

Light Intensity and Fertilizer Concentration: II. Optimal Fertilizer Solution Concentration for Species Differing in Light Requirement and Growth Rate

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Abstract. To evaluate the effects of increasing photosynthetic photon flux (*PPF*) on optimal fertilizer concentrations, we grew wax begonia (*Begonia semperflorens-cultorum* Hort.) and petunia (*Petunia ×hybrida* Hort. Vilm-Andr.) seedlings in a soilless growing medium without starter fertilizer under three *PPF* treatments (high, medium, and low corresponding to an average daily *PPF* of 23.2, 15.6, and 9.8 mol·m⁻²·d⁻¹, respectively) and subirrigated with six fertilizer concentrations [electrical conductivity (EC) of 0.12, 0.65, 1.18, 1.71, 2.24, and 2.77 dS·m⁻¹]. Compared to low *PPF*, shoot dry mass of wax begonia and petunia seedlings increased 2- and 3-fold, respectively, at high *PPF*. Fertilizer EC resulting in maximum shoot dry mass was the same (1.28 and 1.87 dS·m⁻¹ for wax begonia and petunia, respectively) in the three *PPF* treatments. Shoot dry mass and leaf area of petunias decreased little at higher than optimal fertilizer EC in the three *PPF* treatments, while growth of begonia was inhibited at high fertilizer EC. The optimal fertilizer range, calculated as the lower and upper limits of fertilizer EC within which plant growth was not reduced by >10% as compared to the optimum EC was 0.65 to 1.71 dS·m⁻¹ in wax begonia and 1.18 to >2.77 dS·m⁻¹ for petunia. Compared to those grown at 1.18 dS·m⁻¹, wax begonias grown at 1.71 dS·m⁻¹ had similar dry mass, but were shorter in all three *PPF* treatments (average height reduction of 6.5%). In general, EC of the top layer of the growing medium was higher than that of the bottom layer of the growing medium, and this difference increased with increasing EC.

Stricter environmental regulations and increased competition for water resources from urban areas provide strong motivation for greenhouse growers to reduce runoff and use water efficiently. This has increased interest in the use of recirculating subirrigation systems for greenhouse production (Elliot, 1990; Yelanich and Biernbaum, 1990; van Iersel, 1996; Morvant et al., 1997; Uva et al., 1998). Although fertilizer requirements of subirrigated plants are well documented in the literature (Kent and Reed, 1996; van Iersel, 1999; Cox, 2001; James and van Iersel, 2001), not much work has been done on the possible effects of the greenhouse environment on fertilization of subirrigated plants. However, there is evidence that the environment affects both nutrient uptake and optimal fertilizer concentrations. Kang and van Iersel (2001) concluded that the optimal fertilizer concentration for petunia decreased with increasing temperature. Li et al. (2001) reported the

modulating effect of transpiration on salinity in tomato (*Lycopersicon esculentum* L.) plants. In their experiment, tomatoes grown at a root zone EC of 9.0 dS·m⁻¹ had a higher marketable fresh yield in treatments with lower evapotranspiration (reduced to 65% of reference) than those with high evapotranspiration. At high relative humidity (RH), dry mass of begonia (*Begonia ×hiemalis* Fotsch) was found to be higher at higher fertilizer concentrations (Gislerød and Mortensen, 1990). These studies indicate that environmental factors, including temperature and humidity, can modify the optimal fertilizer concentration.

In modern greenhouses, computer-generated models may be used to determine the required fertilizer concentration by predicting photosynthesis and transpiration rates from environmental data (Klärning and Cierpinski, 1998). The so-called quantity concept (adding the amounts of water and nutrients expected to be taken up by plants; Klärning, 2001) can be reduced to a simple mathematical equation for determining the optimal fertilizer concentration. Since crop growth rate determines the nutrient requirement and evapotranspiration provides an estimate of the volume of nutrient solution to be supplied (Bugbee, 1995), the optimal fertilizer concentration (mg·L⁻¹ N) can be calculated as the product of the desired tissue nitrogen concentration (mg·g⁻¹)

and water-use efficiency [WUE, the ratio of crop growth to evapotranspiration (g·L⁻¹); Nemali and van Iersel, 2004]. Plants with a high growth to transpiration ratio or high WUE, absorb a relatively small amount of water while producing a gram of dry matter. Thus, a high fertilizer concentration should be supplied to these plants to maintain the desired tissue nutrient level. Both growth and transpiration are affected by *PPF* (Wong et al., 1978; Lawlor, 1995), and WUE generally increases with increasing *PPF* (Alexander and Connelly, 1995; Israeli et al., 1996; Nemali and van Iersel, 2004). Since *PPF* varies widely both throughout the year and among locations, we wanted to determine its effect on optimal fertilizer concentrations.

In addition, we wanted to determine whether the optimal growing medium EC depends on *PPF*. Kang and van Iersel (2001) showed that optimal fertilizer concentrations for subirrigated petunias were temperature dependent, but that optimal growing medium EC was similar at different temperatures. Electrical conductivity of the growing medium is a good indicator of the amount of fertilizer available to the plants in the root zone. In subirrigation, root growth, and thus nutrient uptake, is more pronounced in the bottom layer than the top layer of the growing medium due to higher moisture availability (Morvant et al. 1995; Todd and Reed, 1998). Therefore, the EC of the bottom layer is usually lower than that of the top layer (Todd and Reed, 1998; Cox, 2001). Moreover, evaporation from the surface of the growing medium can also increase the nutrient concentration in the top layer (Todd and Reed, 1998). Unless the growing medium is top-watered occasionally, the accumulated nutrients in the top layer cannot migrate down and are unavailable to the plants. Therefore, the EC of the bottom layer is more directly related to crop growth rate than that of the top layer.

In this experiment, we planned to quantify the effects of increasing *PPF* on the optimal fertilizer concentration and EC of the growing medium in a fast growing, sun-loving species (petunia) and slow growing, shade-tolerant species (wax begonia). These species were chosen because they are among the most popular bedding plants, and possible differences in responses to light between sun and shade species. We hypothesized that the optimal fertilizer concentration would be higher for plants grown at high *PPF* and the optimal EC of the growing medium would not be affected by *PPF* treatments.

Materials and Methods

Plant material. Plug seedlings of wax begonia 'Cocktail Vodka' and petunia 'Scarlet Purple' were obtained from a commercial grower (Sunbelt greenhouses, Douglas, Ga.) and transplanted into 10 cm (510 mL) pots filled with soilless growing medium (Fafard 2P mix, Fafard, Anderson, S.C.) on 15 Feb. 2002. The growing medium was a special mix and did not contain any starter fertilizer. After transplanting, the pots were moved to 1.2 × 2.4-m² ebb-and-flow benches (Midwest Gro-

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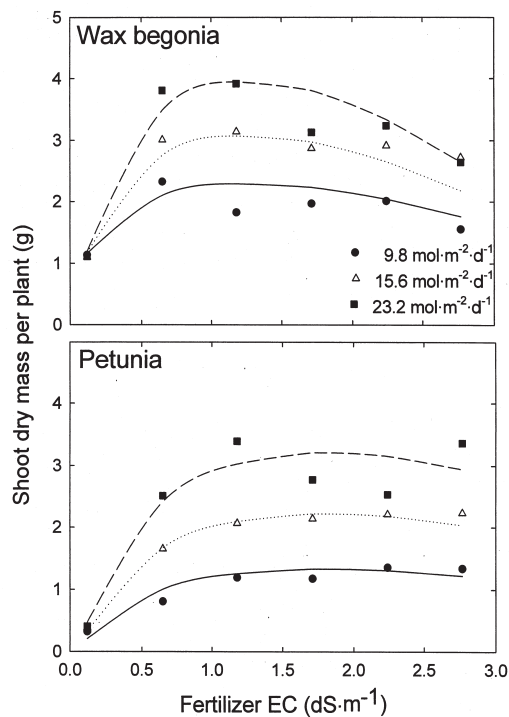


Fig. 1. Effect of increasing fertilizer EC and photosynthetic photon flux (PPF) on shoot dry mass (DW) of wax begonia and petunia. Data represent the mean of 2 replications of 7 and 15 plants of wax begonia and petunia, respectively at low (\bullet), medium (Δ), and high (\blacksquare) PPF levels. Lines pass through the estimated shoot dry mass at 35 (solid line), 63 (dotted line), and 90 (dashed line) percent of incident PPF ($PPF_{\%}$) (corresponding to 9.8, 15.6, and 23.2 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, respectively).
 $DW_{\text{begonia}} = 1.134 - 0.0325 \times PPF_{\%} + 0.113 \times PPF_{\%} \times \sqrt{EC} - 0.05 \times PPF_{\%} \times EC$ ($R^2 = 0.83$),
 $DW_{\text{petunia}} = 0.021 - 0.02 \times PPF_{\%} + 0.082 \times PPF_{\%} \times \sqrt{EC} - 0.03 \times PPF_{\%} \times EC$ ($R^2 = 0.96$).

Master, St. Charles, Ill.) and subirrigated with 20N-4.4P-16.6K fertilizer solutions (Peter's 20-10-20 peat-lite special, The Scotts Co. Marysville, Ohio).

Fertilizer solutions were stored in plastic barrels (210L) and pumped into the watertight trays of the ebb-and-flow system daily using submersible pumps (NoKorode-2; Little Giant, Oklahoma City, Okla.). The bottom of the pots were immersed in the fertilizer solution for ≈ 13 min (5 min for pumping and 8 min for draining) every day, during which the growing medium absorbed it by capillary action. The fertilizer EC in the barrels was measured using an EC meter (model M90; Corning, Corning, N.Y.) and adjusted weekly when the barrels were refilled. Plants were grown in a greenhouse covered with double-layered polythene. Incident PPF above the experimental units was measured throughout the experiment with a quantum sensor (LI-190SA; LI-COR, Lincoln, Nebr.) and temperature and RH in various experimental units were measured with dataloggers (Hobo H8; Onset Computer Corp., Pocasset, Mass.). At the end of the experiment, quantum sensors (QSO-SUN; Apogee Instruments Inc., Logan, Utah) connected to a datalogger (CR10X; Campbell Sci., Logan, Utah) were arranged in the center of each experimental unit to measure

PPF as a percentage of incident PPF in each treatment.

Treatments. Plants were subirrigated with one of the six fertilizer concentrations [EC of 0.12, 0.65, 1.18, 1.71, 2.24, or 2.77 $\text{dS}\cdot\text{m}^{-1}$ (corresponding to fertilizer concentrations of 0, 80, 160, 240, 320, and 400 $\text{mg}\cdot\text{L}^{-1}$ N, respectively)] and grown under one of the three PPF treatments (high, medium, and low corresponding to an average daily PPF of 23.2, 15.6, and 9.8 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, respectively). Each ebb-and-flow bench was divided into three zones using shade cloth of varying density (0%, 35%, or 63% shade) to provide different PPF levels. In each PPF treatment, both wax begonia and petunia seedlings were grown in groups of 30 plants each.

Although all plants were subirrigated daily, this does not imply that plants in all treatments received the same amount of fertilizer solution. With ebb-and-flow irrigation, the pots are watered to near saturation, and the amount of water absorbed by the growing medium therefore depends on the evapotranspiration since the previous irrigation.

Measurements. At the end of the experiment [4 weeks after transplanting (WAT) for petunia and 6 WAT for wax begonia], data on plant height, leaf area, shoot and root dry mass, EC of the top and bottom layers, and pH of the growing medium were collected for wax begonia and petunia seedlings. Plant height (average of 3 plants) was measured as the vertical length between the top of the plants and the growing medium. Leaf area of three plants was measured using an area meter (LI-3100, LI-COR). Shoots (from 7 and 15 plants for wax begonia and petunia, respectively) were dried in a forced-air oven maintained at 80 $^{\circ}\text{C}$ for a week before measuring the dry mass. Shoot to root ratio was estimated from shoot and root dry mass of a separately measured plant. Leaf area ratio (LAR) was determined as the ratio of leaf area to shoot dry mass.

Electrical conductivity and pH of the growing medium were measured using a pore water conductivity probe (Sigma probe EC1; Delta-T, Burwell, Cambridge, U.K.) and a pH meter (IQ-150; IQ scientific instruments, San Diego, Calif.) which could directly be inserted into the growing medium. To measure the EC of the growing medium, the probe was inserted

to one-third (for the top layer) or two-thirds depth (for the bottom layer). Both measurements were taken from the same pots and the used plants were discarded after measurement. Data collected with the conductivity probe are similar to those collected with the pour-through method (unpublished results). pH of the growing medium was measured by inserting the probe into the bottom layer of the growing medium.

Experimental design and data analysis. Treatments were organized in a split-split-plot design with two replications. Each fertilizer concentration was a whole plot, PPF levels were the main splits, and species were the subsplit plots. A group of 30 plants (either wax begonia or petunia) under each PPF level constituted an experimental unit. Data were analyzed separately for each species by linear and quadratic regression, using Statistical Analysis Software (SAS institute, Cary, N.C.) and correlations with $P < 0.05$ were considered statistically significant. To obtain acceptable fits of the regression models, a square root transformation of the predictor variable (fertilizer EC) was performed. Because the PPF differed slightly among experimental units within each shade level, the actual PPF in each experimental unit, expressed as a percentage of incident PPF ($PPF_{\%}$), was used in the regression analyses, thus resulting in 36 $PPF_{\%}$ levels. However, for simplicity the three average levels of 35, 63, and 90% of incident PPF (average $PPF_{\%}$ in the different PPF treatments) corresponding to 9.8, 15.6, and 23.2 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ respectively, were used in the graphs. The following polynomial regression model with interaction terms was fitted to describe the effects of treatments on response variables: $Y = \beta_0 + \beta_1 \times PPF_{\%} + \beta_2 \times \sqrt{EC} + \beta_3 \times PPF_{\%} \times \sqrt{EC} + \beta_4 \times PPF_{\%}^2 + \beta_5 \times EC + \beta_6 \times PPF_{\%} \times EC + \beta_7 \times PPF_{\%}^2 \times \sqrt{EC}$, where 'Y' is any response variable, $PPF_{\%}$ = percentage of incident PPF , EC = fertilizer EC, and $\beta_0 \dots \beta_7$ are regression coefficients. This equation was further reduced using backward selection ($P < 0.05$). The optimal fertilizer EC for any response variable was calculated as the EC value at which the first derivative of the function was equal to zero.

Results and Discussion

Environmental conditions. Despite differences in PPF levels, mean temperature during the growth period was similar in the three PPF

Table 1. Regression parameters of the fitted functions among electrical conductivity (EC) of fertilizer, photosynthetic photon flux (percentage of incident, $PPF_{\%}$), shoot to root ratio, and leaf area ratio in wax begonia and petunia ($Y = \beta_0 + \beta_1 \times PPF_{\%} + \beta_2 \times \sqrt{EC} + \beta_3 \times PPF_{\%} \times \sqrt{EC} + \beta_4 \times PPF_{\%}^2 + \beta_5 \times EC + \beta_6 \times PPF_{\%} \times EC + \beta_7 \times PPF_{\%}^2 \times \sqrt{EC}$). Interactions between fertilizer EC and PPF (β_3 , β_6 , and β_7) on shoot to root and leaf area ratios were not significant ($P > 0.05$).

Regression coefficient	Shoot to root ratio		Leaf area ratio ($\text{m}^2\cdot\text{kg}^{-1}$)	
	Wax begonia	Petunia	Wax begonia	Petunia
Intercept (β_0)	-4.26 ^{ns}	-1.03 ^{ns}	46.7 ^{***}	38.92 ^{***}
\sqrt{EC} (β_2)	59.0 ^{***}	20.4 ^{***}	27.4 ^{**}	---
EC (β_5)	-29.0 ^{***}	NS	-13.6 ^{**}	---
$PPF_{\%}$ (β_1)	---	---	-0.59 ^{**}	-0.20 ^{**}
$PPF_{\%}^2$ (β_4)	---	---	0.0031 [*]	---
R^2	0.40	0.64	0.70	0.24

ns,***,****Nonsignificant or significant at $P < 0.05$, 0.005, or 0.0005, respectively.

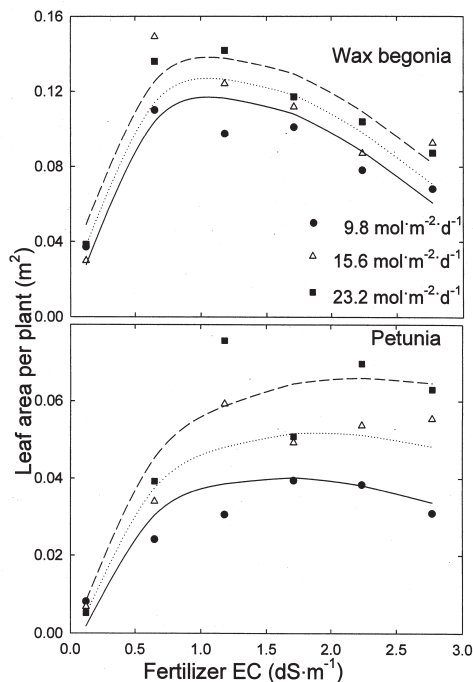


Fig. 2. Effect of increasing fertilizer EC and photosynthetic photon flux (*PPF*) on leaf area (*LA*) of wax begonia and petunia. Data represent the mean of two replications of three plants each of wax begonia and petunia at low (●), medium (Δ), and high (■) *PPF* treatments. Lines pass through the estimated leaf area at 35 (solid line), 63 (dotted line), and 90 (dashed line) percent of incident *PPF* ($PPF_{\%}$) (corresponding to 9.8, 15.6, and 23.2 mol·m⁻²·d⁻¹, respectively). $LA_{\text{wax begonia}} = -0.09 + 0.355 \times \sqrt{EC} + 0.00042 \times PPF_{\%} - 0.164 \times EC$ ($R^2 = 0.81$), $LA_{\text{petunia}} = -0.03 + 0.099 \times \sqrt{EC} + 0.00035 \times PPF_{\%} \times \sqrt{EC} - 0.044 \times EC$ ($R^2 = 0.77$).

treatments. Averaged over the entire growth period, the temperature in the three *PPF* treatments was 21.7 ± 0.2 EC. Average RH was slightly higher (about 6 percent) in the low than medium or high *PPF* treatments. The RH level was similar between medium and high *PPF* treatments (55 and 57%, respectively).

Plant growth. There was an interactive effect ($P < 0.05$) of fertilizer EC and *PPF* on shoot dry mass of petunia and wax begonia (Fig. 1). Shoot dry mass of fertilized plants was higher (roughly twice and thrice in wax begonia and petunia, respectively) for plants grown at high *PPF* than for those grown at low *PPF*. In both species, shoot dry mass was similar in the three *PPF* treatments without fertilizer, and increased rapidly with increasing fertilizer EC from 0.15 to 0.65 dS·m⁻¹. This increase in shoot dry mass was more pronounced at high *PPF*. When fertilizer EC was increased from 1.18 to 2.77 dS·m⁻¹, shoot dry mass of wax begonia decreased on average by 28%. There was little decrease in the shoot dry mass of petunia at high fertilizer EC (> 1.7 dS·m⁻¹). The optimal fertilizer EC was 1.28 dS·m⁻¹ for wax begonia and 1.87 dS·m⁻¹ for petunia. However, in both species, we did not find an effect of *PPF* on optimum fertilizer EC.

Since shoot dry mass in both species was similar over a range of fertilizer concentra-

tions (Fig. 1), we estimated the range of fertilizer EC in which the change was $\pm 10\%$ of the estimated dry mass at the optimum fertilizer EC (hereafter, 'optimal range'). In wax begonia and petunia, the optimal range of fertilizer EC for shoot dry mass ranged from 0.65 to 2.0 dS·m⁻¹ and 1.18 to > 2.77 dS·m⁻¹ among the three *PPF* treatments (shoot dry mass in petunia did not decrease by 10% even at the highest EC tested), respectively. This shows that both species can be grown with a wide range of fertilizer concentrations, and the range is higher for petunia than wax begonia.

The optimal fertilizer EC values obtained in our experiment agree with those obtained by James and van Iersel (2001). Their results indicated that dry mass of wax begonias and petunias was acceptable when fertilized with solutions with an EC of 1.0 to 2.4 and 1.4 to 2.9 dS·m⁻¹, respectively. Kang and van Iersel (2001) reported that the optimal fertilizer EC for petunias (*Petunia xhybrida* Hort. Vilm-Andr.) grown at a constant temperature of 25/17 EC was 2.6 dS·m⁻¹. However, optimal fertilizer EC for petunias in their experiment depended on the temperature. An earlier study by Gislerød and Mortensen (1990) indicated that optimal fertilizer EC for begonia (*Begonia xhiemalis* Fotsch) remained same for plants grown at two different RH levels. In their study, maximum dry mass was seen at the same fertilizer EC (2.0 dS·m⁻¹) for plants grown at 60% and 90% RH. However, further increase in fertilizer EC in their experiment resulted in greater reduction in dry mass of plants grown at 60% than 90% RH.

Shoot to root ratio of petunia and begonia increased with fertilizer EC (Table 1). Similar changes were also reported in poinsettia (*Euphorbia pulcherrima*. Willd. ex Klotzsch; Yelanich and Biernbaum, 1993) and salvia (*Salvia splendens* F. Sellow ex Roem.-Schult. 'Scarlet Sage'; Kang and van Iersel, 2004). Shoot root ratio was not affected by *PPF*.

Leaf area responses to *PPF* and fertilizer EC were similar to effects on dry mass (Fig. 2), although there was no interactive effect of fertilizer EC and *PPF* on leaf area of wax begonia. Leaf area of wax begonia increased with increasing *PPF* and as EC increased from 0.15 to 1.18 dS·m⁻¹, but decreased again at high fertilizer EC (> 1.18 dS·m⁻¹). The fertilizer EC resulting in maximum leaf area was the same for all the three *PPF* treatments (1.14 dS·m⁻¹, Fig. 2) which is close to the optimal fertilizer EC for shoot dry mass in wax begonia (1.28 dS·m⁻¹). Like shoot dry mass, leaf area of wax begonia was also similar over a range of fertilizer concentrations (Fig. 2). The optimal range for leaf area of begonia was 0.65 to 1.71 dS·m⁻¹.

The interaction between fertilizer EC and *PPF* on leaf area of petunia was significant and the optimal fertilizer EC for leaf area of petunia was different for the three *PPF* treatments [3.2, 1.9 and 1.6 dS·m⁻¹, at high, medium, and low *PPF* treatments, respectively (Fig. 2)].

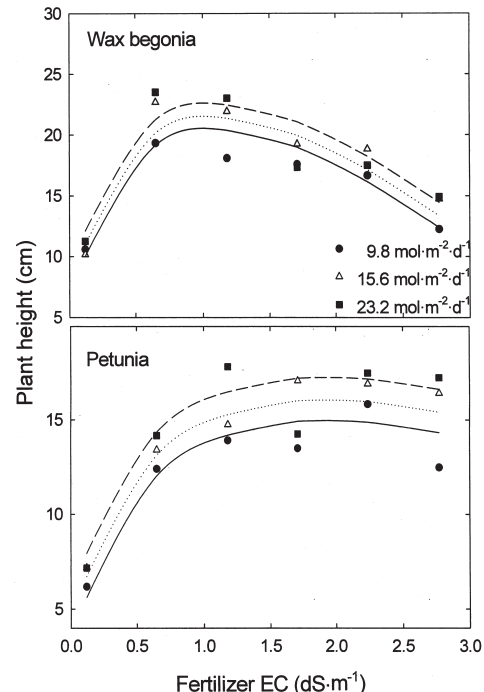


Fig. 3. Effect of increasing fertilizer EC and photosynthetic photon flux (*PPF*) on plant height (*H*) of wax begonia and petunia. Data represent the mean of two replications of three plants each of wax begonia and petunia at low (●), medium (Δ), and high (■) *PPF* treatments. Lines pass through the estimated plant height at 35 (solid line), 63 (dotted line), and 90 (dashed line) percent of incident *PPF* ($PPF_{\%}$) (corresponding to 9.8, 15.6, and 23.2 mol·m⁻²·d⁻¹, respectively). $H_{\text{wax begonia}} = -4.19 + 0.039 \times PPF_{\%} + 44.2 \times \sqrt{EC} - 21.1 \times EC$ ($R^2 = 0.75$), and $H_{\text{petunia}} = -3.24 + 0.043 \times PPF_{\%} + 23.9 \times \sqrt{EC} - 8.6 \times EC$ ($R^2 = 0.83$).

Although these differences in optimal EC for leaf area may appear large, the optimal range was similar at the different *PPF* levels. The lower limits of the optimal EC range were 1.18, 1.30, and 1.50 dS·m⁻¹ for low, medium, and high *PPF*, while the upper EC limit was > 2.77 dS·m⁻¹ in all three *PPF* treatments.

Leaf area ratio of wax begonia was affected by both fertilizer EC and *PPF* (Table 1). Leaf area ratio decreased at high fertilizer EC (negative coefficient for EC). Although shoot dry mass of wax begonia decreased along with leaf area at high fertilizer EC, the decrease in leaf area was more pronounced than that of shoot dry mass (Figs. 1 and 2), which resulted in a decrease in LAR at high fertilizer EC (> 1.0 dS·m⁻¹). The decrease in LAR indicates that wax begonia does not efficiently produce leaf area at high fertilizer concentrations, which is typical for bedding plants. Kang and van Iersel (2004) reported that LAR of salvia increased up to 1× full strength and decreased at 2× full strength of Hoagland nutrient solution. Leaf area ratio of pansy (*Viola xwittrockiana* Gams.) reached a maximum at a fertilizer EC of 2.0 dS·m⁻¹ and decreased at a fertilizer EC of 3.0 dS·m⁻¹ (van Iersel and Kang, 2002).

Leaf area ratio in wax begonia decreased with increasing *PPF*, similar to reports on other species with contrasting light requirements, like tall fescue [*Festuca arundinacea* Schreb.,

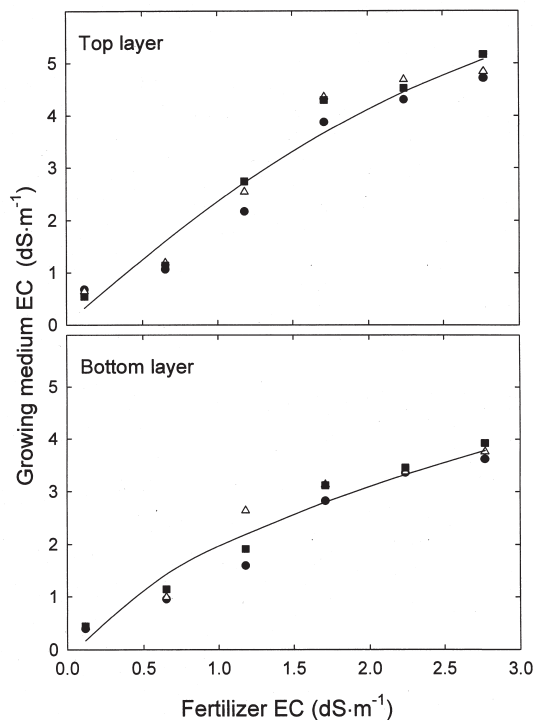


Fig. 4. Effect of increasing electrical conductivity (EC) of the fertilizer solution on EC of the growing medium in the top and bottom layers of wax begonia. Data represent the mean of two replications of three plants at low (●), medium (Δ), and high (■) PPF treatments (corresponding to 9.8, 15.6, and 23.2 mol·m⁻²·d⁻¹, respectively). $EC_{\text{bottom}} = -0.78 + 2.74 \times \sqrt{EC}$ ($R^2 = 0.91$), $EC_{\text{top}} = 0.0074 + 2.64 \times \sqrt{EC} - 0.29 \times EC$ ($R^2 = 0.94$).

(Allard et al., 1991)] and dracaena [*Dracaena sanderana* hort Sander ex Mast, (Vladimirova et al., 1997)]. Plants grown in low PPF increase their LAR to capture more light, thereby increasing their growth rate. Although LAR of petunia also decreased with increasing PPF, the correlation among LAR, fertilizer EC, and PPF was poor and we did not find any effect of EC on LAR of petunia (Table 1).

Effects of fertilizer EC and PPF on plant height in both species were similar to those on shoot dry mass. The optimal fertilizer EC for plant height in wax begonia was 1.1 dS·m⁻¹ (Fig. 3). Averaged over the three PPF treatments, plant height in wax begonia decreased by 38 percent, when fertilizer EC was increased from 1.18 to 2.77 dS·m⁻¹. The fertilizer range resulting in maximum begonia height was 0.65 to 1.71 dS·m⁻¹ in the three PPF treatments. Plant height of petunia was less sensitive to increasing fertilizer EC than that of wax begonia (Fig. 3). Although optimal fertilizer EC for petunia height was 1.9 dS·m⁻¹, the optimal range was from 1.18 to > 2.77 dS·m⁻¹ in the three PPF treatments. These results agree with those of James and van Iersel (2001), who reported that a fertilizer EC of 1.4 and 1.8 dS·m⁻¹ resulted in maximum plant height in wax begonia and petunia, respectively. A decrease in plant height of wax begonia with increasing fertilizer EC has been reported in earlier studies (Chase and Poole, 1987; Gislerød and Mortensen, 1990; James and van Iersel, 2001). Decreasing plant

height without affecting the overall quality is desirable for bedding plants. Compared to those grown at 1.18 dS·m⁻¹, wax begonias grown at 1.71 dS·m⁻¹ had similar dry mass, but were shorter in all three PPF treatments (average height reduction of 6.5%).

These results indicate that the optimal range of fertilizer EC for plant growth was similar in the three PPF treatments for both species (0.65 to 1.71 dS·m⁻¹ and 1.18 to >2.77 dS·m⁻¹, respectively for wax begonia and petunia). The lack of increase in optimal fertilizer EC with increasing PPF does not support our hypothesis that optimal fertilizer concentration for subirrigated plants increases with increasing PPF. Therefore, fertilizer concentrations for subirrigated bedding plants need not be adjusted based on the PPF.

Based on our results, PPF levels do not need to be considered when developing fertilizer guidelines for different growing seasons or regions of the country.

Electrical conductivity of the growing medium. Photosynthetic photon flux affected the EC of the growing medium of petunia, but had no effect on the EC of either the top or bottom layer of wax begonia (Fig. 4, only data from wax begonia are shown). However, the effect of PPF on the growing medium EC of petunia was negligible compared to the effect of fertilizer EC (results not shown). In both species, the EC of both the bottom and top layers of the growing medium increased with increasing fertilizer EC.

The EC of the bottom layer of wax begonia increased from 0.17 to 3.78 dS·m⁻¹, when the fertilizer EC was increased from 0.12 to 2.77 dS·m⁻¹. The electrical conductivity of the bottom layer in the optimal range of fertilizer EC (0.65 to 2.0 dS·m⁻¹) was 1.43 to 2.8 dS·m⁻¹ and was the same in the three PPF treatments (Fig. 4). Changes in dry mass with increasing PPF were not reflected in the EC of the bottom or top layers of wax begonia. Plants grown at high PPF had higher dry mass than those grown at low PPF, and presumably absorbed more nutrients from the growing medium. However, since larger plants likely transpired more as well, the growing medium of these plants absorbed more fertilizer solution at each irrigation. A dry growing medium would have absorbed more fertilizer solution, thus replenishing the nutrients taken up by the plants.

The EC of the bottom layer of petunia in the optimal fertilizer EC range was 2.2 to >3.5 dS·m⁻¹ at low PPF, 2.3 to >3.5 dS·m⁻¹ at medium PPF, and 2.4 to >3.6 dS·m⁻¹ at high PPF (results not shown). Kang and van Iersel (2001) reported that a growing medium EC of 3.5 dS·m⁻¹ resulted in maximum shoot

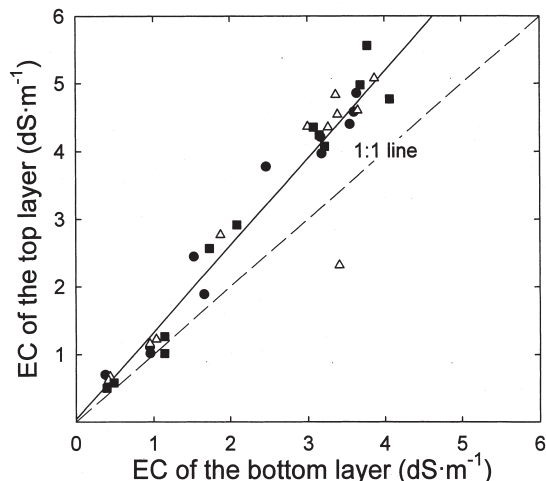


Fig. 5. Correlation between the electrical conductivity of the top (EC_{top}) and bottom (EC_{bottom}) layers of the growing medium in wax begonia. Data represent the mean of three plants from all experimental units at low (●), medium (Δ), and high (■) PPF treatments (corresponding to 9.8, 15.6, and 23.2 mol·m⁻²·d⁻¹, respectively). $EC_{\text{top}} = 0.041 + 1.285 \times EC_{\text{bottom}}$ ($r^2 = 0.93$).

dry mass in petunia, which is consistent with our findings.

In general, growing medium EC was higher in the top than in the bottom layer in both species. This was most evident at a fertilizer EC > 0.65 dS·m⁻¹ (Fig. 5, only data from wax begonia are shown). Electrical conductivity of the top layer was closely correlated to that of the bottom layer in both species ($r = 0.96$; Fig. 5, only data from wax begonia are shown), and the difference in EC between the top and bottom layers increased as the EC of the bottom layer increased. Higher EC in the top than in the bottom layer of the growing medium of subirrigated poinsettia was reported by van Iersel (2000) and Cox (2001). Kent and Reed (1996) found that the growth of New Guinea impatiens (*Impatiens xhawkeri*) and spathiphyllum (*Spathiphyllum* Schott) was not affected by the high EC in the top layer, and they concluded salt accumulation in the top layer did not necessarily have detrimental effects on plant growth. This is consistent with the finding that respiration of poinsettia is affected by the EC of the bottom, but not the top layer of the growing medium (van Iersel, 2000). These experiments also indicated that the EC of the top layer was only excessively high at supraoptimal fertilizer concentrations, indicating that excess soluble salts in the bottom layer migrate to the top layer during the course of crop growth. This is supported by the finding that nitrate was not detected in the top layer until the nitrogen concentration in the fertilizer was >4 mM (Kent and Reed, 1996). Since accumulation of salts can be greatly reduced by minimizing evaporation from the pots (Argo and Biernbaum, 1995), this accumulation presumably occurs because salts accumulate as water evaporates from the medium surface.

In both species, the pH of the growing medium was in or near the recommended range (5.5 to 6.5) for most greenhouse crops (Lang,

1996). There was an interactive effect of fertilizer EC and PPF on pH of the growing medium in both species, however the correlation among pH, EC, and PPF was poor for begonia ($R^2 = 0.43$). In petunia, pH of the growing medium increased with PPF, but decreased with increasing fertilizer EC (due to acidic nature of the fertilizer) and this decrease was higher at high PPF than at low PPF ($\text{pH} = 5.35 + 0.0109 \times \text{PPF}_{\%} - 0.00787 \times \text{PPF}_{\%} \times \sqrt{\text{EC}}$, $R^2 = 0.62$, data not shown).

Conclusions

The optimal fertilizer EC for subirrigated bedding plants (0.65 to 2.0 $\text{dS}\cdot\text{m}^{-1}$ for begonia and 1.2 to > 2.8 $\text{dS}\cdot\text{m}^{-1}$ for petunia) was not affected by PPF levels varying from 9.8 to 23.2 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, implying that growers need not adjust the fertilizer EC based on PPF. Crop growth was better under high than low PPF levels. There was little or no effect of PPF on the EC of growing medium, indicating that the optimal EC of the growing medium was similar in all PPF treatments as well. The optimal EC of the bottom layer of the growing medium was 1.43 to 2.8 $\text{dS}\cdot\text{m}^{-1}$ for begonia and ≈ 2.2 to >3.5 $\text{dS}\cdot\text{m}^{-1}$ for petunia. Although the optimal EC of the bottom layer of the growing medium increased with PPF in petunia, this effect was too small to be of practical significance.

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