Effects of EC and Fertigation Strategy on Water and Nutrient Uptake of Tomato Plants

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Abstract

In this study, water and nutrient uptake from the substrate and responses of the crop to fertigation strategies were analysed. In an experiment and simulation study, the amount and frequency of fertigation and electrical conductivity (*EC*) of the fertigation water were changed for a tomato crop grown on rockwool. In a climate chamber, tomato plants were grown on rockwool while five different *EC* levels and two fertigation frequencies were maintained. Effects on plant growth, water uptake, and nutrient uptake were measured. The experimental data were compared with simulated results. We used two simulation models: a plant growth model and a model that describes water movement and nutrient transport within the substrate, i.e. rockwool, and root uptake of water and nutrients from the substrate. The key idea behind the simulation of uptake of water and nutrients is to consider transport (mass flow and diffusion) from the bulk substrate surrounding the roots towards the root surface. Water uptake may also be hindered due to osmotic potential differences between substrate solution and root sap. The results confirmed the hypothesis that at lower *EC* growth is reduced due to limitations in nutrient availability (transport rate towards the root) while at higher *EC* growth is reduced mainly due to water stress (low osmotic potential).

INTRODUCTION

The goal of managing water and nutrient supply to greenhouse crops is to control crop growth and product quality as well as to minimise losses of water and nutrients to the environment. Precise supply of water and nutrients is necessary to reach this goal, where supply of water and the individual nutrients is in proportion to the demand of the crop. In order to do so, quantitative information on demand and uptake of water and the individual nutrients is required. Information on crop behaviour when either of them is in surplus or in shortage is also necessary. Knowledge of the transport of water and nutrients from the bulk substrate towards the root surface must be known in order to determine whether the plant demand can be fulfilled or not (shortage). Such information could be obtained from a large number of experiments, but a simulation model in combination with a limited number of experiments is a more powerful tool for such an analysis.

The electrical conductivity (*EC)* of the nutrient solution as well as the amount and frequency of fertigation (irrigation with nutrient solution) are the most important variables used by growers to control the supply of water and nutrients to the crop. The aim of this study was to analyse the water and nutrient uptake from the substrate and the responses of the crop to fertigation strategies. In an experiment and simulation study, the amount and frequency of fertigation and *EC* were changed to explore the following two hypotheses for a tomato crop grown on rockwool:

Crop growth reduction may occur at both low and high *EC*.

- At low *EC*, not enough nutrients may be available to the roots (unless in a well-mixed water culture) resulting in a reduction of nutrient uptake, which may result in reduced crop growth.
- At high *EC*, ample nutrients are available. However, reduction of water uptake may

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occur due to osmotic effects in the irrigation water (highly negative osmotic potential), which may result in reduced crop growth.

Fertigation frequency may affect both water and nutrient availability. A difference in availability may exist between frequent fertigation with small volumes versus less frequent fertigation with large volumes of nutrient solution. In the latter situation, *EC* in the substrate will fluctuate more strongly resulting in lower crop production.

MATERIALS AND METHODS

Experimental Conditions

Tomato plants (*Lycopersicon esculentum* Mill cv. Capita) were raised in rockwool cubes (10 x 10 x 6.5 cm) in a greenhouse. About five weeks after sowing, plants were transferred to a climate controlled chamber and put on rockwool slabs (100 x 15 x 7.5 cm); three plants per slab. Each plant was watered with nutrient solution via a dripper. Excess fertigation water could leave the rooting zone along the entire bottom of the substrate. Treatments consisted of two fertigation frequencies and five *EC* levels of the nutrient solution. The frequently irrigated plants each received 20 mL per plant, while less frequently irrigated plants each received 100 mL per plant. By tracking the water balance, the leaching fraction for both fertigation frequencies was maintained at about 30%. Hence, cumulative water supply was similar for both fertigation frequencies. As plant water uptake increased with time, the intervals between fertigations were decreased. For example, for the high frequency treatment the interval was shortened from 45 min to 15 min and from 2.5 hours to 1.5 hours for the low frequency treatment. No nutrient solution was supplied at night time. *EC* levels of 1, 2, 4, 6, and 7.5 dS m^{-1} were created by increasing concentrations of all macro-nutrients, while activity ratios between cations were kept constant. Drainage water was not re-used to assure constant *EC* input. For each experiment, one rockwool slab was used per treatment and the slabs were randomly distributed in a climate chamber. The experiment was repeated three times.

Air temperature in the climate chamber was 24 °C and photosynthetically active radiation was 250 µmol m^{-2} s^{-1} for 16 hours each day. The duration of the experiments was four weeks. Plant weight, leaf area, nutrient uptake (from determinations of dry weight and nutrient concentration in the plant), and water use (from the water mass balance) were determined. Data were analysed by analysis of variance.

The Simulation Model

The simulation model applied in this study consisted of a plant model and a substrate model. Only brief descriptions of the two models are presented here.

1. The Plant Model. The plant model is primarily based on models described by Gijzen (1994), Heuvelink (1996), and Marcelis et al. (2000). The model considers radiation absorption by leaf layers. Leaf photosynthesis is described by a biochemical model (Farquhar et al., 1980) and leaf transpiration is described by the Penman-Monteith model. Dry matter production is a function of photosynthesis and respiration. Partitioning of dry matter among the organs is a function of their sink strengths. Fresh weight is calculated by dividing dry weight of the organs by their respective dry matter percentage. *EC* effects on dry matter percentage of the fruits was modeled according to De Koning (1994). Nutrient demand is determined by potential growth (i.e., growth as determined by above ground climate conditions) and optimal nutrient concentration at the current age of each organ. Water demand is determined by potential fresh weight growth and transpiration. The substrate model (as described below) determines whether the root system can fulfil the demand for water and nutrients. If demand is satisfied, actual growth equals potential growth. Water shortage leads to stomatal closure resulting in reduced transpiration and photosynthesis, while nutrient shortage leads to growth reduction.

The plant model was originally developed for glasshouse conditions and not for climate chamber conditions. All light was considered diffuse. At first, simulations overestimated total above-ground dry matter production by 4.4% and underestimated daily water uptake rate by 4.4%. Since the primary aim of this study was to analyse the water and nutrient uptake from the substrate and crop responses to fertigation strategies, this can only be done thoroughly if the demand, and thus plant growth, is perfectly simulated by the plant model. Therefore, the model was calibrated for daily water uptake at EC = 2 dS m^{-1} by setting daytime roof temperature to 34°C (this primarily affects the thermal radiation from roof to canopy). This also reduced the overestimation of total above-ground dry matter production to 3.3%.

2. The Substrate Model. The substrate model (Heinen, 1997; Heinen and De Willigen, 1998; Heinen, 2001) describes water movement, solute transport, and root uptake of water and nutrients in the rooting zone. Water movement is described by the Richards equation, which is numerically solved for given boundary conditions. The hydraulic properties of the rockwool of Da Silva et al. (1995) were described by the Van Genuchten (1980) and Mualem (1976) relationships, while hysteresis was described according to Mualem (1984). Solute transport is described by the classical advection-dispersion/diffusion equation, which is explicitly solved (for given boundary conditions) using the new outcome of the water states and rates. For systems with multiple ions, the EC is computed from the concentrations of each of the nutrients. Root uptake of water and nutrients is described by models of De Willigen and Van Noordwijk (1987; 1994a,b). Actual uptake is equal to the demand if transport from the bulk soil towards the root surface is sufficient. If maximum transport towards the root surface is less than the demand, actual uptake equals maximum transport to the root surface. For this purpose the root distribution, as given by the root length density distribution, must be known. Root length density distribution as a function of time and place is modelled as a diffusion type process (De Willigen et al., 2002) based on dry matter production of roots (as obtained from the plant model). In the computation of water uptake, the water potential inside the root system is estimated. At low root water potential, h_r, actual water uptake, T_a, is reduced with respect to demanded water uptake, T_p, according to the relationship of Campbell (1985, 1991)

$$\frac{T_a}{T_p} = \left(1 + \left(\frac{h_r}{h_{r,1/2}}\right)^a\right)^{-1} \tag{1}$$

where $h_{r,1/2}$ is the water potential at T_a/T_p = 0.5 and a is a plant specific parameter that determines the slope at the point of inflection. Campbell (1985, 1991) gave a = 10 as a typical value, which we adopted here. The treatment low fertigation frequency with EC = 7.5 dS m^{-1} served as the reference treatment for which the parameter $h_{r,1/2}$ in Eq. (1) was calibrated: $h_{r,1/2}$ = -4000 cm.

RESULTS AND DISCUSSION

Leaf Area, Plant Fresh Weight, and Plant Dry Weight

The leaf area and fresh weight reached maximum values when EC was between 2 to 4 dS m^{-1}, while these were lowest at lower and higher EC (Fig. 1a,c). These findings are in correspondence with the expectations of hypothesis one. The effect of EC on plant dry weight was less pronounced (Fig. 1b). The difference between the two fertigation frequencies was not significant, but the tendency was that fresh weight production was less at the low, compared to the high, than at high fertigation frequency (cf. hypothesis two; for a more thorough discussion see section 3.2).

Water Uptake

Measured water uptake was highest at EC = 2 dS m^{-1} and was less at lower or higher EC (Fig. 2; symbols). Except at EC = 2 dS m^{-1}, the water uptake for the low fertigation frequency treatment was always lower (especially when EC = 7.5 dS m^{-1}) than that for the high fertigation frequency treatment (cf. hypothesis two).

Except at the lowest *EC* level, the simulation model predicted similar behaviour of water uptake as measured (Fig. 2). The measurements indicate that reduction in water uptake occurs at the lowest *EC* level (compare water uptake at $EC = 1$ dS m^{-1} to $EC = 2$ dS m^{-1}), which was not predicted by the simulation model.

Using measured leaf area index (*LAI*) as input, the model showed that the reduction in leaf area could explain a reduction in water uptake of 10% at $EC = 1$ dS m^{-1} compared to $EC = 2$ dS m^{-1}, which is comparable to the measured response (Fig. 2). However, when *LAI* was not input in the model, simulated *LAI* was comparable for $EC = 1$ dS m^{-1} and $EC = 2$ dS m^{-1}. The reduction in plant growth and *LAI* at low *EC* was not predicted well by the plant model probably because no direct effects of N or P shortage on *LAI* were considered by the model, while effects of K, Ca, Mg and S shortage on plant growth or *LAI* were not considered by the model. The effects of limited uptake of these elements are not yet well documented. Another reason for the difference between observed and simulated water uptake can be due to the assumptions in the uptake model: all roots are equally active and in zones of equal root length density, all roots are evenly distributed.

The simulation model indicated that at $EC = 4$, 6, and 7.5 dS m^{-1} the actual water uptake was less than the demand. This was due to the osmotic effect. A simulation that did not consider the osmotic effect on water uptake at $EC = 7.5$ dS m^{-1} resulted in actual water uptake equal to demanded water uptake. This indicated that shortage of water availability did not occur. Thus, for all *EC* treatments, water supply was non-limiting. However, at higher *EC* levels, water uptake is limited due to osmotic effects. These findings are in correspondence with the expectations of hypothesis one.

The simulated time course of *EC* for the two fertigation treatments at $EC = 6$ dS m^{-1} showed only small differences between the two fertigation frequencies (Fig. 3). Apparently, for both fertigation frequencies, the time between two fertigations was not long enough to induce significant fluctuations in *EC* in the root zone. Although the differences are small, at low fertigation frequency, osmotic effects were more pronounced and root pressure potential was more negative than at high fertigation frequency. According to Eq. (1) this will lead to a lower actual water uptake at low fertigation frequency than for the more frequently irrigated treatment. This is in correspondence with hypothesis two, i.e., fertigation frequency affects water and nutrient availability through *EC* effects.

Nutrient Uptake

At high *EC* levels, no *EC* effect on nitrogen (N) and phosphorus (P) uptake was simulated. Except for the low fertigation frequency treatment at $EC = 1$ dS m^{-1} (N, P) and at $EC = 2$ dS m^{-1} (P), the simulated crop concentrations of N and P were close to the measured concentrations (Fig. 4). At low fertigation frequency, the simulation model predicted a sharper decrease in N concentration at $EC = 1$ dS m^{-1} than measured. Also, for P, the decrease in concentration at low *EC* (1 or 2 dS m^{-1}) was overpredicted.

CONCLUSIONS

We have shown that effects of *EC* on plant growth and transport and uptake processes in the root zone can be modelled in tomato grown on rockwool.

At low *EC* (< 2 dS m^{-1}) of the fertigation water less nutrient uptake occurs resulting in lower nutrient concentrations in the plant, while at high *EC* (> 4 dS m^{-1}) less water uptake occurs due to osmotic effects (confirmation of hypothesis one). Furthermore, the effects at high *EC* levels are more pronounced when fertigation occurs at a lower frequency. This is due to the fact that between two fertigations the *EC* in the root zone increases more than at high fertigation frequencies thus inducing more negative osmotic pressure potentials (confirmation of hypothesis two).

Once such models are thoroughly validated, they offer prospects for fertigation management: supply on crop demand, prevent pollution, and possibilities for directing uptake (quality control).

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Tables

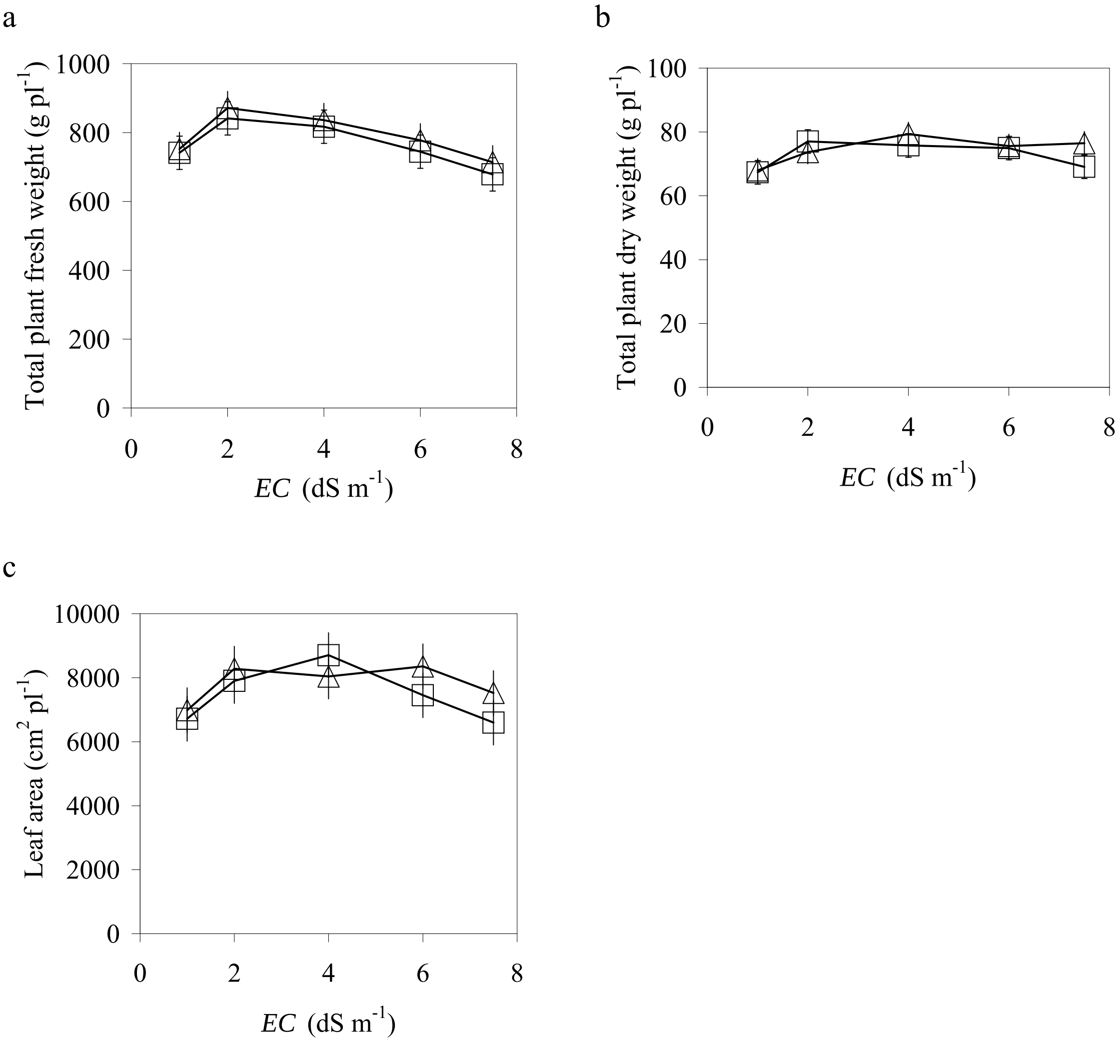

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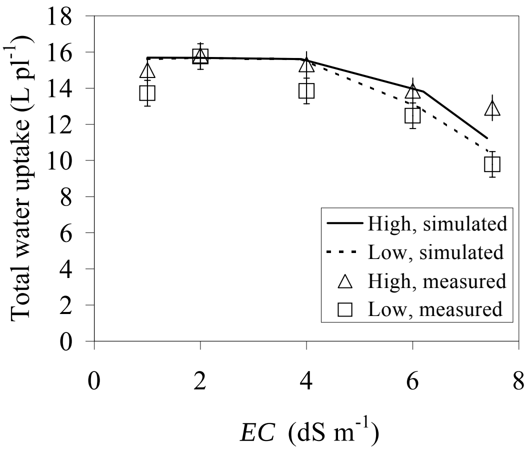
Fig. 1. Measured (a) total fresh weight, (b) total dry weight, and (c) leaf area, all per plant, as a function of *EC* of the fertigation water at high (Δ) and low (□) fertigation frequencies. Vertical bars represent standard errors of means



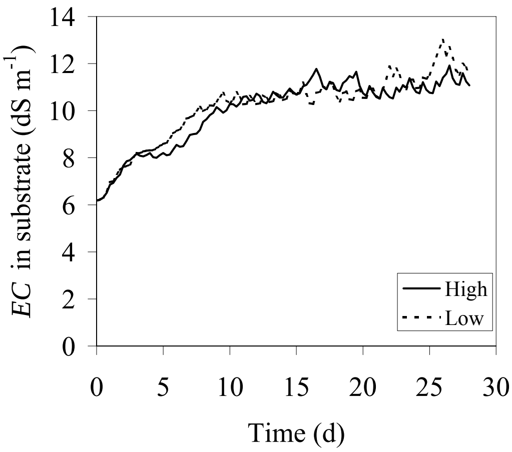


Fig. 2. Measured and simulated water use as a function of *EC* of the fertigation water at low and high fertigation frequencies. Vertical bars represent standard errors of means.

Fig. 3. Simulated time courses of *EC* in the rockwool (4.4 cm above bottom) below the plant position for the high and low fertigation frequencies for the treatment *EC* = 6 dS m^{-1}.

a b

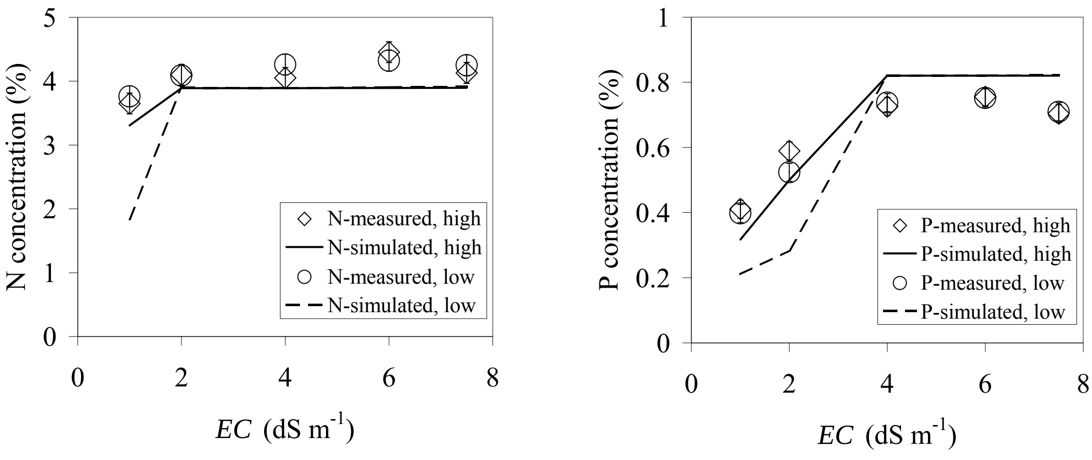


Fig. 4. Measured and simulated concentrations in the plant (by weight) for (a) nitrogen (N) and (b) phosphorus (P) as a function of *EC* of the fertigation water at low and high fertigation frequencies. Vertical bars represent standard errors of means.