

# Salinity Effects on Fruit Yield in Vegetable Crops: a Simulation Study

Ep Heuvelink and Menno Bakker  
Wageningen University  
Horticultural Production Chains Group  
Wageningen, The Netherlands

Cecilia Stanghellini  
Institute of Agricultural and  
Environmental Engineering (IMAG)  
Wageningen, The Netherlands

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## Abstract

Salinity can reduce crop growth and yield through its impact on plant water relations by: (1) increased fruit dry matter content, (2) reduced leaf expansion and (3) stomatal closure. In this simulation study the tomato model TOMSIM was used to predict salinity impact on fruit fresh yield, based on single or combined effects through plant water relations. The following influences were tested: Increase in fruit dry matter content (5% at  $EC=2 \text{ dS m}^{-1}$ ) by 0.2% per  $\text{dS m}^{-1}$ ; decrease in specific leaf area (SLA) by 8% per  $\text{dS m}^{-1}$  starting from a threshold of 3 or 6  $\text{dS m}^{-1}$ ; increase in stomatal resistance ( $r_s$ ) by a factor 2 or 4 over the range 1 to 10  $\text{dS m}^{-1}$ . Simulations showed threshold salinity levels of 2.9-4.4  $\text{dS m}^{-1}$ , except when only  $r_s$  or only SLA was affected (higher threshold). Impact of  $r_s$  was small as total resistance for  $\text{CO}_2$  import is determined by a series of resistances in which  $r_s$  is rather small, under non-stressed conditions. Yield decline in % per  $\text{dS m}^{-1}$  varied between 1.9 and 17.8. When only an effect of salinity on  $r_s$  was simulated this decline was lowest, whereas a salinity effect on SLA from  $EC=3 \text{ dS m}^{-1}$  onwards, gave the strongest decline per unit rise in EC. Simulations showed that delayed leaf picking or increased plant density mitigate the negative effect of salinity via leaf expansion, as average leaf area index increases. For example, at  $EC=7 \text{ dS m}^{-1}$  one week delay in leaf picking resulted in 10% yield increase (24.2 instead of 22.0  $\text{kg m}^{-2}$ ), whereas at  $EC=9 \text{ dS m}^{-1}$  this was 25% (14.7 instead of 11.8  $\text{kg m}^{-2}$ ). Applicability of these results, if confirmed by targeted experiments, would not be limited to tomato as the processes described in the model are general.

## INTRODUCTION

There are several means by which salinity reduces plant growth. In a recent review Munns (2002) has argued that, apart from salt-specific toxicities in sensitive plants, the effects of increased salinity in the root environment are “basically identical to those due to soil water deficit”. In this paper we will limit ourselves to analysing these “water relation effects”, without dealing with toxicity nor interaction among uptake of  $\text{Na}^+$  and  $\text{Cl}^-$  with nutrient ions.

Even when limiting the scope of salinity stress to the effect upon water relations, there are at least three factors to be considered. In the first place, uptake of water is reduced by a high osmotic pressure in the root zone, and as a result organ size is smaller (e.g. Ehret and Ho, 1986; Van Ieperen, 1996; Sonneveld, 2000). By showing that manipulating the pressure in the root zone can compensate the effect of increased salinity on leaf elongation, Passioura & Munns (2000) have demonstrated that this response is solely due to cell water relations. Similarly, although on a different time scale, Li et al. (2003) have shown that it was possible to modify the yield response to salinity in tomato by manipulating water outflow from the leaves, i.e. increased vapour pressure in the greenhouse air. Indeed, reduction of fresh weight at mild salinity is, in most cases, not coupled to reduction of dry matter. Passioura & Munns (2000) have also shown that this effect is reversible: when the salt treatment is withdrawn, the elongation rate recovers in a matter of minutes. Li et al. (2002) observed a fast recovery of size of tomato fruits, when a salt treatment of a few months was stopped.

Reduced leaf elongation, when protracted, results in small final leaf size and

reduced light interception, when leaf area index is smaller than the “saturating value” (about 3 for tomato). As crop biomass production shows a positive linear relationship with the amount of intercepted light (Monteith, 1994), reduced light interception will have a negative effect on dry matter accumulation, which means a more lasting reduction in growth. For instance, Giuffrida et al. (2001) attributed yield loss of strawberry to reduced individual leaf area, reduced number of leaves and reduced leaf duration. Not all these effects need to be present, however. For instance, Li & Stanghellini (2001) observed in tomato only a reduced individual leaf area; and Giorio et al. (1996) concluded that the effect on leaf expansion rate was the most important also in sunflower. In addition, dry matter accumulation may also be reduced by partial stomatal closure caused by turgor loss in the stomatal guard cells or a hormonal signal from the roots. Stomatal closure, however, is a very expensive reaction (in terms of forgone assimilation) and may well be the very last “defence mechanism” called upon. Indeed, Steduto et al. (2000) attributed the lack of stomatal closure observed often in mild-salinity experiments, and in their own with sunflower, to an optimal behaviour of plant processes.

Obviously, although all three mechanisms may be active, it is well possible that not all of them are equally important in all conditions. This question is particularly relevant for the somewhat controlled conditions in which greenhouse crops are grown. In the first place because the environment (particularly the transpiration/assimilation ratio) is different from the field environment where the response mechanisms developed. In addition, the controlled growing conditions of greenhouse crops may well provide a tool for growers to reduce impact of saline irrigation water.

The general yield response curve to the root zone EC first described by Maas and Hoffman (1977) assumes that crop yield depression is evident above a root-environment-EC threshold, beyond which yield decreases linearly, until a “zero-yield” value. Van Genuchten (1983) has proposed a more realistic S-shaped response curve, with the drawback, however, that the meaning of the parameters of the curve is less self-evident. In addition, for most practical purposes (that is salinities well short of the “zero-yield” value) there is little difference between the two approaches, so that the Maas & Hoffman (1977) parameterisation has become a sort of benchmark in the yield response to salinity literature.

In this paper we have modelled the response to salinity of an “ideal” greenhouse crop, under various assumptions about the underlying processes. We have described the results in terms of the Maas & Hoffman (1977) parameters, in order to establish whether the sensitivity of a crop could be described in terms of the processes playing a role. Things have proven more complex than we hoped. However, we will show that this analysis can help in understanding the mutual importance of the processes in the modified environment of a greenhouse, and in selecting possible damage-control actions for growers in saline environments.

## MATERIALS AND METHODS

### Simulation Model

We used the model TOMSIM (Heuvelink, 1999), an explanatory crop-growth and -development model for indeterminately growing tomato crops. Growth of the crop is potential, i.e. dry matter is accumulated under ample supply of water and nutrients in a pest, disease and weed-free environment, under the prevailing greenhouse climatic conditions. Dry matter production is calculated according to:

$$dW/dt = C_f(P_{gc,d} - R_m)$$

in which  $dW/dt$  is the crop growth rate ( $g\ m^{-2}\ d^{-1}$ ),  $C_f$  is the conversion efficiency from assimilates to dry matter,  $P_{gc,d}$  is the crop growth assimilation rate and  $R_m$  is the maintenance respiration rate (both  $g\ CH_2O\ m^{-2}\ d^{-1}$ , referred to unit ground area).  $P_{gc,d}$  depends on the light absorption by the canopy, mainly determined by the incoming radiation and the crop leaf area.  $R_m$  is calculated from the mass of the plant parts multiplied by their specific maintenance coefficients and increases with temperature and

crop relative growth rate (measure for metabolic activity). Dry matter partitioning is simulated on a daily basis and is primarily regulated by the sinks and individual fruit trusses and vegetative units (three leaves and stem internodes between two trusses) are distinguished. The appearance rate and harvest rate of trusses depends on temperature only. All sinks derive their assimilates from one common assimilate pool. Daily available biomass is distributed among the total number of sinks per plant, according to their relative sink strength, which is defined as their potential growth rate, relative to the total sink strength of all sinks together. Partitioning within the vegetative plant part is 7:3:1.5 for leaves, stem and roots, respectively. Values for the model parameters were the same as in Heuvelink (1999). Leaf stomatal resistance to H<sub>2</sub>O diffusion was 50 s m<sup>-1</sup>, leaf boundary layer resistance to H<sub>2</sub>O diffusion was 100 s m<sup>-1</sup> and mesophyll resistance to CO<sub>2</sub> transport at 20°C was 250 s m<sup>-1</sup>. All resistances are referred to one projected leaf area. Specific leaf area (SLA; cm<sup>2</sup> g<sup>-1</sup>) is a function of the day of the year (t; day 1 being 1 January):

$$SLA = 266 + 88 \sin(2\pi(t+68)/365)$$

Simulations were conducted for 20°C greenhouse air and plant temperature, CO<sub>2</sub> concentration was 350 μmol mol<sup>-1</sup> in the greenhouse and outside global radiation of selected months from the 1971-1980 weather records of De Bilt, The Netherlands (Breuer and Van de Braak, 1989) was used. This so-called 'selected year' results in the same average irradiance as observed for the 30-year average global radiation in De Bilt, however, it contains a representative variability in radiation.

Greenhouse transmissivity for diffuse radiation was set to 63% and light inside the greenhouse was calculated according to the model of Bot (1983). Simulations started on 10 January, which was assumed to be the anthesis date of the first truss and simulations were ended on 7 September (day 250), a reasonable estimate for the date when the top is cut-off and plants are left to ripen the remaining trusses, in Dutch commercial practice. Plant density was assumed to be 2.5 plants m<sup>-2</sup>, no side shoots retained, and all trusses to have seven fruits.

### Salinity Effects Introduced in the Model

The model TOMSIM simulates potential crop growth (no salinity stress). We investigated growth reduction when the three types of salinity responses outlined earlier were introduced, either alone or in various combinations.

**1. Fruit Dry Matter Content:** based on Li et al. (2001) a linear increase by 0.2% per dS m<sup>-1</sup> in fruit dry matter content (5% at EC=2 dS m<sup>-1</sup>) with salinity (EC; dS m<sup>-1</sup>) was introduced. Note that there is an obvious variety effect in these values: for instance, De Koning (1994), working with another tomato variety, determined a slightly gentler increase (0.17%), on a higher-level altogether.

**2. Leaf Area Expansion:** Li & Stanghellini (2001) observed a decrease in individual leaf area in tomato of 8% per dS m<sup>-1</sup>, for EC exceeding 6 dS m<sup>-1</sup>. In the model, however, LAI is a result and not an input. Therefore, we simulated an effect of salinity upon specific leaf area. Schwarz and Kuchenbuch (1997) showed that effect of salinity on SLA was different for different varieties. In the range EC=1 to EC=6 dS m<sup>-1</sup> they observed either no effect or a 5% decrease with 1 dS m<sup>-1</sup> increase in EC. Between EC=1 and EC=3.5 dS m<sup>-1</sup> this decrease was as large as 12%. In our simulation study we assumed that after a threshold, 1 dS m<sup>-1</sup> increase in EC will decrease SLA by 8%. We assumed a seasonal pattern and decreasing by 8% per dS m<sup>-1</sup>, starting from a threshold value of 3 or 6 dS m<sup>-1</sup>. The resulting average LAI has a slope of about 12%.

**3. Stomatal Resistance:** We deliberately simulated the effect of two strong responses, i.e. an increase with EC over the range 1 to 10 dS m<sup>-1</sup> by either a factor 2 or a factor 4.

### Mitigate Salinity Effects

It is common in some crops, e.g. in tomato and cucumber, to pick older leaves. Delayed leaf picking and/or increased plant density could have a mitigating effect on yield response to salinity as light interception will reduce less drastically. In the standard

simulations, leaves of a section below a truss were removed at stage 0.9 of that truss. This was delayed to stage 1.0, implying that the 3 leaves below a truss were removed when the first fruit of that truss reached harvest stage. At 20°C this meant a systematic delay in leaf picking of about one week. Plant density effects were tested by doubling plant density from 2.5 to 5.0 plants m<sup>-2</sup>.

### Processing the Results

Yield predictions were obtained for simulations at salinity level 1, 3, 5, 7, 9 & 11 dS m<sup>-1</sup>. We then calculated the Maas & Hoffman (1977) parameters, i.e. threshold and slope of the salinity response. Threshold was defined as the EC level where yield was 90% of maximum yield (in view of the acknowledged variability of measured yield data). All simulated yields below or on the threshold EC were used in a linear regression to determine the slope of the yield-salinity response. This slope (kg m<sup>-2</sup> per dS m<sup>-1</sup>) was expressed in % decrease per dS m<sup>-1</sup> relative to the yield level at the threshold EC. Based on threshold and slope yield responses were categorised according to Shannon & Grieve (1999).

## RESULTS

Assuming that salinity only affects fruit dry matter content, would result in a rather modest yield reduction with increasing EC, compared to the assumption that only an effect on SLA or a combination of both effects plays a role (Fig. 1). Assuming that salinity increases stomatal conductance by a factor 2 or 4, between 1 and 10 dS m<sup>-1</sup>, did not result in a strong yield reduction (Fig. 1; maximum 18% yield reduction at EC=11 dS m<sup>-1</sup>). Simulations showed threshold salinity levels of 2.9-4.4 dS m<sup>-1</sup>, except when only stomatal conductance or only SLA was affected. In those situations the threshold was higher (Table 1). Yield decline in % per dS m<sup>-1</sup> varied between 1.9 and 17.8. When only an effect of salinity on leaf stomatal conductance was assumed, this decline was lowest, whereas a salinity effect on SLA from EC = 3 dS m<sup>-1</sup> onwards gave the largest decline per unit rise in EC. Both factors affect yield via biomass production: decreased stomatal conductance reduces photosynthesis, whereas reduced SLA results in a reduced LAI, light interception and hence total biomass production.

A delay in leaf picking by one week or a double plant density resulted in a higher leaf area index (Fig. 2A). This mitigated the negative effect of salinity on SLA. At EC=7 delayed leaf picking resulted in 10% yield increase (24.2 instead of 22.0 kg m<sup>-2</sup>), whereas at EC=9 this was 25% (14.7 instead of 11.8 kg m<sup>-2</sup>). Doubling the plant density increased yield by 11% (24.4 instead of 22 kg m<sup>-2</sup>) and 36% (16 instead of 11.8 kg m<sup>-2</sup>) at EC of 7 or 9 dS m<sup>-1</sup>, respectively (Fig. 2B).

## DISCUSSION

The model TOMSIM has allowed us to simulate separately the different effects of salinity and to get insight into the relevance of the individual responses. Many experiments (that should be performed under constant environmental conditions, in order to avoid possible adaptations) would be necessary to proof beyond doubt the results of this exploratory study. Given the span of the processes considered, it seems reasonable to infer that the trends found here would apply to other vegetable fruit crops as well.

Salinity impact on yield through reduced water import into the fruits (increased dry matter content in the fruits alone), results in a response that can be classified as resistant. The same holds for an impact on stomatal resistance alone. Salinity impact on stomatal resistance is not an important way by which salinity influences yield, as total resistance for CO<sub>2</sub> transport onto the chloroplast is the result of three resistances connected in series: the boundary layer resistance; the stomatal resistance and the mesophyll resistance. The boundary layer resistance is particularly large in greenhouses (low wind speed), which reduces the importance of changes in the stomatal resistance for photosynthesis. For the parameter values used in our model, a fourfold increase in stomatal resistance would increase total resistance for CO<sub>2</sub> transport only by 40%.

The strongest responses (yield decline per  $\text{dS m}^{-1}$ ) are observed when salinity influences SLA, i.e. leaf expansion. Since light interception shows a saturation type response to LAI, such a response can affect yield only in the “linear” part of the light interception vs. LAI curve, i.e. at relatively low leaf area. The LAI at which saturation is reached depends on the crop (leaf orientation). In tomato this happens at about 3: if LAI is high ( $>3$ ) a reduction by 10 or 20% in leaf area will hardly influence the fraction of intercepted light. Hence, no large effects on yield are expected. However, when LAI is e.g. 2 or 1.5, a change in LAI results in a substantial change in light interception and hence yield. Our results clearly show that salinity effects caused by reduced leaf area index might be mitigated through actions that increase leaf area index. In the case of tomato, this was obtained via delayed leaf picking or an increased plant density. The effects were quantified by the model (Fig. 2), however, they still have to be proven by experiments. No literature reports on this mitigation effect are known to us.

A limitation of the present work is that number of fruits produced is equal for all simulations, as in the model truss appearance rate only depends on temperature and number of fruits per truss is constant. De Koning (1994) indeed reported that salinity does not influence truss appearance rate. However, a reduction in number of fruits per truss at increased salinity has been observed (Van Ieperen, 1996). This may result from a reduced fruit set at low source-to-sink ratio (Marcelis et al., 1998) and could have been included in the model in this way. However, accurate prediction of fruit set is still a weak part of crop growth models (Marcelis et al., 1998). Furthermore, additional reduction in economic yield may occur due to negative effects of salinity on fruit quality, e.g. occurrence of blossom-end-rot in tomatoes (Van Ieperen, 1996) and sweet peppers, which is not included in the model.

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## **Tables**

Table 1. Summary of simulated total fruit fresh yields produced by tomato crops from day 10 (first anthesis) until day 250 (decapitation) of the year. DMC indicates whether an effect of EC upon dry matter content is included; specific leaf area (SLA): No indicates that no effect was included, T3 and T6 indicate that there is a decrease with salinity starting at EC = 3 and 6 dS m<sup>-1</sup>, respectively. For the stomatal resistance (r<sub>s</sub>) there is either no effect (No) or a multiplying factor linearly increasing to 2 and 4 (F2 and F4), respectively, at EC = 10 dS m<sup>-1</sup>. 'Threshold' is the EC at which yield has decreased to 90% of the maximum, and 'slope' is the slope of the linear regression line through the points on or exceeding the threshold. 'No yield' indicates the EC at which the regression line would result in no yield.

Simulation settings		r <sub>s</sub>	Yield response			Category <sup>4)</sup>
DMC	SLA		Threshold (dS m <sup>-1</sup> )	Slope (% per dS m <sup>-1</sup> )	No yield (dS m <sup>-1</sup> )	
No	No	F2	>11	ND <sup>1)</sup>	ND	Resistant
No	No	F4	6.3	1.9	59.7	Resistant
Yes	No	No	3.3	2.8	38.5	Resistant
Yes	T6	No	4.4	7.9	17.0	Intermediate
No	T6	No	8.5	13.1	16.1	Intermediate
Yes	T6	F2	4.2	9.0	15.3	Intermediate
Yes	T6	F4	2.9	10.3	13.5	Intermediate
No	T3	No	6.0	17.8	11.6	Intermediate
Yes	T3	F2	4.4	12.9	13.0	Intermediate/Sensitive
Yes	T3	F4	2.9	12.4	12.1	Intermediate/Sensitive
Yes	T3	No	4.0	13.2	11.6	Intermediate/Sensitive
Yes <sup>2)</sup>	T3	No	4.1	12.9	12.6	Intermediate/Sensitive

- 1) ND = Not Determined, as threshold was not reached. <sup>2)</sup> Leaf removal was delayed by about 1 week. <sup>3)</sup> Plant density was doubled. <sup>4)</sup> Qualification of salinity response according to Shannon & Grieve (1999).

**Figures**

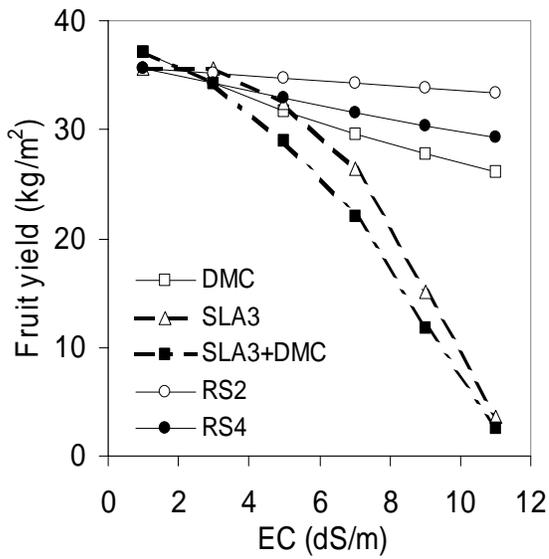


Fig. 1. Total fruit fresh yield as affected by salinity at 5 different underlying assumptions: DMC, fruit dry matter content increases by 0.2% per  $\text{dS m}^{-1}$ ; SLA3, specific leaf area decreases with 8% per  $\text{dS m}^{-1}$  starting from a threshold of  $3 \text{ dS m}^{-1}$ ; DMC+SLA3, combination of both former effects; RS2 and RS4, stomatal resistance increases with a factor 2 or 4 over the salinity range 1 to  $10 \text{ dS m}^{-1}$ .

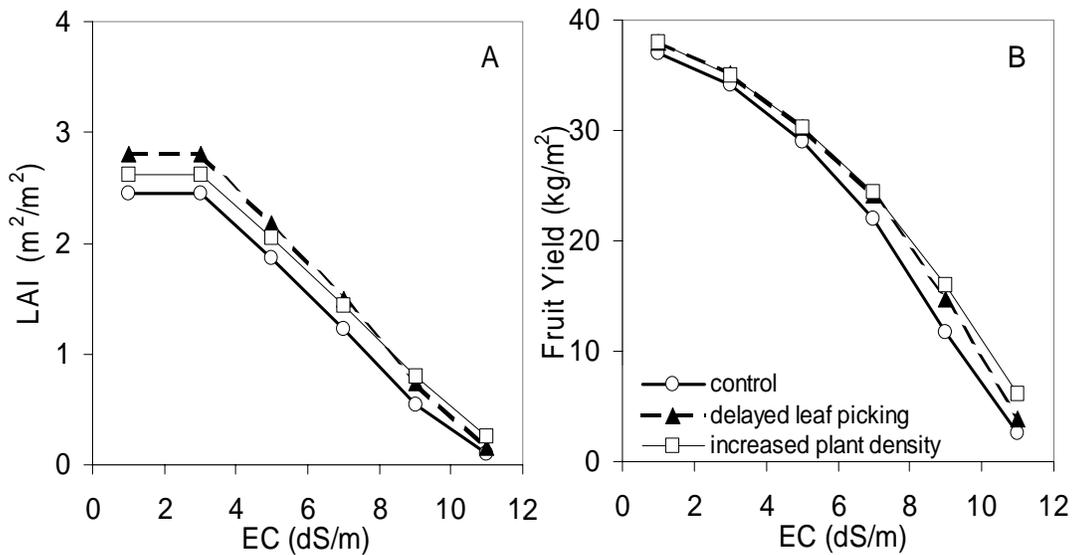


Fig. 2. Average leaf area index (LAI; day 60 until day 250), A; and total fruit fresh yield, B, as affected by salinity in 3 situations. Control: leaves from a vegetative unit were removed when the developmental stage of the corresponding truss (above these leaves) was 0.9 and a plant density at  $2.5 \text{ plants m}^{-2}$ ; delayed leaf picking: leaf removal at truss stage 1.0 (harvest ripe) and plant density as control; increased plant density: leaf picking as control, plant density at  $5 \text{ plants m}^{-2}$ .