Model-based Control of Nutrient Solution Concentration Influences Tomato Growth and Fruit Quality

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ABSTRACT. Diurnal changes in microclimate in a greenhouse are often greater than changes in daily averages over weeks or months. Thus, one may hypothesize that changing the nutrient solution concentration supplied to plants at intervals less than one day would improve tomato yield and quality. To test this hypothesis research was conducted to compare four nutrient control strategies for their effects on plant growth, fruit yield, fruit quality, and root characteristics of ‘Counter’ tomato [Lycopersicon esculentum (L.) Mill.]. The four strategies were 1) ECvariable, adjustment of nutrient solution electrical conductivity (EC) at 15-min intervals according to greenhouse microclimate over the previous 15-min and empirical models of photosynthesis and transpiration; 2) ECdaily, daily adjustment of nutrient solution EC based on each morning’s 24-hour weather forecast; 3) EC1.5 , supply of a single high nutrient solution of 3.7 dS·m–1; or 4) EC3.7 , low nutrient solution EC of 1.5 dS·m–1 for the entire growth period. Mean effluent EC levels were 1.8 dS·m–1 for treatment ECvariable, 5.1 dS·m–1 for treatment ECdaily, and 3.6 dS·m–1 for treatment EC1.5 and 3.4 dS·m–1 for treatment EC3.7. Except for fresh weight (FW) of roots, growth characteristics did not differ significantly among treatments. Total production of fruit averaged 12.2 kg·m–2·FW and 1.0 kg·m–2·dry weight (DW); and fruit yield averaged 6.7 kg·m–2. Dry matter content, yield loss to blossom-end rot, and firmness responded linearly to treatment EC. In general, ECvariable yielded higher fruit quality and EC3.7 lower fruit quality than that predicted by linear regression. Although our strategy of short-term dynamic changes of nutrient solution EC according to changes in climate variables did not increase yield, daily adjustment of nutrient solution EC improved external fruit quality characteristics and may be practical for grower adoption.

In commercial hydroponic culture, growers generally provide plants with nutrient solutions having constant mineral nutrient concentrations and they control the volume of nutrient solution provided based on time or amount of solar radiation. Most growers rely on standardized recommendations to set the composition and concentration of nutrient solution. Over recent years, recommended concentrations of mineral nutrients in solutions have increased, especially in production of high-quality vegetables such as tomato (Lycopersicon esculentum). These recommendations are often expressed in terms of electrical conductivity (EC). Whereas 10 years ago an EC level of 2.0 to 2.5 dS·m–1 was recommended for tomato culture (Göhler and Drews, 1989) advisers currently recommend nutrient solutions with EC between 3.0 and 4.5 dS·m–1 depending on the tomato cultivar (De Kreij et al., 1997). Higher EC results in a better flavor, which results from a higher concentration of total soluble solids, acids, sugars, and aromatic volatiles (Auerswald et al., 1999).

Controlling nutrient solution EC in the root environment is more complicated than it appears. Even supply of nutrient solution with constant EC results in changes in solution EC in the root environment because plants do not take up nutrients and water in a constant ratio. These plant-mediated changes in solution EC may lead to nutrient deficiency or enrichment of salts in the root environment. Therefore, growers monitor effluent EC, that is, solution leaving the growing media, at least weekly. Typically, effluent EC is greater than nutrient solution EC. Growers control effluent EC by adjusting the nutrient solution EC and amount of solution supplied to the plants. Excessively high effluent EC reduces biomass production and consequently yield (Al-Harbi, 1995; Satti et al., 1995). Maas and Hoffman (1977) reported that crop yield decreases linearly with increasing solution EC after passing a threshold value. Sonneveld (1988) and Adams (1991) determined that increasing EC reduced tomato yields from 6% to 10% per 1 dS·m–1 EC depending on cultivar and salts used. Depending on microclimate and cultivar, increasing root zone EC also increases the incidence of blossom-end rot (BER; Ho and Adams, 1994), a physiological disorder in tomato fruit caused by local Ca deficiency.

Nutrient solution EC is directly proportional to dry matter content but inversely proportional to Ca content in tomato fruit (Ho and Adams, 1989). As tomato fruit accumulate most dry matter and water during the day, high nutrient solution EC during the day may diminish net water accumulation and increase dry matter content. Low nutrient solution EC at night may facilitate accumulation of Ca in fruit, possibly by increasing root pressure (Bradfield and Guttridge, 1984; Ho and Adams, 1989). To produce tomato fruit with both high dry matter content and high Ca content several investigators developed systems that change nutrient solution concentration supplied to plants during the day.
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status in the short term to the extent that plant growth responds
than BER.

Another approach to managing nutrient solution to improve
yield and quality of tomato is to synchronize nutrient and water
supply with plant demand. Kläring et al. (1997) developed models and strategies to compute and control the optimum
nutrient solution EC depending on greenhouse microclimate. Based on forecast greenhouse microclimate, models calculate
transpiration, photosynthesis, and the expected ratio of nutrient to
water uptake for the day. From this ratio Kläring and Cierpinski
(1998) estimated the best practical nutrient solution EC and
adjusted it in the morning for the whole day. In experiments with
tomato and pepper (Capsicum annuum L. var. annuum), such a
control strategy to improve synchronization of nutrient and water
supply with plant uptake increased marketable yield because of
reduced incidence of BER compared with the growers standard
practice (Kläring et al., 1999). These experiments did not address
the question whether daily adjustment of nutrient solution EC
based on the model influenced fruit quality characteristics other
than BER.

Changes in nutrient solution EC will not alter plant nutritional
status in the short term to the extent that plant growth responds
immediately. Water potentials, related cell expansion rates, and
transport processes, on the other hand, change within 60 s of a
change in osmotic pressure in the root environment (Van Ieperen,
1996a). Short-term nutrient solution control strategies would
have both short and long-term effects that must be evaluated
before such strategies could be used to improve yield and quality
in tomato culture (Van Ieperen, 1996b).

We hypothesize that short-term adjustment of nutrient solution
EC according to measured changes in microclimate will
improve tomato quality as compared with a high constant nutrient
solution EC but will not reduce yield as compared with a low constant solution EC.

Materials and Methods

General treatment conditions. Research was conducted at the Envirotron of the College of Agricultural and Environmental Sciences, Griffin Campus, University of Georgia. 'Counter' tomato seeds were germinated and transplanted to 0.27-L pots filled with coarse sand when 12 d old. Seedlings grew in an indoor growth chamber for 50 d, until the first truss started to flower. On 17 Apr. 1998, the sand was washed from the roots and plants were transferred to shallow troughs (0.1 × 0.2 × 2.2 m³) in a greenhouse (7 × 7 m²). Sixteen troughs were arranged in a randomized complete block design. Seven tomato plants were grown in each trough using a nutrient film technique without reuse of effluent solution. Greenhouse temperature controls were set for heaters to turn on if temperatures dropped below 20 °C and for cooling to start if temperatures exceeded 25 °C. Humidity and CO₂ concentration were ambient and not controlled. Pollination was facilitated by gently vibrating flowering stems twice weekly.

Stock solution was prepared according to the recipe of Voogt and Bloemhard (1994). To produce nutrient solutions for different treatment EC levels, stock solution was mixed with tap water (EC < 0.1 dS·m⁻¹). Ten barrels, each 200 L, stored nutrient solutions with different EC levels (Fig. 1). Each morning, supply tanks were filled and pH was adjusted to 5.6 by adding H₃PO₄ or Ca(OH)₂. Nutrient solution was supplied to troughs in pulses at 15-min intervals, with the amount supplied calculated at 3 × transpiration demand according to the transpiration model of A. Heisner (unpublished). Nutrient solution was pumped from barrels through a drip irrigation system with one emitter per plant and an emitter flow rate of 4 mL·s⁻¹. In one trough of each treatment, effluent EC was measured continuously with an in-line sensor (Fig. 1).

Nutrient solution control strategies. Four strategies to control EC of the nutrient solution supplied to the plants were tested: 1) constant EC at 1.5 dS·m⁻¹ (EC₁.₅); 2) constant EC at 3.7 dS·m⁻¹ (EC₃.₇); 3) daily EC adjustment based on expected greenhouse microclimate forecast from cloudiness and rain from local weather reports (EC.daily); and 4) short-term EC adjustment based on continuously monitored greenhouse microclimate over the preceding 15-min period (EC{'sub'}daily). The procedure to change the nutrient solution concentration with greenhouse climate (treatments 3 and 4) was described in detail by Kläring et al. (1997). In brief, the calculation procedure for solution EC in EC{'sub'}daily was based on empirical models of crop net photosynthesis (P₁net, CO₂ at mg·m⁻²·s⁻¹) and crop transpiration

![Diagram of nutrient solution control strategies](image-url)
Assuming a constant nutrient concentration of the nutrient X in dry matter \( [N_x, X \text{ at mg} \times [mg \text{ carbohydrate} (CH2O)]^{-1}] \) the nutrient uptake of the crop \( (NU_x, X \text{ at mg} \cdot m^{-2} \cdot s^{-1}) \) was predicted as \( NU_x = 30/44 \times N_x \times P_{net} \), where 30 corresponds to the mass of 1 mol CH2O and 44 corresponds to the mass of 1 mol CO2. Neglecting the uptake of water for plant growth, the ratio of nutrient X to water uptake of the crop \( (C_x, X \text{ at mg} \cdot kg^{-1} H2O) \), which we call nutrient uptake concentration, may be calculated as \( C_x = NU_x/TR \).

Using a standard composition for the nutrient solution (Voogt and Bloemhauard, 1994) we derived the nutrient solution \( EC_{cal} \) from the calculated potassium (K) to water uptake ratio \( CF = C_k/EC_{cal} \), where \( C_k = (dtm^{-1}) \) and \( EC_{cal} = C_k \times (EC)^{C_k} \times C_x \), EC and K concentration of the standard nutrient solution. Note that \( EC_{cal} \) depends on the nutrient used in the calculation procedure. Using K, the K concentration in the supply solution is in the following the rule: \[ CF = \frac{D}{PDD} \times \frac{(P500 – P100)/(PDD500 – PDD100)}. \]

Model input data were obtained as follows. Greenhouse microclimate data were monitored using a data logger (CR10X, Campbell Scientific, Logan, Utah). Monitored variables included: solar radiation (LI-195B, LI-COR, Lincoln, Nebr.), air and root temperature (copper-constantan thermocouples), and relative humidity (HMP 35C, Campbell Scientific, Logan, Utah). Atmospheric CO2 was assumed constant at 380 \( \mu \text{mol} \cdot \text{mol}^{-1} \). Leaf area was estimated from leaf length and width measurements as \( \frac{LAI, m^2 \cdot m^{-2}}{P_{net}} \), where \( 30 \) corresponds to the mass of 1 mol CH2O and 44 corresponds to the mass of 1 mol CO2. Neglecting the uptake of water for plant growth, the ratio of nutrient X to water uptake of the crop \( (C_x, X \text{ at mg} \cdot kg^{-1} H2O) \), which we call nutrient uptake concentration, may be calculated as \( C_x = NU_x/TR \).

A rainy day in the forecast increased the \( EC_{sup} \) for one level while a dry day did not change the level. This adjustment for forecast rain was based on the assumption that high humidity accompanied rainfall and would decrease transpiration more than it would decrease plant demand for nutrient uptake.

Results

Control of nutrient solution supply. Micrometeorological conditions in the greenhouse during the growing period are given in Fig. 2. Daily solar radiation fluctuated from a low of 5 MJ-m^{-2} to a high of 19 MJ-m^{-2}, with a mean of 13.6 MJ-m^{-2} (Fig. 2A). Daily minimum and mean night temperatures increased \( \approx 2.1 ^\circ C \) during the harvest period, whereas daily maximum temperature increased \( 3.2 ^\circ C \) and mean daytime temperature increased \( 2.9 ^\circ C \) (Fig. 2B). Mean root zone temperature (data not presented) was \( 0.75 ^\circ C \) lower than greenhouse temperature. Relative humidity increased during the first 20 d after planting but was relatively constant thereafter (Fig. 2C). Early in the season, plants were smaller and transpired less, so relative humidity in the greenhouse was lower and affected more by the external environment than by the plants. As plants grew, they transpired more and increased the relative humidity within the greenhouse resulting in constant daily relative humidity between 70% and 80%.

Daily averages for nutrient solution and effluent EC are presented in Fig. 3A and B, whereas Table 1 shows the total
season averages. Examples of 2 d with different microclimate show the great variability in EC of nutrient supply to treatment ECvariable during the day (Fig. 3C).

The amount of nutrient solution supplied to each plant averaged 5.19 L·d⁻¹. Water uptake per plant calculated by the transpiration model was 1.56 L·d⁻¹. Thus, the actual nutrient solution supply was 3.4 times the transpiration demand (Fig. 3D).

**GROWTH ANALYSIS.** Total plant FW and DW, the sum of shoot, root, mature and immature fruit weights, averaged 12.2 kg·m⁻² and 0.9 kg·m⁻², respectively. DWs did not differ significantly among treatments (Table 2). Total root FW was significantly lower in treatment ECvariable than in the other treatments (Table 2). None of the other measured root characteristics differed significantly among treatments.

At the final harvest, treatments provided with higher nutrient solution EC had significantly smaller leaf surface area than that of treatment EC1.5 (Table 2). Leaf area index of EC1.5 was 20% greater than that of the other treatments.

At 81 d, after five harvest dates, total fruit yield was highest in treatment EC3.7, which averaged 6.93 kg·m⁻², but did not differ significantly among treatments (Table 2) or harvest dates. Cumulative fruit yield, as a proportion of total plant weight, an estimate of harvest index, also did not differ significantly among treatments.

**FRUIT CHARACTERISTICS.** Compared with ECvariable, yield loss to BER was significantly higher in treatment EC1.7, and lower in treatments EC1.5 and ECdaily (Table 2). Fruit dry matter content was significantly lower for treatment EC3.7 than for treatment EC1.7 (Table 2). Yield loss to BER and dry matter content of fruit correlated with effluent solution EC: BER = −23.4 + 25.6 × EC, r = 0.53 significant, DMC = 54.2 + 1.36 × EC, r = 0.35 significant.

When these variables were combined with solar radiation and temperature in multiple correlation analysis, correlation coefficients increased from 0.35 to 0.92 for dry matter content and from 0.53 to 0.80 for yield loss to BER. Regression coefficients describing the relationships are given in Table 3. Based on simple correlation coefficients, temperature explained the most variability in dry matter content, whereas nutrient solution EC explained the most variability in yield loss to BER.

Treatments significantly affected single fruit weight. Treatments EC3.7 and ECdaily had higher fruit weights than EC1.7 (Table 2). Single fruit weight was significantly correlated with solar radiation and temperature, but not with effluent solution EC (Table 3). Firmness of the undamaged mature fruit with diameter ≥50 mm used for quality analysis was 7% lower in ECdaily than in EC1.5. Nutrient solution EC did not significantly influence compression force. Firmness was negatively correlated with temperature (Table 3). Fruit weight, dry matter content, yield loss to BER, and compressibility all differed significantly among harvest dates (Table 4).

**Discussion**

Microclimate conditions at the end of the experiment approached the high temperature limit for tomato production with daily maximum temperatures above 30 °C (Fig. 2B). Root zone temperature was only 0.75 °C lower than air temperature because barrels were stored in the greenhouse, each trough was covered with a black and white plastic film, and solution supplied per emitter was only 4 mL·s⁻¹. Mean daily solar radiation was 13.7 MJ·m⁻², which is higher than solar radiation for tomato production areas in Canada or western Europe. For example, the maximum value Heuvelink (1995) measured in a series of experiments in the Netherlands was 10.7 MJ·m⁻² mean daily solar radiation. Daily average microclimate conditions were relatively
constant during the experiment, but they changed strongly during the day (Fig. 3C). Thus, the conditions were suitable to test the strategy of short-term adjustment of nutrient solution EC.

Solution EC increased from supply to effluent despite supplying 3.4 times the amount of solution needed to meet transpiration (Fig. 4). We covered the top of each trough with plastic film to minimize evaporation from the nutrient solution, so an increase in EC from supply to effluent suggests that the ratio of nutrient to water uptake by plants was lower than the ratio of nutrient to water in the nutrient solution supplied. Either more frequent application of nutrient solution or a greater total amount applied could reduce this difference between effluent and supply EC. The difference between effluent EC and supply solution EC increased with supply solution EC.

None of the treatments had significantly greater total dry matter production or fruit yield than the others. According to the models of Sonneveld (1988) and Adams (1991), the constant treatment EC3.7 should have reduced yield reduction. Its increase in mean effluent EC from 1.8 to 5.1 dS·m–1 should diminish yield

Table 1. Means of supply and effluent solution EC for different nutrient solution management strategies tested with tomato in a greenhouse experiment, 17 Apr. to 7 July 1998.

| Treatments | Nutrient solution EC (dS·m–1) |
|------------|-------------------------------|
|            | Supply solution | Effluent solution |
| Constant EC at 1.5 dS·m–1 (EC1.5) | 1.50 | 1.83 |
| Constant EC at 3.7 dS·m–1 (EC3.7) | 3.70 | 5.11 |
| Daily adjustment (ECdaily) | 2.99 | 3.57 |
| Short-term 15-min adjustment (ECvariable) | 2.53 | 3.43 |

Table 2. Plant growth characteristics of tomato cultivated with four nutrient solution management strategies from 17 Apr. to 7 July 1998. Planting density was 2.86 plants/m2. Blossom-end rot (BER), yields, and leaf area index were related to a growing area of 1 m2. Dry matter content (DMC) and compression force (Cf, dimensionless) are fruit quality characteristics. All data are from the final harvest at 81 d after planting, except for yield data, which are cumulative.

| Treatment | Shoot wt | Root wt | Root length | Mean Fruit | Leaf |
|-----------|----------|---------|-------------|------------|------|
|           | Fresh (kg·m–2) | Dry (g·m–2) | Fresh (g·m–2) | Dry (g·m–2) | Spec. root (m·g–1) | Total area (km·m–2) | Mean leaf area (mm) | Total yield (kg·m–2) | BER (g·kg–1) | DMC (g·kg–1) | Individual wt (g) | Cf (dimensionless) |
| EC1.5     | 3.98 a1 | 371 a | 953 a | 72.4 a | 212 a | 15.5 a | 0.299a | 6.93 a | 26.6 c | 56.2 b | 68.5 a | 20.2 a | 4.23 a |
| EC3.7     | 3.72 a | 376 a | 967 a | 74.2 a | 203 a | 15.1 a | 0.297a | 6.75 a | 82.3 a | 61.1 a | 63.1 b | 19.9 a | 3.08 b |
| ECdaily   | 3.92 a | 386 a | 984 a | 88.0 a | 194 a | 17.3 a | 0.296 a | 6.75 a | 35.4 c | 58.0 ab | 69.1 a | 18.7 a | 3.22 b |
| ECvariable | 3.81 a | 374 a | 834 b | 76.0 a | 218 a | 16.5 a | 0.293 a | 6.36 a | 74.0 b | 60.6 ab | 63.3ab | 19.2 a | 3.34 b |

*Mean separation within columns by Tukey’s studentized range test at $P = 0.05$.

Table 3. Coefficients of determination ($R^2$) and regression coefficients for the influence of solar radiation, temperature, and effluent solution EC during fruit development on fruit dry matter content, yield loss to blossom-end rot (BER), single fruit weight, and compression force in a greenhouse experiment, 9 June to 7 July 1998 in Griffin, Ga. Data from ‘Counter’ tomato were measured from weekly harvests and data of temperature and EC were averaged over the 2 weeks preceding each harvest.

| Influencing factor | Fruit dry matter content (g·kg–1) | Yield loss to BER (g·m–2) | Single fruit wt (g) | Compression force, dimensionless |
|--------------------|----------------------------------|---------------------------|---------------------|-------------------------------|
| Solar radiation (MJ·m–2) | –0.103 | 2.39 | 0.170 | –0.016 |
| Temperature (°C) | 5.38 | 31.0 | 9.09 | –0.782 |
| Effluent solution EC (dS·m–1) | 1.41 | 27.0 | –1.66 | –0.106 |
| $R^2$ full model | 0.85 | 0.64 | 0.71 | 0.09 |

*Significant at $P = 0.05$ (n = 20).

Table 4. Fruit fresh weight (FW), dry matter content (DMC), yield loss to blossom-end rot (BER), and 2% compression force (Cf, dimensionless) for red ripe ‘Counter’ tomato fruit harvested on five dates, 9 June to 7 July 1998, in a greenhouse experiment at Griffin, Ga. Results are mean values from plants grown under four nutrient solution EC management systems. FW and DMC were determined for all undamaged fruit without BER.

| Days after transplanting | FW (g/fruit) | DMC (g·kg–1) | BER (g·kg–1) | Cf |
|-------------------------|--------------|--------------|--------------|----|
| 53 | 53.2 c1 | 53.3 d | 10.1 b | 22.9 a |
| 60 | 62.0 bc | 56.2 cd | 96.6 ab | 16.8 d |
| 67 | 71.4 a | 58.0 c | 93.8 ab | 19.0 bc |
| 74 | 71.1 ab | 61.6 b | 124.0 a | 20.6 b |
| 81 | 70.0 ab | 65.7 a | 37.6 b | 18.2 cd |
| HSD | 9.50 | 3.60 | 83.0 | 1.96 |

*Mean separation within columns by Tukey’s studentized range test [honestly significant difference (HSD)], $P = 0.05$. 

constant during the experiment, but they changed strongly during the day (Fig. 3C). Thus, the conditions were suitable to test the strategy of short-term adjustment of nutrient solution EC.

Solution EC increased from supply to effluent despite supplying 3.4 times the amount of solution needed to meet transpiration demand (Fig. 4). We covered the top of each trough with plastic film to minimize evaporation from the nutrient solution, so an increase in EC from supply to effluent suggests that the ratio of nutrient to water uptake by plants was lower than the ratio of nutrient to water in the nutrient solution supplied. Either more frequent application of nutrient solution or a greater total amount applied could reduce this difference between effluent and supply EC. The difference between effluent EC and supply solution EC increased with supply solution EC.

None of the treatments had significantly greater total dry matter production or fruit yield than the others. According to the models of Sonneveld (1988) and Adams (1991), the constant treatment EC3.7 should have reduced yield reduction. Its increase in mean effluent EC from 1.8 to 5.1 dS·m–1 should diminish yield
by 25%, or 1.8 kg·m⁻² for this experiment, but it did not.

Dalton et al. (1997) found that root-zone temperature strongly affects how biomass production responds to EC. They found that an increase in root-zone temperature from 18 to 25 °C shifted the salinity threshold for biomass decrease from 33 to 60 mM Cl/L, which corresponds to 4.0 to 7.0 dS·m⁻¹. The high mean temperature of 24 °C during this experiment could explain why increasing nutrient solution EC did not significantly reduce yield. Although in treatment EC.daily and EC.variable, the nutrient solution EC changed often in the root environment, it did not influence fruit production.

Nutrient solution EC changes affect root growth mainly by changing osmotic pressure in the root environment (Kafkafi, 1996). An increase in EC increases root growth up to a threshold depending on cultivar (Schwarz and Kuchenbuch, 1997; Shannon et al., 1987), temperature (Dalton et al., 1997), and plant age (Knight et al., 1992). Further increase in EC reduces root growth. Although daily change of nutrient solution EC did not affect root growth in treatment EC.daily, frequent changes of EC in treatment EC.variable, although adjusted to microclimate, significantly reduced root FW. Plants may have compensated for this reduction of root FW by producing thinner roots with greater specific root length in treatment EC.variable. So that total root length and surface area were similar to those in the constant EC treatments. From tomato experiments with split root systems where the parts of the root system were provided with different solution ECs, Sonneveld and Voogt (1989) reported that plants readily adapted with respect to uptake of water and nutrients in the different root parts. Comparable experiments where the same roots had to adjust fluctuating solution EC conditions during the day have not been found in the literature, therefore, results presented herein remain to be confirmed.

Treatments significantly affected fruit quality characteristics, including dry matter content, individual fruit weight, yield loss to BER, and firmness (Table 2). These effects are in line with results of other authors (Auerswald et al., 1999; Petersen et al., 1998). Relatively high temperatures and solar radiation during the harvest period could explain the small influence of nutrient solution EC according to microclimate improve external fruit quality characteristics when applied on a daily basis.

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