratic)	NS/*	**/NS	**/***		**/NS	**/NS					
Media											
Peat	53	10	33.0	6	16.5	3.1	19.1	3.50	0.4	5.8	1.2
Peat/Perlite	51	10	35.3	6	22.2	4.2	19.3	4.00	0.5	5.7	1.1
Bark	56	8	26.4	5	16.2	3.0	18.6	4.50	0.6	5.3	0.8
Significance	NS	NS	**	*	NS	NS	NS				
WSF Rate (ppm)											
31N-3P-31K	57	9	31.8	7	16.6	3.1	19.2	3.75	0.1	6.3	0.6
125N-12P-125K	51	10	35.3	6	22.2	4.2	19.3	4.00	0.5	5.7	1.1
250N-24P-250K	64	9	28.1	6	17.8	3.4	19.3	3.75	0.9	5.2	1.5
Significance	*	NS	**	NS	NS	NS	NS				
Trends (Linear/Quadratic)	NS/*		NS/*								
Low P WSF (ppm)											
125N-8P-125K	52	7	29.2	6	15.6	3.0	19.2	4.00	0.5	5.5	0.9
125N-12P-125K	51	10	35.3	6	22.2	4.2	19.3	4.00	0.5	5.7	1.1
Significance	NS	NS	**	NS	NS	*	NS				
pH Drench											
ph<5.5	63	7	27.1	6	12.6	2.4	19.2	3.25	0.4	4.7	1.0
5.8<pH<6.2	51	10	35.3	6	22.2	4.2	19.3	4.00	0.5	5.7	1.1
pH>6.5	64	7	28.6	5	13.7	2.5	18.5	3.75	0.5	6.7	1.1
Significance	*	NS	*	NS	*	*	NS				
Nutrient Solution											
5% NH4/320 ALK	56	7	30.2	6	12.2	2.5	20.8	3.75	0.5	6.4	1.2
25% NH4/120 ALK	51	10	35.3	6	22.2	4.2	19.3	4.00	0.5	5.7	1.1
50% NH4/20ALK	62	8	29.7	5	17.2	3.1	18.6	4.00	0.5	5.2	0.9
Significance	*	NS	NS	**	*	*	*				
Trends (Linear/Quadratic)	NS/*			NS/**	NS/*	NS/**	**/NS				

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

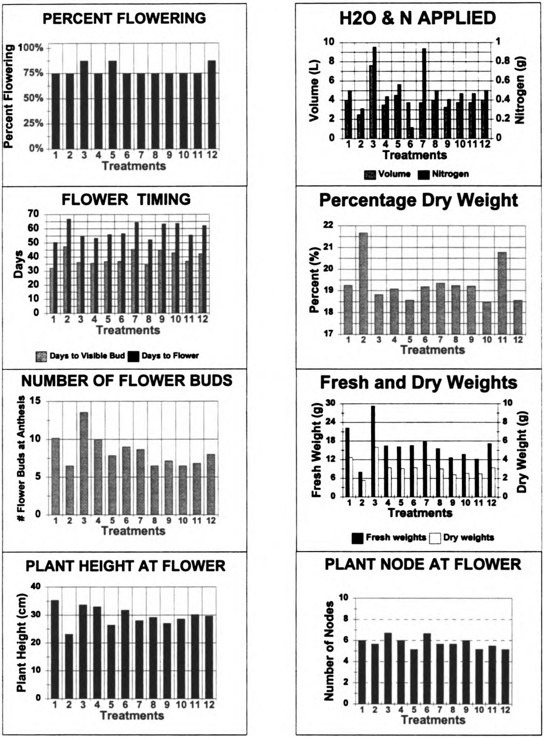


Figure 8. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Hemerocallis* 'Stella de Oro'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 9. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Heuchera sanguinea* 'Firefly'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	57	4	32.4	9	48.4	9.3	19.3	2.38	0.3	5.6	1.4
>50% CC	51	2	33.8	10	47.3	9.3	19.6	3.75	0.5	5.5	1.4
>75% CC	46	5	42.7	10	78.1	14.4	18.4	7.25	0.9	5.5	1.4
Significance	NS	*	NS	NS	***	***	*				
Trends (Linear/Quadratic)		NS/*			***/NS	***/NS					
Media											
Peat	50	4	35.6	8	63.3	12.3	19.3	4.25	0.5	5.3	1.6
Peat/Perlite	51	2	33.8	10	47.3	9.3	19.6	3.75	0.5	5.5	1.4
Bark	51	3	37.2	11	52.9	9.8	18.6	3.75	0.5	4.8	1.2
Significance	NS	NS	NS	NS	*	*	*				
WSF Rate (ppm)											
31N-3P-31K	46	4	38.5	10	65.3	12.3	19.0	4.50	0.1	5.6	1.0
125N-12P-125K	51	2	33.8	10	47.3	9.3	19.6	3.75	0.5	5.5	1.4
250N-24P-250K	43	4	33.4	11	55.3	10.3	18.7	3.50	0.9	5.3	1.7
Significance	NS	NS	NS	NS	**	**	NS				
Trends (Linear/Quadratic)					*/**	**/**					
Low P WSF (ppm)											
125N-8P-125K	51	3	32.2	13	44.2	8.7	21.0	3.75	0.5	5.7	1.2
125N-12P-125K	51	2	33.8	10	47.3	9.3	19.6	3.75	0.5	5.5	1.4
Significance	NS	NS	NS	NS	NS	NS	NS				
pH Drench											
ph<5.5								1.75	0.2	4.0	0.9
5.8<pH<6.2	51	2	33.8	10	47.3	9.3	19.6	3.75	0.5	5.5	1.4
pH>6.5	52	3	34.6	13	42.6	8.2	19.3	3.25	0.4	6.5	1.1
Significance	NS	NS	NS	NS	NS	NS	NS				
Nutrient Solution											
5% NH4/320 ALK	49	4	39.9	14	59.8	11.3	18.9	4.00	0.5	6.9	1.2
25% NH4/120 ALK	51	2	33.8	10	47.3	9.3	19.6	3.75	0.5	5.5	1.4
50% NH4/20ALK	50	3	36.9	10	52.3	10.3	20.7	4.00	0.5	6.1	0.8
Significance	NS	NS	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)											

NS, *, **, *** Nonsignificant or significant at $P < 0.05, 0.01, 0.001$, respectively.

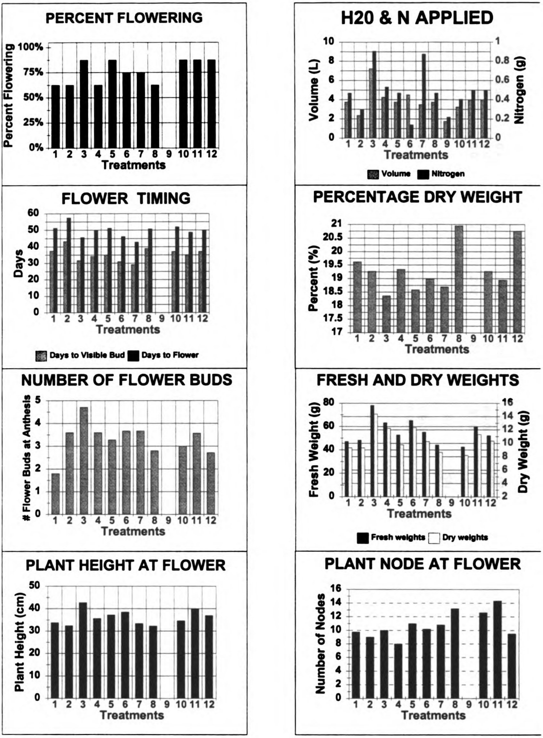


Figure 9. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Heuchera sanguinea* 'Firefly'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 10. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Hibiscus moscheutos* 'Disco Belle Hybrid'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	93	18	58.8	25	84.3	17.1	20.2	4.38	0.5	6.1	1.9
>50% CC	94	32	74.5	27	126.9	25.1	19.8	7.50	0.9	6.3	1.7
>75% CC	92	35	81.4	26	160.9	28.8	18.0	9.13	1.1	6.3	1.5
Significance	NS	***	***	NS	***	**	NS				
Trends (Linear/Quadratic)		***/NS	***/NS		***/NS	***/NS					
Media											
Peat	95	25	67.6	27	119.5	21.6	18.1	7.75	1.0	6.0	2.1
Peat/Perlite	94	32	74.5	27	126.9	25.1	19.8	7.50	0.9	6.3	1.7
Bark	94	28	66.1	27	126.9	22.7	17.9	7.50	0.9	5.1	1.5
Significance	NS	NS	**	NS	NS	NS	NS				
WSF Rate (ppm)											
31N-3P-31K	96	21	69.2	27	94.4	16.6	17.5	6.50	0.4	5.8	1.3
125N-12P-125K	94	32	74.5	27	126.9	25.1	19.8	7.50	0.9	6.3	1.7
250N-24P-250K	99	28	63.5	29	96.1	17.4	18.0	6.00	1.5	5.1	2.2
Significance	NS	*	*	NS	**	**	NS				
Trends (Linear/Quadratic)		NS/*	*/*		NS/**	NS/**					
Low P WSF (ppm)											
125N-8P-125K	87	28	75.6	22	125.3	24.0	19.2	8.25	1.0	5.8	2.0
125N-12P-125K	94	32	74.2	27	126.9	25.1	19.8	7.50	0.9	6.3	1.7
Significance	**	NS	NS	*	NS	NS	NS				
pH Drench											
ph<5.5	90	24	73.1	21	111.4	20.1	18.7	7.00	0.9	4.5	1.4
5.8<pH<6.2	94	32	74.5	27	126.9	25.1	19.8	7.50	0.9	6.3	1.7
pH>6.5	93	23	74.6	26	118.6	16.6	14.2	7.25	0.9	7.6	1.3
Significance	NS	**	NS	NS	NS	**	*				
Nutrient Solution											
5% NH4/320 ALK	93	23	68.0	20	97.8	19.8	20.2	7.50	0.9	7.9	1.3
25% NH4/120 ALK	94	32	74.5	27	126.9	25.1	19.8	7.50	0.9	6.3	1.7
50% NH4/20ALK	95	21	73.9	30	120.2	21.9	18.1	7.75	1.0	5.8	1.2
Significance	NS	**	NS	NS	*	NS	NS				
Trends (Linear/Quadratic)		NS/**			NS/*						

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

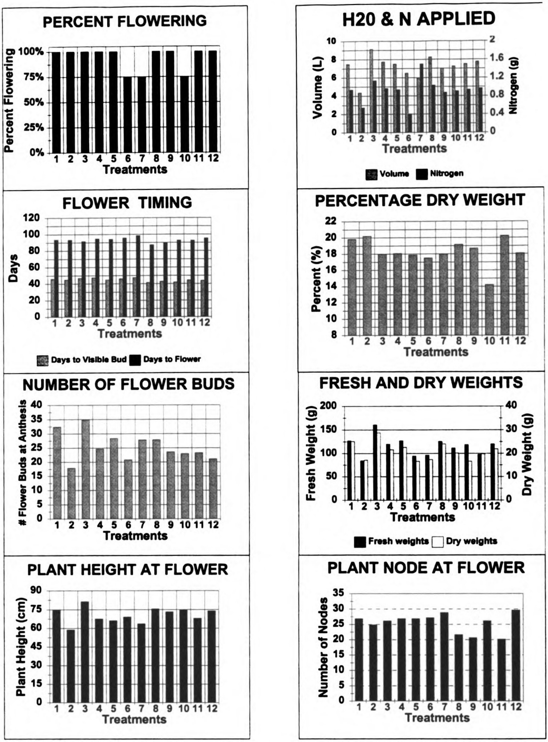


Figure 10. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Hibiscus moscheutos* 'Disco Belle Hybrid'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 11. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Hosta* 'Undulata Variegata'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	76	11	42.4	10	15.6	2.9	18.5	2.25	0.3	5.9	0.7
>50% CC	73	15	58.5	11	22.9	4.4	19.0	4.50	0.6	5.8	1.1
>75% CC	75	17	63.4	11	36.3	6.6	18.5	6.13	0.8	5.6	1.0
Significance	NS	NS	***	NS	***	***	NS				
Trends (Linear/Quadratic)			***/NS		***/NS	***/NS					
Media											
Peat	75	14	53.1	9	30.1	5.1	17.0	4.75	0.6	6.0	1.7
Peat/Perlite	73	15	58.5	11	22.9	4.4	19.0	4.50	0.6	5.8	1.1
Bark	74	16	50.9	12	32.6	5.7	17.6	4.75	0.6	5.2	0.9
Significance	NS	NS	NS	NS	NS	NS	*				
WSF Rate (ppm)											
31N-3P-31K	70	14	66.5	10	22.3	4.0	17.8	4.25	0.1	6.0	0.9
125N-12P-125K	73	15	58.5	11	22.9	4.4	19.0	4.50	0.6	5.8	1.1
250N-24P-250K	74	16	49.7	11	22.0	4.1	18.8	3.75	0.9	4.9	1.5
Significance	NS	NS	*	NS	NS	NS	NS				
Trends (Linear/Quadratic)			*/NS								
Low P WSF (ppm)											
125N-8P-125K	73	14	57.8	10	23.3	4.2	18.1	4.50	0.6	5.6	0.7
125N-12P-125K	73	15	58.5	11	22.9	4.4	19.0	4.50	0.6	5.8	1.1
Significance	NS	NS	NS	NS	NS	NS	NS				
pH Drench											
ph<5.5	74	12	55.5	10	27.6	4.7	17.2	3.75	0.5	4.9	0.9
5.8<pH<6.2	73	15	58.5	11	22.9	4.4	19.0	4.50	0.6	5.8	1.1
pH>6.5	73	21	64.5	12	27.9	5.0	18.0	4.00	0.5	6.5	1.0
Significance	NS	NS	NS	NS	NS	NS	NS				
Nutrient Solution											
5% NH4/320 ALK	74	22	57.1	10	23.4	4.8	21.1	4.00	0.5	6.9	0.8
25% NH4/120 ALK	73	15	58.5	11	22.9	4.4	19.0	4.50	0.6	5.8	1.1
50% NH4/20ALK	75	14	60.9	11	28.6	5.2	17.9	4.00	0.5	5.9	0.7
Significance	NS	NS	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)											

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

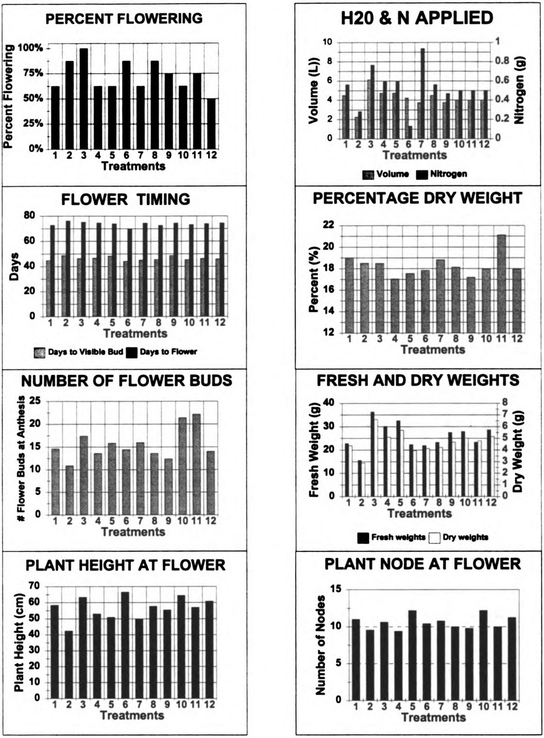


Figure 11. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Hosta* 'undulata variegata'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 12. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Lavandula angustifolia* 'Munstead'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	43	20	27.3	23	38.1	8.0	22.3	2.75	0.3	4.6	1.3
>50% CC	47	15	32.6	23	45.0	9.8	22.1	4.25	0.5	4.8	1.5
>75% CC	44	44	34.6	21	82.0	15.6	19.9	6.63	0.8	4.4	1.2
Significance	NS	**	**	NS	***	***	NS				
Trends (Linear/Quadratic)		**/*	**/NS		***/NS	***/NS					
Media											
Peat	45	9	28.2	23	40.2	8.1	20.9	4.25	0.5	5.0	1.4
Peat/Perlite	47	15	32.6	23	45.0	9.8	22.1	4.25	0.5	4.8	1.5
Bark	45	12	28.3	23	40.6	9.8	26.3	4.00	0.5	4.4	1.2
Significance	NS	NS	*	NS	NS	NS	NS				
WSF Rate (ppm)											
31N-3P-31K	45	18	32.5	23	49.3	10.2	21.0	4.25	0.1	4.9	1.1
125N-12P-125K	47	15	32.6	23	45.0	9.8	22.1	4.25	0.5	4.8	1.5
250N-24P-250K	45	17	25.9	22	54.2	9.9	18.8	3.75	0.9	4.7	2.1
Significance	NS	NS	**	NS	NS	NS	NS				
Trends (Linear/Quadratic)			**/NS								
Low P WSF (ppm)											
125N-8P-125K	45	17	29.7	23	44.0	10.3	28.2	4.25	0.5	4.6	1.6
125N-12P-125K	47	15	32.6	23	45.0	9.8	22.1	4.25	0.5	4.8	1.5
Significance	NS	NS	NS	NS	NS	NS	NS				
pH Drench											
ph<5.5	45	16	27.5	25	41.8	9.3	23.2	2.50	0.3	4.4	1.5
5.8<pH<6.2	47	15	32.6	23	45.0	9.8	22.1	4.25	0.5	4.8	1.5
pH>6.5								4.50	0.6	0.0	0.0
Significance	NS	NS	*	NS	NS	NS	NS				
Nutrient Solution											
5% NH4/320 ALK	45	11	30.6	24	47.3	11.0	25.8	5.50	0.7	6.0	1.6
25% NH4/120 ALK	47	15	32.6	23	45.0	9.8	22.1	4.25	0.5	4.8	1.5
50% NH4/20ALK	44	21	31.3	24	59.7	13.1	23.4	4.50	0.6	5.0	1.3
Significance	NS	NS	NS	NS	NS	*	NS				
Trends (Linear/Quadratic)						*/*					

NS, *, **, *** Nonsignificant or significant at $P < 0.05, 0.01, 0.001$, respectively.

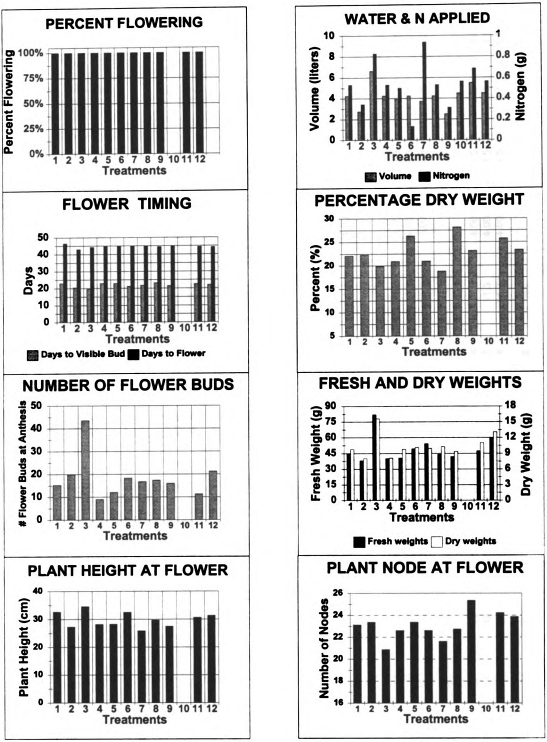


Figure 12. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Lavandula angustifolia* 'Munstead'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 13. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Leucanthemum* x *superbum* 'Snow Cap'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	55	10	16.4	17	71.3	9.5	13.3	2.88	0.4	6.3	0.8
>50% CC	57	12	15.4	18	97.6	11.1	11.3	4.00	0.5	6.1	1.0
>75% CC	57	14	19.8	17	135.7	14.3	10.5	6.38	0.8	6.6	1.1
Significance	**	**	***	NS	***	***	***				
Trends (Linear/Quadratic)	*/*	***/NS	***/**		***/NS	***/NS	***/**				
Media											
Peat	54	13	18.0	21	108.2	12.4	11.5	4.50	0.6	6.0	1.0
Peat/Perlite	57	12	15.4	18	97.6	11.1	11.3	4.00	0.5	6.1	1.0
Bark	54	13	17.0	17	101.9	12.1	11.9	4.00	0.5	5.3	1.0
Significance	*	NS	**	*	**	NS	NS				
WSF Rate (ppm)											
31N-3P-31K	57	10	17.5	18	69.5	9.4	13.6	4.00	0.1	6.0	0.9
125N-12P-125K	57	12	15.4	18	97.6	11.1	11.3	4.00	0.5	6.1	1.0
250N-24P-250K	55	13	16.7	20	101.6	12.6	12.4	3.75	0.9	5.5	1.6
Significance	*	***	*	NS	***	***	***				
Trends (Linear/Quadratic)	*/NS	***/NS	NS/*		***/***	***/NS	*/***				
Low P WSF (ppm)											
125N-8P-125K	54	13	18.3	17	103.0	12.6	12.3	4.25	0.5	6.0	1.3
125N-12P-125K	57	12	15.4	18	97.6	11.1	11.3	4.00	0.5	6.1	1.0
Significance	***	NS	**	NS	NS	*	NS				
pH Drench											
ph<5.5	56	11	15.9	16	72.7	10.2	14.3	3.75	0.5	4.2	1.5
5.8<pH<6.2	57	12	15.4	18	97.6	11.1	11.3	4.00	0.5	6.1	1.0
pH>6.5	57	11	19.1	19	96.3	11.3	11.8	4.00	0.5	7.1	0.9
Significance	NS	NS	***	**	***	NS	***				
Nutrient Solution											
5% NH4/320 ALK	57	13	18.9	19	99.7	11.4	11.5	4.00	0.5	7.6	0.8
25% NH4/120 ALK	57	12	15.4	18	97.6	11.1	11.3	4.00	0.5	6.1	1.0
50% NH4/20ALK	57	12	18.2	18	96.9	11.4	11.7	4.00	0.5	6.7	0.6
Significance	NS	NS	***	NS	NS	NS	NS				
Trends (Linear/Quadratic)			NS/***								

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

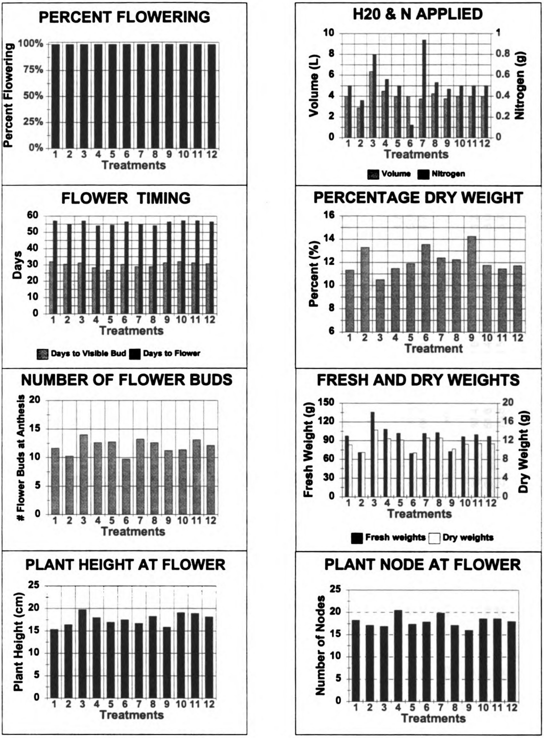


Figure 13. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Leucanthemum* x*superbum* 'Snow Cap'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 14. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Perovskia atriplicifolia*. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	73	39	73.3	23	38.7	9.2	23.9	3.38	0.4	5.7	1.9
>50% CC	69	46	81.0	21	51.6	12.4	24.0	6.00	0.8	5.6	1.7
>75% CC	65	63	86.9	21	82.5	19.4	23.5	8.00	1.0	5.7	2.0
Significance	***	***	**	NS	***	***	NS				
Trends (Linear/Quadratic)	***/NS	***/NS	**/NS		***/***	***/**					
Media											
Peat	65	59	79.9	19	68.2	16.0	23.5	6.50	0.8	5.6	2.3
Peat/Perlite	69	46	81.0	21	51.6	12.4	24.0	6.00	0.8	5.6	1.7
Bark	64	57	77.1	20	63.1	14.8	23.4	6.50	0.8	5.0	1.7
Significance	*	*	NS	*	***	***	NS				
WSF Rate (ppm)											
31N-3P-31K	69	50	82.9	22	61.0	14.6	23.9	6.50	0.4	6.3	1.4
125N-12P-125K	69	46	81.0	21	51.6	12.4	24.0	6.00	0.8	5.6	1.7
250N-24P-250K	68	51	75.9	20	52.4	12.1	23.0	5.00	1.3	5.3	2.4
Significance	NS	NS	NS	NS	***	***	NS				
Trends (Linear/Quadratic)					***/***	***/**					
Low P WSF (ppm)											
125N-8P-125K	71	56	78.0	22	69.9	17.2	24.7	6.25	0.8	5.6	2.1
125N-12P-125K	69	46	81.0	21	51.6	12.4	24.0	6.00	0.8	5.6	1.7
Significance	NS	*	NS	NS	***	***	NS				
pH Drench											
ph<5.5								4.75	0.6	4.0	1.7
5.8<pH<6.2	69	46	81.0	21	51.6	12.4	24.0	6.00	0.8	5.6	1.7
pH>6.5	70	50	83.9	22	64.1	14.1	22.0	4.75	0.6	7.2	1.5
Significance	NS	NS	NS	NS	***	*	NS				
Nutrient Solution											
5% NH4/320 ALK	69	42	76.2	22	58.4	13.6	23.3	5.25	0.7	7.0	1.5
25% NH4/120 ALK	69	46	81.0	21	51.6	12.4	24.0	6.00	0.8	5.6	1.7
50% NH4/20ALK	70	59	83.9	22	70.8	16.5	23.4	5.75	0.7	5.7	1.4
Significance	NS	**	NS	NS	***	***	NS				
Trends (Linear/Quadratic)		**/NS			***/***	***/***					

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

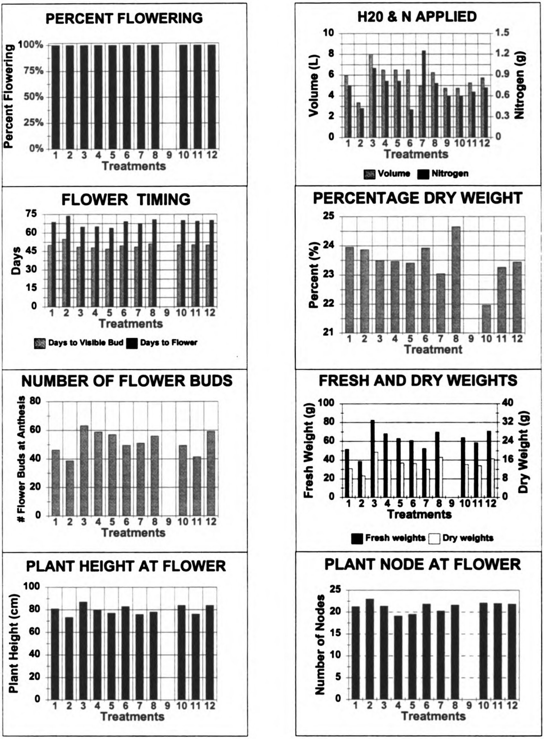


Figure 14. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Perovskia atriplicifolia*. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 15. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Rudbeckia fulgida* 'Goldsturm'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	76	27	30.3	8	76.0	14.9	19.6	5.13	0.6	5.4	1.3
>50% CC	72	30	39.1	9	146.2	26.1	17.9	10.00	1.3	5.2	1.7
>75% CC	75	46	42.1	9	203.2	33.9	16.7	13.75	1.7	4.9	1.9
Significance	*	***	***	NS	***	***	***				
Trends (Linear/Quadratic)	NS/**	***/*	***/NS		***/NS	***/NS	***/NS				
Media											
Peat	75	39	34.9	10	132.9	23.8	17.9	9.25	1.2	5.5	2.1
Peat/Perlite	72	30	39.1	9	146.2	26.1	17.9	10.00	1.3	5.2	1.7
Bark	75	30	32.1	10	106.7	19.6	18.4	8.50	1.1	5.0	1.3
Significance	NS	NS	**	NS	***	***	NS				
WSF Rate (ppm)											
31N-3P-31K	77	16	36.6	9	73.5	14.0	19.1	7.25	0.2	5.0	1.2
125N-12P-125K	72	30	39.1	9	146.2	26.1	17.9	10.00	1.3	5.2	1.7
250N-24P-250K	76	24	31.5	8	86.7	16.6	19.1	6.75	1.7	5.0	2.2
Significance	**	*	**	NS	***	***	NS				
Trends (Linear/Quadratic)	NS/**	NS/*	*/*		NS/***	NS/***					
Low P WSF (ppm)											
125N-8P-125K	72	35	37.1	10	134.6	26.8	19.9	9.75	1.2	4.9	1.8
125N-12P-125K	72	30	39.1	9	146.2	26.1	17.9	10.00	1.3	5.2	1.7
Significance	NS	NS	NS	NS	NS	NS	**				
pH Drench											
ph<5.5	82	19	23.4	9	63.4	12.2	19.4	6.00	0.8	4.6	1.2
5.8<pH<6.2	72	30	39.1	9	146.2	26.1	17.9	10.00	1.3	5.2	1.7
pH>6.5	83	18	29.0	7	127.2	19.7	15.5	7.50	0.9	6.2	1.4
Significance	**	*	***	*	***	***	***				
Nutrient Solution											
5% NH4/320 ALK	73	28	38.8	9	130.7	22.7	17.4	8.50	1.1	8.0	1.3
25% NH4/120 ALK	72	30	39.1	9	146.2	26.1	17.9	10.00	1.3	5.2	1.7
50% NH4/20ALK	75	34	40.3	10	170.7	26.8	15.7	9.75	1.2	5.6	1.1
Significance	NS	NS	NS	NS	***	*	**				
Trends (Linear/Quadratic)					***/NS	**/NS	**/*				

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

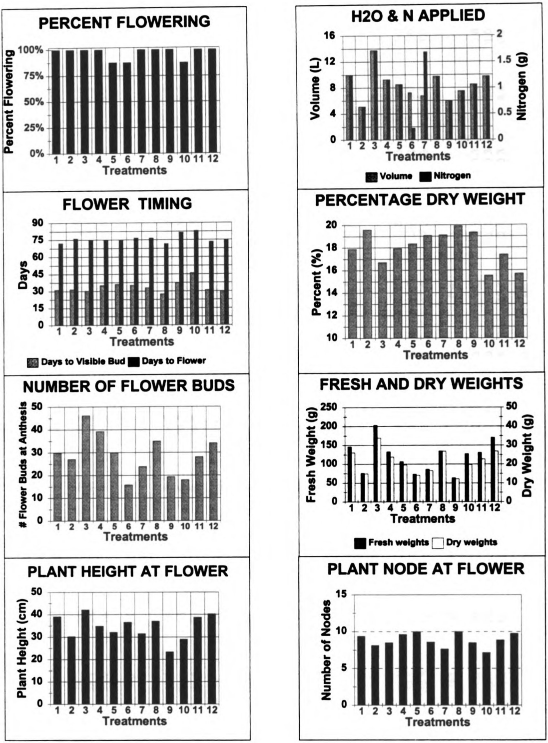


Figure 15. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Rudbeckia fulgida* 'Goldsturm'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 16. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Salvia* x *superba* 'Blue Queen'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	39.5	9	33	6	19.1	3.4	17.8	1.75	0.2	5.8	1.2
>50% CC	38.1	15	32	5	30.8	4.9	15.8	2.75	0.3	6.0	1.0
>75% CC	39.9	14	39	5	31.4	4.8	15.4	3.88	0.5	6.2	0.8
Significance	NS	NS	*	NS	**	*	**				
Trends (Linear/Quadratic)			*/NS		**/NS	*/NS	**/NS				
Media											
Peat	40.0	14	34	5	24.2	4.1	16.7	2.50	0.3	5.7	0.8
Peat/Perlite	38.1	15	32	5	30.8	4.9	15.8	2.75	0.3	6.0	1.0
Bark	36.1	16	34	5	34.8	5.8	16.7	3.00	0.4	5.2	0.7
Significance	*	NS	NS	NS	**	*	NS				
WSF Rate (ppm)											
31N-3P-31K	39.6	11	37	6	22.5	4.0	17.7	2.50	0.1	6.3	0.8
125N-12P-125K	38.1	15	32	5	30.8	4.9	15.8	2.75	0.3	6.0	1.0
250N-24P-250K	40.0	15	35	6	26.8	4.8	17.8	2.50	0.6	5.6	1.3
Significance	NS	NS	NS	NS	**	NS	*				
Trends (Linear/Quadratic)					NS/**		NS/**				
Low P WSF (ppm)											
125N-8P-125K	36.1	14	34	5	28.3	5.1	18.1	2.50	0.3	6.1	0.8
125N-12P-125K	38.1	15	32	5	30.8	4.9	15.8	2.75	0.3	6.0	1.0
Significance	NS	NS	NS	NS	NS	NS	*				
pH Drench											
ph<5.5	37.6	12	27	5	18.2	3.1	17.4	2.00	0.3	5.0	1.2
5.8<pH<6.2	38.1	15	32	5	30.8	4.9	15.8	2.75	0.3	6.0	1.0
pH>6.5	36.5	12	32	6	23.8	4.0	17.0	2.25	0.3	6.7	1.0
Significance	NS	NS	NS	NS	***	***	NS				
Nutrient Solution											
5% NH4/320 ALK	37.0	15	36	6	32.4	5.3	16.2	2.75	0.3	7.2	0.8
25% NH4/120 ALK	38.1	15	32	5	30.8	4.9	15.8	2.75	0.3	6.0	1.0
50% NH4/20ALK	36.0	14	34	5	34.3	5.6	16.4	2.75	0.3	6.4	0.6
Significance	NS	NS	NS	NS	NS	NS	NS				
Trends (Linear/Quadratic)											

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

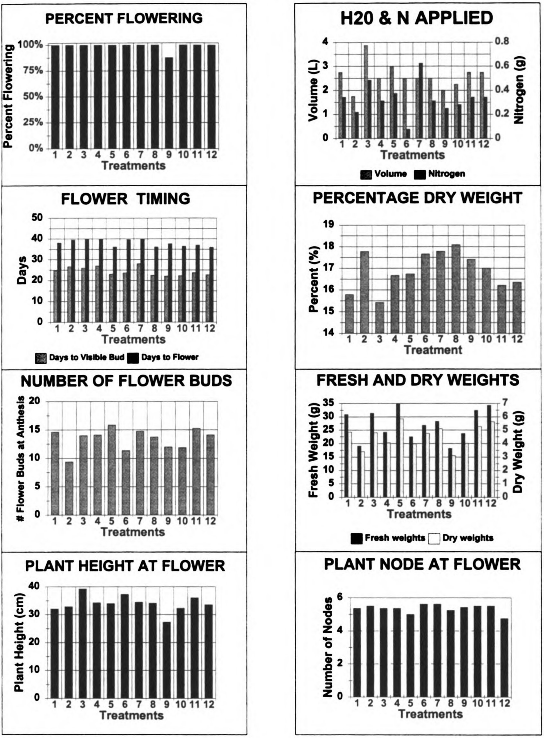


Figure 16. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Salvia* x*superba* 'Blue Queen'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 17. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Scabiosa caucasica* 'Butterfly Blue'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	43	23	31.0	10	46.6	8.5	18.2	2.38	0.3	5.4	1.3
>50% CC	43	26	36.4	10	61.6	11.2	18.2	3.75	0.5	5.5	1.1
>75% CC	42	33	35.6	10	79.3	13.0	16.5	4.63	0.6	5.6	1.1
Significance	NS	*	NS	NS	***	***	**				
Trends (Linear/Quadratic)		*/NS			***/NS	***/NS	*/*				
Media											
Peat	44	22	33.8	10	52.9	9.1	17.2	3.75	0.5	5.6	1.1
Peat/Perlite	43	26	36.4	10	61.6	11.2	18.2	3.75	0.5	5.5	1.1
Bark	45	27	30.6	9	55.0	10.4	18.9	3.00	0.4	4.7	1.0
Significance	NS	NS	*	NS	NS	NS	NS				
WSF Rate (ppm)											
31N-3P-31K	43	21	35.4	9	56.4	10.3	18.2	3.50	0.1	6.0	0.8
125N-12P-125K	43	26	36.4	10	61.6	11.2	18.2	3.75	0.5	5.5	1.1
250N-24P-250K	43	22	33.1	10	51.4	9.4	18.3	3.25	0.8	5.3	1.4
Significance	NS	NS	NS	NS	*	*	NS				
Trends (Linear/Quadratic)					NS/*	NS/*					
Low P WSF (ppm)											
125N-8P-125K	44	24	35.4	11	60.0	10.8	18.0	3.75	0.5	5.5	1.1
125N-12P-125K	43	26	36.4	10	61.6	11.2	18.2	3.75	0.5	5.5	1.1
Significance	NS	NS	NS	NS	NS	NS	NS				
pH Drench											
ph<5.5	48	14	23.5	9	20.2	4.2	20.9	1.75	0.2	3.9	0.9
5.8<pH<6.2	43	26	36.4	10	61.6	11.2	18.2	3.75	0.5	5.5	1.1
pH>6.5	44	22	33.9	10	49.5	9.1	18.4	2.50	0.3	6.9	1.1
Significance	NS	***	***	NS	***	***	**				
Nutrient Solution											
5% NH4/320 ALK	41	27	32.3	9	55.1	10.2	18.5	3.75	0.5	7.1	0.8
25% NH4/120 ALK	43	26	36.4	10	61.6	11.2	18.2	3.75	0.5	5.5	1.1
50% NH4/20ALK	40	29	32.1	8	69.2	12.5	18.1	3.25	0.4	6.6	0.7
Significance	NS	NS	NS	NS	**	**	NS				
Trends (Linear/Quadratic)					**/NS	**/NS					

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, respectively.

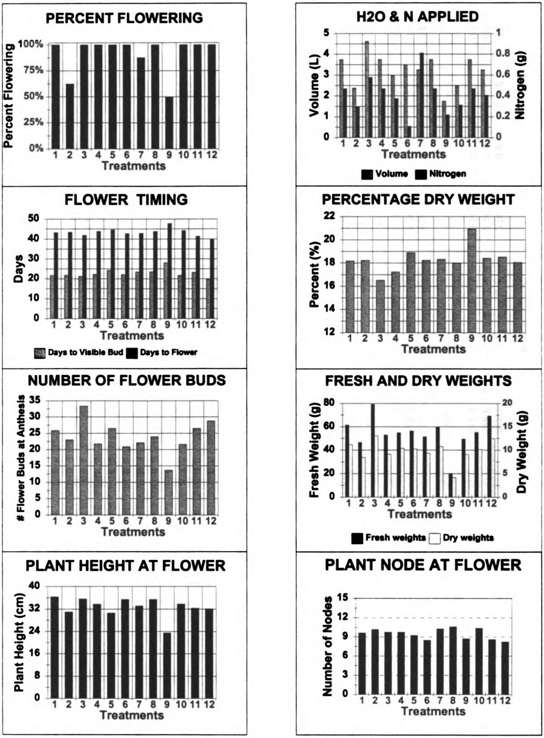


Figure 17. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Scabiosa caucasica* 'Butterfly Blue'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).

Table 18. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Sedum* 'Autumn Joy'. WSF=water-soluble fertilizer. ALK=alkalinity (mg $CaCO_3 \cdot L^{-1}$).

Treatment	Days to Flower	Flower Number	Plant Height (cm)	Final Node	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	%Dry Weight	Total Applied Water (liters)	Total Applied N (g/pot)	Final Medium pH	Final Medium EC
Moisture Level											
<60% CC	91	2713	24.6	22	204.3	16.3	8.0	2.88	0.4	5.9	0.6
>50% CC	92	4263	27.1	20	268.9	20.7	7.7	5.50	0.7	5.7	0.9
>75% CC	94	4510	27.5	17	295.6	22.7	7.7	5.88	0.7	5.3	1.0
Significance	NS	***	*	NS	**	**	NS				
Trends (Linear/Quadratic)		***/NS	**/NS		***/NS	**/NS					
Media											
Peat	91	3190	25.6	20	237.4	17.7	7.4	5.00	0.6	6.1	1.0
Peat/Perlite	92	4263	27.1	20	268.9	20.7	7.7	5.50	0.7	5.7	0.9
Bark	94	3823	28.2	19	267.6	20.8	7.8	5.50	0.7	5.1	0.7
Significance	NS	*	NS	NS	NS	NS	NS				
WSF Rate (ppm)											
31N-3P-31K	90	3331	25.8	21	227.6	18.6	8.2	5.00	0.3	4.6	0.9
125N-12P-125K	92	4263	27.1	20	268.9	20.7	7.7	5.50	0.7	5.7	0.9
250N-24P-250K	91	3548	25.1	20	219.8	17.2	7.8	4.50	1.1	5.3	1.0
Significance	NS	*	NS	NS	NS	NS	**				
Trends (Linear/Quadratic)		NS/*					NS/*				
Low P WSF (ppm)											
125N-8P-125K	94	3603	26.9	19	248.0	19.6	8.0	5.00	0.6	5.6	0.9
125N-12P-125K	92	4263	27.1	20	268.9	20.7	7.7	5.50	0.7	5.7	0.9
Significance	NS	*	NS	NS	NS	NS	NS				
pH Drench											
ph<5.5	92	3105	29.8	22	263.2	20.7	7.9	5.00	0.6	4.6	0.8
5.8<pH<6.2	92	4263	27.1	20	268.9	20.7	7.7	5.50	0.7	5.7	0.9
pH>6.5	93	3215	30.5	20	271.8	19.8	7.3	4.25	0.5	7.3	0.6
Significance	NS	***	*	NS	NS	NS	*				
Nutrient Solution											
5% NH4/320 ALK	91	2954	28.3	21	271.5	19.7	7.2	5.25	0.7	7.7	0.6
25% NH4/120 ALK	92	4263	27.1	20	268.9	20.7	7.7	5.50	0.7	5.7	0.9
50% NH4/20ALK	92	3465	30.1	22	262.7	20.3	7.7	5.00	0.6	6.0	0.5
Significance	NS	***	*	NS	NS	NS	*				
Trends (Linear/Quadratic)		NS/***	NS/*				*/NS				

NS, *, **, *** Nonsignificant or significant at $P < 0.05, 0.01, 0.001$, respectively.

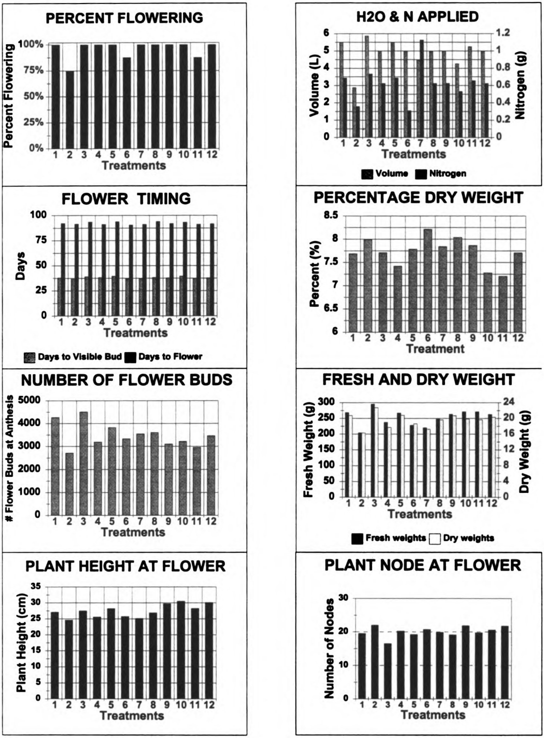


Figure 18. The effect of various root-zone conditions including levels of water availability, fertilizer concentration, and root-medium pH on growth and flowering of *Sedum* 'Autumn Joy'. The standard (1) root-zone conditions were compared to low and high a) moisture level (2=dry, 3=wet); b) porosity of media components (4=peat, 5=bark); c) fertilizer concentration (6=31 mg•L^{-1} N, 7=250 mg•L^{-1} N); d) phosphorus concentration (8=low P); e) pH drench (9=pH<5.5, 10=pH>6.5); and f) nutrient-solution reaction (11=5% NH_4-N/320 mg $CaCO_3$ •L^{-1}, 12=50% NH_4-N/20 mg $CaCO_3$ •L^{-1}).