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

D. Schwarz[1] and H.-P. Kläring
Institute for Vegetable and Ornamental Crops, Großbeeren/Erfurt e.V., D-14979 Großbeeren, Germany

K.T. Ingram and Y.-C. Hung[2]
The University of Georgia, College of Agriculture and Environmental Science–Griffin Campus, Department of Crop and Soil Sciences, 1109 Experiment Street, Griffin, GA 30223-1797

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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) $EC_{variable}$, 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) EC_{daily}, daily adjustment of nutrient solution EC based on each morning's 24-hour weather forecast; 3) $EC_{3.7}$, supply of a single high nutrient solution of 3.7 $dS \cdot m^{-1}$; or 4) $EC_{1.5}$, low nutrient solution EC of 1.5 $dS \cdot m^{-1}$ for the entire growth period. Mean effluent EC levels were 1.8 $dS \cdot m^{-1}$ for treatment $EC_{1.5}$, 5.1 $dS \cdot m^{-1}$ for treatment $EC_{3.7}$, 3.6 $dS \cdot m^{-1}$ for treatment EC_{daily}, and 3.4 $dS \cdot m^{-1}$ for treatment $EC_{variable}$. Except for fresh weight (FW) of roots, growth characteristics did not differ significantly among treatments. Total production averaged 12.2 $kg \cdot m^{-2}$ FW and 1.0 $kg \cdot m^{-2}$ dry weight (DW); and fruit yield averaged 6.7 $kg \cdot m^{-2}$. Dry matter content, yield loss to blossom-end rot, and firmness responded linearly to treatment EC. In general, EC_{daily} yielded higher fruit quality and $EC_{variable}$ 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 $dS \cdot m^{-1}$ was recommended for tomato culture (Göhler and Drews, 1989) advisers currently recommend nutrient solutions with EC between 3.0 and 4.5 $dS \cdot m^{-1}$ 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 $dS \cdot m^{-1}$ 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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[1] Corresponding author: Institute for Vegetable and Ornamental Crops, Großbeeren/Erfurt e.V., Theodor Echtermeyer Weg 1, D-14979 Großbeeren, Germany; e-mail: Schwarz@igzev.de.

[2] Department of Food Safety and Quality Enhancement.

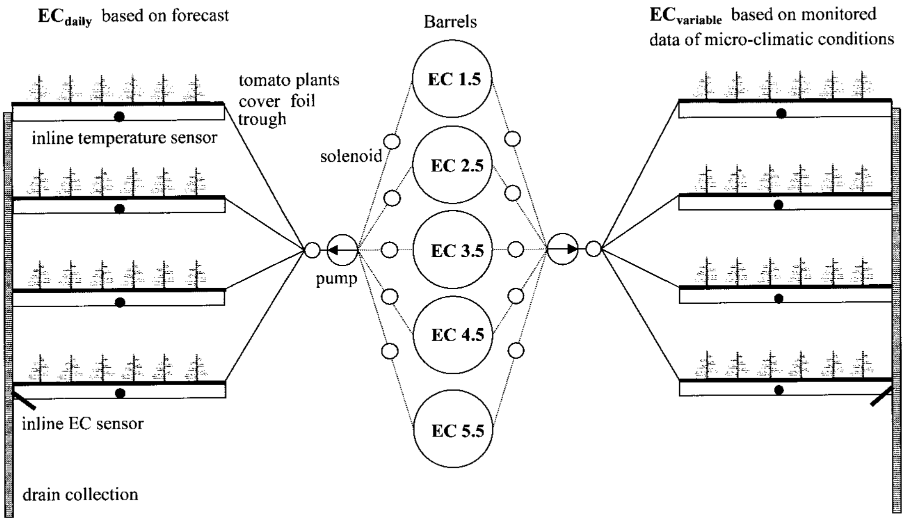

Fig. 1. Schematic view of two strategies tested in a greenhouse experiment at the Georgia Envirotron, Griffin, Ga. with varying nutrient solution EC (EC_{daily} and $EC_{variable}$) on 'Counter' tomato, during 17 Apr. to 7 July 1998. Nutrient solution was supplied in pulses at 15-min intervals without recirculating effluent solution.

and night (Adams and Ho, 1989; Brugging et al., 1987; Guttridge et al., 1981; Van Ieperen, 1996a). Guttridge et al. (1981) found the highest Ca content with a high solution EC during the day and a low EC during the night (DH/NL). Adams and Ho (1989) did not find any advantages for DH/NL or DL/NH treatments compared with a constant EC. Brugging et al. (1987) and Van Ieperen (1996a) found DL/NH gave the lowest BER but also gave a low dry matter content. Thus, results are inconsistent.

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. Producing greenhouse microclimate forecasts requires effort and such forecasts are only as accurate as the ability to predict the weather. Using a short-term, that is every 15-min, adjustment of nutrient solution based on measured microclimate avoids both the possible errors and effort of using a daily forecast without loosing the advantages of the daily adjustment. A hydroponic system was constructed and greenhouse research was conducted to compare different nutrient solution control strategies to test the aforementioned hypotheses.

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 ($0.1 \times 0.2 \times 2.2$ m^3) in a greenhouse (7×7 m^2). 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 CO_2 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 ($EC < 0.1$ $dS \cdot m^{-1}$). 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 H_3PO_4 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. Heissner (unpublished). Nutrient solution was pumped from barrels through a drip irrigation system with one emitter per plant and an emitter flow rate of 4 $mL \cdot s^{-1}$. 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 $dS \cdot m^{-1}$ ($EC_{1.5}$); 2) constant EC at 3.7 $dS \cdot m^{-1}$ ($EC_{3.7}$); 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 ($EC_{variable}$).

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 $EC_{variable}$ was based on empirical models of crop net photosynthesis (P_{net}, CO_2 at $mg \cdot m^{-2} \cdot s^{-1}$) and crop transpiration

(TR, H_2O at $g \cdot m^{-2} \cdot s^{-1}$). Both models use inputs of leaf area index (LAI, $m^2 \cdot m^{-2}$), radiation (I, $\mu mol \cdot m^{-2} \cdot s^{-1}$), CO_2 concentration (C, $\mu mol \cdot mol^{-1}$), air temperature (T, °C), and vapor pressure deficit of the greenhouse air (VPD, hPa) (A. Heissner, unpublished): $P_{net} = a_0 \times (1)/(1 + a_1 \times LAI^2) \times [1 - e^{-a_2 \times I}) \times (1 - e^{-a_3 \times C}) \times (a_4 \times T + a_5 \times T^2) + a_6 \times T + a_7 \times T^2]$; $TR = b_0 \times (1 - e^{-b_1 \times VPD}) \times \sum^3_{i=1} (1 - e^{-b_2 \times I \times e^{-b_3 \times (i/3) LAI} + b4})$.

Assuming a constant nutrient concentration of the nutrient X in dry matter [N_x, X at mg × [mg carbohydrate (CH_2O)]$^{-1}$] the nutrient uptake of the crop (NU_x, X 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 CH_2O and 44 corresponds to the mass of 1 mol CO_2. Neglecting the uptake of water for plant growth, the ratio of nutrient X to water uptake of the crop (C_x, X at $mg \cdot kg^{-1}$ H_2O), 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 Bloemhard, 1994) we derived the nutrient solution EC_{cal} from the calculated potassium (K) to water uptake ratio C_K: $EC_{cal} = C_k \times (EC^s)/C^S_K$, where EC^S ($dS \cdot m^{-1}$) and $C_K{}^S$ (mg K/kg H_2O) denote 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 agreement with the ratio of K to water uptake by the crop and the N and P concentrations are close to the corresponding nutrient to water uptake ratios. As result of this procedure, the EC_{cal} is lowered when temperature increases and relative humidity decreases, both of which increase transpiration demand but have little influence on photosynthesis or nutrient uptake. On the other hand, radiation has little effect on EC_{cal} because photosynthesis and transpiration are both directly related with radiation. In the greenhouse, however, temperature and vapor pressure deficit often increase with radiation. Therefore, radiation levels near the light saturation point for P_{net}, particularly early in the morning and late in the evening, result in very high EC_{cal} values. Conversely, when radiation is below the light compensation point for P_{net} in the morning, evening, or at night, EC_{cal} values may be negative. To avoid problems that might arise from negative values of EC_{cal}, we set its minimum to 1.5 $dS \cdot m^{-1}$.

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 CO_2 was assumed constant at 380 $\mu mol \cdot mol^{-1}$. Leaf area was estimated from leaf length and width measurements as described below.

In the treatment $EC_{variable}$, solution EC_{cal} was derived from measured input variables averaged over the preceding 15 min. For logistical reasons, 200-L barrels with nutrient solutions were prepared with ECs of 1.5, 2.5, 3.5, 4.5, or 5.5 $dS \cdot m^{-1}$ (Fig. 1). Supply nutrient solution (EC_{sup}) was chosen depending on EC_{cal} following the rule:

$EC_{sup} = 1.5\ dS \cdot m^{-1}$ if $EC_{cal} < 2\ dS \cdot m^{-1}$,
$EC_{sup} = 2.5\ dS \cdot m^{-1}$ if $2\ dS \cdot m^{-1} \leq EC_{cal} < 3\ dS \cdot m^{-1}$,
$EC_{sup} = 3.5\ dS \cdot m^{-1}$ if $3\ dS \cdot m^{-1} \leq EC_{cal} < 4\ dS \cdot m^{-1}$,
$EC_{sup} = 4.5\ dS \cdot m^{-1}$ if $4\ dS \cdot m^{-1} \leq EC_{cal} < 5\ dS \cdot m^{-1}$,
$EC_{sup} = 5.5\ dS \cdot m^{-1}$ if $5\ dS \cdot m^{-1} \leq EC_{cal}$.

At 0800 HR each morning, the solution EC_{sup} was estimated for treatment EC_{daily} based on the forecast for the daily means of cloudiness and rain. The range of 0% to 25% cloudy corresponded to an EC_{sup} level of 1.5 $dS \cdot m^{-1}$, 25% to 50% EC_{sup} 2.5 $dS \cdot m^{-1}$, 50% to 75% EC_{sup} 3.5 $dS \cdot m^{-1}$, and 75% to 100% EC_{sup} 4.5 $dS \cdot m^{-1}$. 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.

PLANT AND FRUIT OBSERVATIONS. Length and width of all leaves of one plant in each replication were measured at 0, 3, 10, 17, 24, 31, 46, or 82 d after transplanting to troughs. Leaf area was calculated as a function of leaf length and leaf width according to a relationship derived by Schwarz and Kläring (2001).

Fruit of all plants except border plants at the ends of each treatment trough were harvested weekly at the red stage beginning 9 June 1998, 53 d after planting. More than 90% of fruit damage resulted from BER. These fruit were weighed fresh and counted separately from the undamaged fruit.

Each week weight, diameter (D), and firmness were recorded for five fruit >50 mm in diameter. Fruit firmness was quantified as the 2% compression force (Cf), which is a measure of tomato pericarp deflection distance (PDD) when exposed to two levels of pressure (P), 100 and 500 kPa, scaled by fruit diameter (Pendalwar, 1989): $Cf = D \times 0.02 \times (P_{500} - P_{100})/(PDD_{500} - PDD_{100})$.

On 7 July, 82 d after transplanting, the last fruit were harvested and all plants were destructively sampled. Shoot and root fresh weights (FWs) were recorded. Four subsamples of ≈1.0 g fresh roots were taken from the middle of the root system of each treatment and replication to measure specific root length and mean root diameter. Root images were obtained with a flatbed scanner and root characteristics measured using WinRhizo software (Regents Instruments, Quebec City, Quebec, Canada). Total root length per plant was calculated as the product of specific root length and total root DW. Plant parts were dried at 80 °C for at least 74 HR before recording DWs of fruit, shoots, and roots.

Data were subjected to analysis of variance procedures and means separated by Tukey's studentized test at $P = 0.05$. Results of weekly sampling for dry matter content, yield loss to BER, and compression force were related to nutrient solution EC, temperature, and solar radiation by linear regression analysis at $P = 0.05$.

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 $MJ \cdot m^{-2}$ to a high of 19 $MJ \cdot m^{-2}$, with a mean of 13.6 $MJ \cdot m^{-2}$ (Fig. 2A). Daily minimum and mean night temperatures increased ≈2.1 °C during the harvest period, whereas daily maximum temperature increased 3.2 °C and mean daytime temperature increased 2.9 °C (Fig. 2B). Mean root zone temperature (data not presented) was 0.75 °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

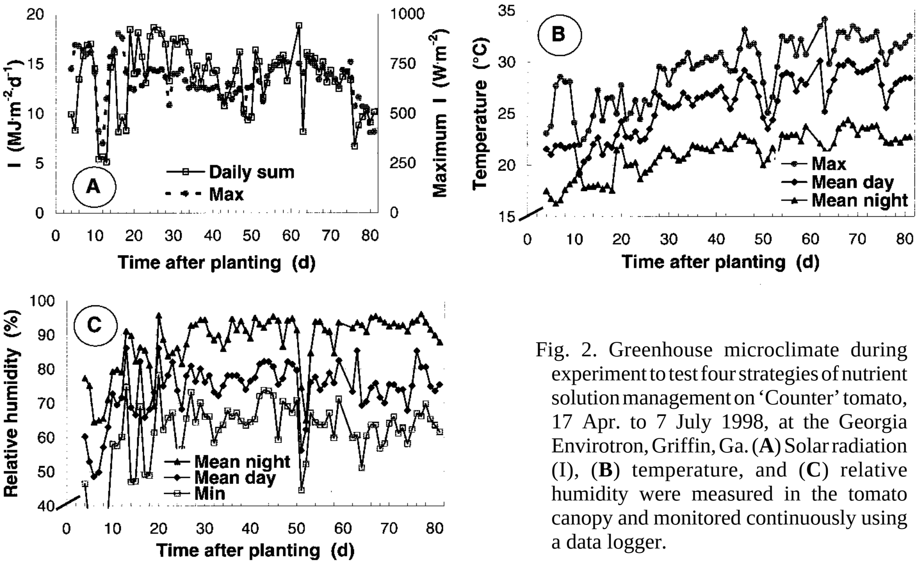

Fig. 2. Greenhouse microclimate during experiment to test four strategies of nutrient solution management on 'Counter' tomato, 17 Apr. to 7 July 1998, at the Georgia Envirotron, Griffin, Ga. (**A**) Solar radiation (I), (**B**) temperature, and (**C**) relative humidity were measured in the tomato canopy and monitored continuously using a data logger.

season averages. Examples of 2 d with different microclimate show the great variability in EC of nutrient supply to treatment $EC_{variable}$ during the day (Fig. 3C).

The amount of nutrient solution supplied to each plant averaged $5.19\ L\cdot d^{-1}$. Water uptake per plant calculated by the transpiration model was $1.56\ L\cdot d^{-1}$. 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 $12.2\ kg\cdot m^{-2}$ and $0.9\ kg\cdot m^{-2}$, respectively. DWs did not differ significantly among treatments (Table 2). Total root FW was significantly lower in treatment $EC_{variable}$ 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 $EC_{1.5}$ (Table 2). Leaf area index of $EC_{1.5}$ was ≈20% greater than that of the other treatments.

At 81 d, after five harvest dates, total fruit yield was highest in treatment $EC_{1.5}$, which averaged $6.93\ kg\cdot m^{-2}$, 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 $EC_{variable}$, yield loss to BER was significantly higher in treatment $EC_{3.7}$, and lower in treatments $EC_{1.5}$ and EC_{daily} (Table 2). Fruit dry matter content was significantly lower for treatment $EC_{1.5}$ than for treatment $EC_{3.7}$ (Table 2). Yield loss to BER and dry matter content of fruit correlated with effluent solution EC: $BER = -23.4 + 25.6 \times EC$, $r = 0.53$ significant, $DMC = 54.2 + 1.36 \times EC$, $r = 0.35$ 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 $EC_{1.5}$ and EC_{daily} had higher fruit weights than $EC_{3.7}$ (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 EC_{daily} than in $EC_{1.5}$. 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 $4\ mL\cdot s^{-1}$. Mean daily solar radiation was $13.7\ MJ\cdot m^{-2}$, 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 $10.7\ MJ\cdot m^{-2}$ mean daily solar radiation. Daily average microclimate conditions were relatively

Fig. 3. EC and amounts of nutrient solution of four strategies of nutrient solution management in a greenhouse experiment on 'Counter' tomato during 17 Apr. to 7 July 1998 at the Georgia Envirotron, Griffin, Ga. Supply solutions were (**A**) adjusted daily and (**B**) effluent solutions were monitored continuously at the end of the trough. Solution supplied by treatment $EC_{variable}$ is given in (**C**) during day 13th (low radiation of $R = 5.1\ MJ\cdot m^{-2}\cdot d^{-1}$, $T = 20.7$ °C, $RH = 86.2\%$ and day 64th (high radiation of $R = 16.2\ MJ\cdot m^{-2}\cdot d^{-1}$, $T = 27.1$ °C, $RH = 69.4\%$) after planting. (**D**) Daily nutrient solution supply and calculated uptake.

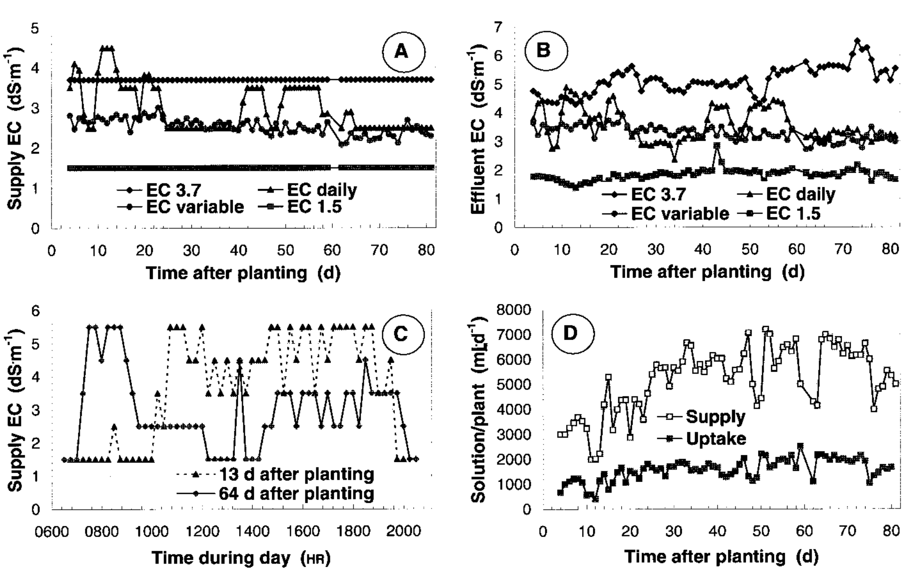

Table 1. Means of supply and effluent solution EC for different nutrient solution management strategies tested with tomato in a greenhouse experiment, 17 Apr. to 7 July 1998.

Treatments	Nutrient solution EC (dS·m^{-1}) Supply solution	Effluent solution
Constant EC at 1.5 dS·m^{-1} (EC$_{1.5}$)	1.50	1.83
Constant EC at 3.7 dS·m^{-1} (EC$_{3.7}$)	3.70	5.11
Daily adjustment (EC$_{daily}$)	2.99	3.57
Short-term 15-min adjustment (EC$_{variable}$)	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/m^2. Blossom-end rot (BER), yields, and leaf area index were related to a growing area of 1 m^2. 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.

	Shoot wt		Root wt		Root length		Mean	Fruit					Leaf
Treatment	Fresh (kg·m^{-2})	Dry (g·m^{-2})	Fresh (g·m^{-2})	Dry (g·m^{-2})	Specific (m·g^{-1})	Total (km·m^{-2})	root diam (mm)	Total yield (kg·m^{-2})	BER (g·kg^{-1})	DMC (g·kg^{-1})	Individual wt (g)	Cf	area index (m^2·m^{-2})
EC$_{1.5}$	3.98 a^z	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
EC$_{3.7}$	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	61.3 b	19.9 a	3.08 b
EC$_{daily}$	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
EC$_{variable}$	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

^{z}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 while solar radiation was cumulated 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 c^z	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

^{z}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 transpirational 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 EC$_{3.7}$ 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 on fruit quality that we observed, in particular for the treatment $EC_{3.7}$ (Table 3). Other researchers have found that increasing irradiance and temperature increase fruit dry matter, firmness, and taste related characteristics (Janse, 1984; Janse and Schols, 1992). Possible confounding effects including changes in fruit quality characteristics or sink/source relationships with harvest date (Table 4) might have overshadowed potential treatment effects.

Increases in nutrient solution EC increase yield loss to BER (Adams and Ho, 1992). Our results from treatment $EC_{1.5}$ and $EC_{3.7}$ confirm this relationship (Table 2). Observations that high osmotic potential of higher nutrient solution EC reduces Ca uptake and decreases Ca distribution towards the distal fruit tissues explain this relationship (Bradfield and Guttridge, 1984). However, higher solution EC does not always result in high BER. Weekly yield losses to BER differed in treatment $EC_{3.7}$, from 20 to 130 g·kg^{-1} FW. Other factors, such as transpiration rate, water flow in the xylem (Ehret and Ho, 1986), imbalance between the rate of fruit growth, and the rate of Ca movement toward fruits (Adams and Ho, 1992) might also be responsible.

Results herein support the hypothesis that it would be possible to improve tomato quality by reducing yield loss to BER and enhancing fruit dry matter content, if not yield, through daily management of nutrient solution, as was demonstrated for yield loss to BER by Kläring et al. (1999). Although simulation models led us to hypothesize that there would be benefits of short-term nutrient solution management, results do not support this strategy. Roots evolve in soils with relatively slow changes in moisture and EC, compared with the rapid changes in atmospheric environment that shoots experience. It is possible that changing nutrient solution EC at 15-min intervals injured roots or overwhelmed their capacity to adapt to environmental changes. It is possible that frequent changes of osmotic conditions in the root environment impose large costs for root system adaptations, which may explain the lack of benefit for treatment $EC_{variable}$. This explanation is supported by the diminished root system of plants in $EC_{variable}$ compared with those in other treatments and by trends in root morphology (Table 2). At the same time, dynamic changes of nutrient solution EC according to microclimate improve external fruit quality characteristics when applied on a daily basis.

Literature Cited

Adams, P. 1991. Effects of increasing the salinity of the nutrient solution with major nutrients or sodium chloride on the yield, quality and composition of tomatoes grown in rockwool. J. Hort. Sci. 66:201–207.

Adams, P. and L.C. Ho. 1989. Effects of constant and fluctuating salinity on the yield, quality and calcium status of tomatoes. J. Hort. Sci. 64:725–732.

Adams, P. and L.C. Ho. 1992. The susceptibility of modern tomato cultivars to blossom-end rot in relation to salinity. J. Hort. Sci. 67:827–839.

Al-Harbi, A.R. 1995. Growth and nutrient composition of tomato and cucumber seedlings as affected by sodium chloride salinity and supplemental calcium. J. Plant Nutr. 18:1403–1416.

Auerswald, H., D. Schwarz, C. Kornelson, A. Krumbein, and B. Brückner. 1999. Sensory analysis, sugar and acid content of tomato at different EC values of the nutrient solution. Sci. Hort. 82:227–242.

Bradfield, E.G. and C.G. Guttridge. 1984. Effects of night-time humidity and nutrient solution concentration on the calcium-content of tomato fruit. Sci. Hort. 22:207–217.

Brugging, G.T., H.E. Schouwink, and E.A.J.M. Coolen. 1987. Effects of different day and night osmotic potentials of the nutrient solution on growth, water potentials and osmotic potentials of young tomato plants. Soilless Cult. 3:9–19.

Dalton, F.N., A. Maggio, and G. Piccinni. 1997. Effect of root temperature on plant response functions for tomato-comparison of static and dynamic salinity stress. Plant and Soil 192:307–319.

De Kreij, C., W. Voogt, A.L. van den Bos, and R. Baas. 1997. Voedingsoplossingen voor de teelt van tomaat in gesloten teeltsystemen. Brochure VG2, Proefstation Naaldwijk, The Netherlands.

Ehret, D.L. and L.C. Ho. 1986. The effect of salinity on dry matter partitioning and fruit growth in tomatoes grown in nutrient film culture. J. Hort. Sci. 61:361–367.

Göhler, F. and M. Drews. 1989. Hydroponic systems for vegetable cultivation in greenhouses (in German). 1st ed. Landwirtschaftsausstellung der DDR, agrabuch, Leipzig.

Guttridge, C.G., E.G. Bradfield, and R. Holder. 1981. Dependence of calcium transport into strawberry leaves on positive pressure in the xylem. Ann. Bot. 48:473–480.

Heuvelink, E. 1995. Growth, development and yield of a tomato crop: Periodic destructive measurements in a greenhouse. Sci. Hort. Amsterdam 61:77–99.

Ho, L. and P. Adams. 1989. Effects of diurnal changes in the salinity of the nutrient solution on the accumulation of calcium by tomato fruit. Ann. Bot. 64:373–382.

Ho, L. and P. Adams. 1994. The physiological basis for high fruit yield and susceptibility to calcium deficiency in tomato and cucumber. J. Hort. Sci. 69:367–376.

Janse, J. 1984. Invloed van licht op de kwaliteit von tomaat en komkommer. Groenten + fruit 40:28–31.

Janse J. and M. Schols. 1992. Specific temperature and transpiration effects on the flavour of tomatoes. Annu. Rpt. Glasshouse Crops Res. Sta. Naaldwijk, The Netherlands.

Kafkafi, U. 1996. Root growth under stress: Salinity, p. 375–391. In: Y. Waisel, A. Eshel, and U. Kafkafi (eds.). Plant roots: The hidden half. 2nd ed. Marcel Dekker, New York.

Kläring, H.-P. and W. Cierpinski. 1998. Control of nutrient solution concentration depending on greenhouse climate in a sweet pepper crop. Acta Hort. 458:141–146.

Kläring, H.-P., D. Schwarz, and W. Cierpinski. 1999. Control of concentration of nutrient solution in soilless growing systems, depending on greenhouse climate—Advantages and limitations. Acta Hort. 507:133–139.

Kläring, H.-P., D. Schwarz, and A. Heissner. 1997. Control of nutrient solution concentration in tomato crop using models of photosynthesis and transpiration: A simulation study. Acta Hort. 450:329–334.

Knight S.L., R.B. Rogers, M.A.L. Smith, and L.A. Spomer. 1992. Effects of NaCl salinity on miniature dwarf tomato 'MicroTom': I. Growth analysis and nutrient composition. J. Plant Nutr. 15:2315–2327.

Maas, E.V. and G.J. Hoffman. 1977. Crop salt tolerance—Current assessment. J. Irr. Drainage Division IR2 103:115–134.

Pendalwar, D.S. 1989. Modeling the effect of ethylene and temperature on physiological responses of tomatoes stored under controlled atmospheres. MS thesis. Univ. of Georgia, Athens.

Petersen, K., J. Willumsen, and K. Kaack. 1998. Composition and taste of tomatoes as affected by increased salinity and different salinity sources. J. Hort. Sci. Biotechnol. 73:205–215.

Satti, S.M.E., M. Lopez, and S.A. Al-Rawahy. 1995. Effects of saline nutrient solutions on the growth and accumulation of mineral elements in some tomato cultivars. Commun. Soil Sci. Plant Anal. 26:2097–2106.

Schwarz, D. and H.P. Kläring. 2001. Allometry to estimate leaf area of hydroponically grown tomato as affected by genotype, salinity, growing system and plant age. J. Plant Nutr. 24(8):1291–1309.

Schwarz, D. and R. Kuchenbuch. 1997. Growth analysis of tomato in a closed recirculating system in relation to the EC-value of the nutrient solution. Acta Hort. 450:169–176.

Shannon, M.C., J.W. Gronwald, and M. Tal. 1987. Effects of salinity on growth and accumulation of organic and inorganic ions in cultivated and wild tomato species. J. Amer. Soc. Hort. Sci. 112:416–423.

Sonneveld, C. 1988. The salt tolerance of greenhouse crops. Neth. J. Agr. Sci. 36:63–73.

Sonneveld, C. and W. Voogt. 1989. Responses of tomatoes (*Lycopersicon esculentum*) to an unequal distribution of nutrients in the root environment. Plant and Soil 124:251:256.

Van Ieperen, W. 1996a. Effect of different day and night salinity levels on vegetative growth, yield and quality of tomato. J. Hort. Sci. 75:99–111.

Van Ieperen, W. 1996b. Consequences of diurnal variation in salinity on water relations and yield of tomato. MS thesis. Agr. Univ. of Wageningen, The Netherlands.

Voogt, V. and A. Bloemhard. 1994. Voedingsoplossingen voor groenten en bloemen geteeld in water of substraten. Proefstation voor Tuinbouw onder Glas, Naaldwijk, The Netherlands.