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# An aggregated model for water requirements of greenhouse tomato grown in closed rockwool culture with saline water

G. Carmassi *, L. Incrocci, R. Maggini, F. Malorgio, F. Tognoni, A. Pardossi

*Dipartimento di Biologia delle Piante Agrarie, Viale delle Piagge, 23 I-56124 Pisa, Italy*

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ABSTRACT

The paper reports an aggregated model for the water requirements (*W*) of greenhouse tomato grown in spring or summer–autumn season in closed (recycling nutrient solution) rockwool culture. A series of experiments were conducted between 2000 and 2003. In each experiment, two different nutrient solution treatments were established in a randomized block design, with three replicates. The nutrient solutions differed only for the concentration of NaCl and the electrical conductivity (EC), which were, respectively, 10 mol $m^{-3}$ and 3.0 dS $m^{-1}$ in T10 treatment, and 20 mol $m^{-3}$ and 3.9 dS $m^{-1}$ in T20 treatment. Fruit yield was 10.1 $\pm$ 0.3 and 9.6 $\pm$ 0.2 kg $m^{-2}$ in T10 and T20 treatments, respectively, and the difference was not significant. Two diverse sub-models were developed, for the daily crop water uptake ($W_U$) and for the leaching requirement (LR) in dependence of a maximum tolerable sodium ($Na^+$) concentration in the recycling nutrient solution. $W_U$ was simulated using a simple regression model, which considered the radiation actually intercepted by the crop. The determination coefficient for the linear regression between predictions (*P*) and measurements (*M*) of daily $W_U$ was 0.853 ($n = 581$), with the slope (0.963) and the intercept (−0.053) of the linear regression not significantly different, respectively, from 1 and 0. There was a good agreement between *P* and *M* values of $W_U$, with a mean deviation between *P* and *M* of 2 $\pm$ 10%. The modelling of LR was less satisfactory, especially in spring crops; the average value for *P* and *M* values of LR was 0.30 and 0.28, respectively. The *P*–*M* residual averaged 11 $\pm$ 25% for LR and 13 $\pm$ 26% for the volume of drainage water or runoff ($W_R$). Nevertheless, the aggregated model accounted well for *W* with an average deviation of 4 $\pm$ 11% between *P* and *M*. The sensitivity analysis showed the great influence of radiation on *W* and suggested that the quality of irrigation water (namely, NaCl concentration) is more relevant for crop water use efficiency than any other factor considered by the LR model, including the affinity of the plant for the salts contained in the nutrient solution.



## 1. Introduction

The technology of closed-loop soilless culture may be an important component of sustainable greenhouse production (Pardossi et al., 2005). In closed growing systems, the drainage nutrient solution resulting from surplus fertigation is recycled, thus reducing the use of water and limiting the leakage of fertilizers to the environment.

Along with the risk consequent to the possible diffusion of root pathogens, the salinity of irrigation water represents the main difficulty for the management of closed systems. In fact, salt accumulation occurs in the root zone when irrigation water contains ions, such as $Na^+$ and $Cl^-$, at concentrations

* *Corresponding author*. Tel.: +39 050 2216500; fax: +39 050 2216524.
E-mail address: gcarmassi@agr.unipi.it (G. Carmassi).
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higher than the plant uptake concentration ($C_U$), which is the ratio between the nutrients and the water taken up by the roots (Sonneveld, 2000; Carmassi et al., 2005; Savvas et al., 2005). Under these conditions, the nutrient solution is generally recirculated until its total salinity (as indicated by electrical conductivity, EC) and/or the concentration of potentially toxic ions reach a threshold value, above which a reduction in crop yield is expected, afterwards it is replaced (at least, partially) with a consequent waste of water and nutrients. This kind of system is named semi-closed. In Holland, where closed growing systems are compulsory for greenhouse production, growers are allowed to leach their systems whenever a crop-dependent ceiling of $Na^+$ concentration (between 3 and 8 mol $m^{-3}$) is reached (Baas and Berg, 1999): for example, 4 mol $m^{-3}$ for rose and 8 mol $m^{-3}$ for tomato.

The development of methods or models to estimate crop water requirement is crucial to improve the irrigation efficiency in greenhouse cultivations. Several studies have been conducted to model the water requirements of important greenhouse crops, including tomato (e.g. Stanghellini, 1987; Jolliet and Bailey, 1992). These models are principally based on the relationships between leaf transpiration (*E*) and climatic parameters, such as solar radiation (*R*) and vapour pressure deficit (VPD). However, in semi-closed systems it is also important to know the leaching requirement (LR), which is defined as the ratio between the water needed to flush out the salts from the root zone (namely, drainage water or runoff, $W_R$) and the genuine water uptake by the plants ($W_U$).

In this work, an aggregated model was developed for the overall water use (*W*) of a semi-closed rockwool culture of tomato, which is the sum of both $W_U$ and $W_R$. In order to develop a model valid in a wide range of growing conditions, two growing seasons (spring and summer–autumn) and two nutrient solutions differing only for the concentration of NaCl and the electrical conductivity (EC), which were, respectively, 10 mol $m^{-3}$ and 3.0 dS $m^{-1}$ in T10 treatment, and 20 mol $m^{-3}$ and 3.9 dS $m^{-1}$ in T20 treatment, were tested.

The main objective of this study, therefore, was not to investigate the tomato response to salinity, but to determine how water use efficiency was affected by the presence in the irrigation water of a specific salt (NaCl) that is scarcely absorbed by the plant.

The aggregated model consists of two sub-models. The $W_U$ sub-model resembles a simple regression model for the relationship between *E* and the *R* actually intercepted by the plants. The $W_R$ sub-model was based on a simulation of the salt accumulation (namely, $Na^+$ concentration) in the recycling nutrient solution as a function of cumulative $W_U$. The $Na^+$ accumulation model was illustrated in details in a recent paper (Carmassi et al., 2005); this work considered slightly different data sets compared to the one reported in that paper.

The aggregated model may be a relevant component of a decision support system (DSS) for greenhouse closed hydroponics; it may be used for on-line (short-term) or off-line (long-term) decisions. For instance, the model could be implemented in the automatic control of fertigation or for simulation study aimed to identify the best allocation of water resources at farm gate.

## 2. Materials and methods

### 2.1. Growing conditions

Several experiments were conducted with round-fruit tomato (*Solanum lycopersicum* L. cv. Jama $F_1$) plants grown under very similar conditions at University of Pisa (Pisa, Italy) in two different seasons of three subsequent years (2000–2002): from March to June, and from August to December (for the latter period, the term 'autumn' is used in the paper).

The plants were cultivated in a heated glasshouse (240 $m^2$) equipped for closed rockwool culture. Minimum night (heating) temperature and ventilation temperature were set to 14 and 27 °C, respectively; indoor air temperature (*T*) reached 30–35 °C in late spring and in summer. Daily mean values of *T* and global radiation (*R*) were: 20.7 °C–8.9 MJ $m^{-2}$ in spring 2000; 20.9 °C–10.7 MJ $m^{-2}$ in spring 2001; 21.3 °C–6.8 MJ $m^{-2}$ in autumn 2001; 21.2 °C–9.4 MJ $m^{-2}$ in spring 2002; 19.4 °C–3.3 MJ $m^{-2}$ in autumn 2002.

Tomato seedlings were grown in rockwool cubes in a growth chamber until 2 weeks after sowing, then in the glasshouse for other 2 or 3 weeks before transplanting in standard (1-m long) rockwool slabs at a density of 3.0 plants $m^{-2}$. Three plants and five drippers were placed in each slab. Tomato plants were cultivated vertically by detaching lateral shoots from the main stem and only five trusses, each bearing not more than five fruits, were left on the plants; in consideration of the short growing period (13–16 weeks), basal leaves were not removed.

Six independent growing systems were used, each consisting of two benches with 60 plants in total and a mixing tank with a volume ($V_T$) of 140 L (7.0 mm, as expressed on the basis of cultivated area); the total amount of recycling water (*V*), including the one retained by the substrate ($V_S$), was approximately 324 L (16.2 mm). In the cultures conducted in 2000, 58 plants were transplanted in each hydroponic system at the same density used in the other experiments; therefore, $V_T$ and *V* were 7.2 and 16.7 mm, respectively.

Drip irrigation was automatically controlled on the basis of incoming *R*, which was measured by a piranometer connected to a datalogger. A high (>60%) drain fraction (i.e. the ratio between drainage water and applied water) was adopted in order to avoid differences in the salt concentration between the solution in the substrate and the one in the mixing tank, where the samples for laboratory analysis were collected.

In the system under investigation, the mixing tank was automatically refilled with complete nutrient solution whenever the water level decreased by 40 L (12% of *V*).

In each experiment, two different nutrient solution treatments were established in a randomized block design, with three replicates. In the 3 years, the EC and the ionic composition of the raw water used for preparing the nutrient solutions averaged (mean ± S.D.): 1.36 ± 0.03 dS $m^{-1}$, N-$NO_3^-$ 0.23 ± 0.01 mol $m^{-3}$, P-$H_2PO_4^-$ < 0.01 mol $m^{-3}$, $K^+$ 0.10 ± 0.01 mol $m^{-3}$, $Mg^{2+}$ 0.76 ± 0.02 mol $m^{-3}$, $Ca^{2+}$ 1.45 ± 0.04 mol $m^{-3}$, $Na^+$ 8.22 ± 0.17 mol $m^{-3}$, $Cl^-$ 7.95 ± 0.15 mol $m^{-3}$, S-$SO_4^{2-}$ 0.04 ± 0.01 mol $m^{-3}$, $HCO_3^-$ 4.52 ± 0.09 mol $m^{-3}$. The water was analyzed in the laboratory at the beginning of each experiment and the EC was periodically checked throughout the culture. To simulate the use of irrigation water with NaCl concentration of

10 mol $m^{-3}$ (T10) and 20 mol $m^{-3}$ (T20), the required quantity of NaCl was added to the raw water whenever fresh nutrient solution was prepared: after the NaCl addition, the EC was 1.52 and 2.48 dS $m^{-1}$ for T10 and T20, respectively.

For both T10 and T20 treatments, the same amounts of commercial sulphuric acid, calcium nitrate, potassium monophosphate, potassium nitrate, magnesium sulphate and nitrate were dissolved in NaCl-enriched water in order to achieve the following macronutrient concentration ($C_R$; mol $m^{-3}$): N-$NO_3^-$ 12.0 mol $m^{-3}$, P-$H_2PO_4^-$ 1.1 mol $m^{-3}$, $K^+$ 8.0 mol $m^{-3}$, $Mg^{2+}$ 2.3 mol $m^{-3}$, $Ca^{2+}$ 3.2 mol $m^{-3}$. Trace elements were added as inorganic salts or as EDDHA or EDTA chelates. The EC ($C_R$) of the nutrient solution used to refill the mixing tanks was approximately 3.0 dS $m^{-1}$ in T10 treatment and 3.9 dS $m^{-1}$ in T20 treatment.

Every morning the nutrient solution was sampled from the mixing tank, following manually activated replenishment and irrigation, and checked for pH (maintained between 5.5 and 6.5 with sulphuric acid), EC and $Na^+$ concentration, the latter determined by means of an ion-specific electrode (CRISON Instruments S.A., Barcelona, Spain) or by flame photometry. Whenever $Na^+$ concentration exceeded 30 or 55 mol $m^{-3}$ in T10 and T20 treatment, respectively, the recycling nutrient solution was partially discharged, that is the water contained in the mixing tank was completely replaced by newly prepared nutrient solution. The EC of exhausted solutions was around 6.0 or 8.0 dS $m^{-1}$ in T10 and T20 treatment, respectively. In the various experiments the recirculating nutrient solution was flushed out 5–12 times depending on the growing period and the quality of irrigation water; the flushing was more frequent in spring and in T20 cultures.

Table 1 summarizes some information on the experiments.

### 2.2. *Measurements*

Daily $W_U$ was measured by recording with a water meter the amount of nutrient solution used to refill the mixing tank. The accuracy of water meter was checked in occasion of periodical flushing by comparing the readings with the known amount of water needed to refill the mixing tank (140 L); the accuracy was 1.5–2.0%.

The same volume $V_T$ was discharged in occasion of flushing, thus $W_R$ was determined as

$$W_R = NV_T \quad (1)$$

where N is the times the mixing tank was emptied, including the disposal at the end of the experiment.

### 2.3. *Modelling*

As it has been introduced in the previous paragraph, in semi-closed systems it takes:

$$W = W_U + W_R \quad (2)$$

LR is defined as $W_R/W_U$ ratio, then

$$W = W_U + W_U LR = W_U(1 + LR) \quad (3)$$

Therefore, an aggregated model was designed for estimating W on the basis of different sub-models. The $W_U$ model was empirical in nature and considered the development of leaf

**Table 1 – Basic information on the experiments conducted with semi-closed rockwool culture of greenhouse tomato**

| Experiment/series | Use | NaCl (mol $m^{-3}$) concentration in irrigation water | Season | Growing period | | Duration (days) | Considered period for modelling daily water uptake | | Number of flushings[a] |
|---|---|---|---|---|---|---|---|---|---|
| | | | | From | To | | Days after transplanting | Number of observations | |
| I-1 | Calibration | 10 | Spring | 16 March 2000 | 5 July 2000 | 112 | 31–112 | 79 | 10 |
| I-2 | Calibration | 20 | Spring | 16 March 2000 | 5 July 2000 | 112 | 31–112 | 79 | 12 |
| II-3 | Validation | 10 | Spring | 19 February 2001 | 12 June 2001 | 114 | 49–114 | 65 | 7 |
| II-4 | Validation | 20 | Spring | 19 February 2001 | 12 June 2001 | 114 | 49–114 | 65 | 9 |
| III-5 | Validation | 10 | Autumn | 23 July 2001 | 22 November 2001 | 123 | 14–123 | 109 | 11 |
| IV-6 | Validation | 10 | Spring | 26 March 2002 | 25 June 2002 | 92 | 19–92 | 73 | 8 |
| IV-7 | Validation | 20 | Spring | 26 March 2002 | 25 June 2002 | 92 | 19–92 | 73 | 10 |
| V-8 | Validation | 10 | Autumn | 1 September 2002 | 10 December 2002 | 101 | 3–101 | 98 | 6 |
| V-9 | Validation | 20 | Autumn | 1 September 2002 | 10 December 2002 | 101 | 3–101 | 98 | 7 |

[a] The values include the discharge of the water in the mixing tank at the end of the experiment.

area index (LAI) and the $R$ intercepted by the crop, as determined by means of the canopy light extinction coefficient ($k$). A mechanistic model, which addresses the phenomenon of $Na^+$ accumulation in the recycling water (Carmassi et al., 2005), was used to predict LR.

Model calibration and validation were based on data collected in independent experiments.

### 2.4. LAI model and k determination

In Experiment I, every 10 d after transplanting three plants were sampled in each salinity treatment for the determination of crop biomass and leaf area.

Leaf area index (LAI), from transplanting to harvest, was modelled using the Boltzmann sigmoid equation (Eq. (4); Motulsky and Christopoulos, 2003), where 8 °C was used as the base temperature (Thornley and Johnson, 1990) to calculate growing degree days (GDD) since the sowing:

$$\mathrm{LAI} = a + \frac{b + a}{1 + \exp[(c - \mathrm{GDD})/d]} \quad (4)$$

where $a$, $b$, $c$ and $d$ are constants.

At transplanting date GDD was 401.

The value of $k$ (dimensionless) was determined on the basis of the following equation based on Lambert–Beer's law (Nobel and Long, 1985):

$$\frac{R}{R_0} = \exp^{-k\,\mathrm{LAI}} \quad (5)$$

in which $R$ and $R_0$ are the radiation measured with a piranometer placed above and below the crop row, respectively. The determinations were performed in two different occasions, when LAI was $1.33 \pm 0.06$ and $2.96 \pm 0.08$.

### 2.5. $W_U$ model

The model consisted of a simple linear regression between daily $W_U$ and the $R$ intercepted by the plant canopy:

$$W_U = A(1 - \exp^{-k\,\mathrm{LAI}})\frac{R}{\lambda} + B \quad (6)$$

where $W_U$ is expressed in mm $d^{-1}$ (that is kg $m^{-2}$ $d^{-1}$), $R$ is the daily value of indoor radiation (MJ $m^{-2}$), $\lambda$ is the latent heat of vaporization (2.45 MJ $kg^{-1}$), $A$ (dimensionless) and $B$ (mm $d^{-1}$) are the regression parameters.

The model was calibrated using the results of the Experiment I. The parameters $A$ and $B$ were computed by means of linear regression analysis of the relationship of $W_U$ against $[(1 - \exp^{-k\,\mathrm{LAI}})R/\lambda]$.

### 2.6. $W_R$ model

The model computed the ratio between the amount of water discharged in occasion of flushing (i.e. $V_T$) and the value of cumulative $W_U$ at which $Na^+$ concentration reaches the pre-set limit.

A model was proposed by Carmassi et al. (2005) to predict the change, over the period $n$ and $n-1$ (days or weeks), in the concentration (mol $m^{-3}$) of a given ion in the recycling water of closed hydroponics, as a function of the cumulated $W_U$ (mm), the ion concentration at the initiation of cumulating $W_U$ ($C_{n-1}$), in the refill water ($C_R$), the apparent uptake concentration ($C_U$) and $V$ (as defined previously):

$$\Delta C = C_n - C_{n-1} = (C_R - C_U)\frac{W_U}{V} \quad (7)$$

This model is based on the salt balance of closed soilless culture, with the assumptions of a well-watered substrate and a constant $V$ (Carmassi et al., 2005). Indeed, the plants were watered frequently, up to 10–12 times during the daytime plus a timer-controlled irrigation at sunset; moreover, the reduction in $V$ due to $W_U$ was compensated with nutrient solution of known salt concentration added to the mixing tank at each time-step, which was short enough to maintain $V$ close to constant.

If $C_U$ is not constant, the ion does not accumulate linearly with $W_u$, as predicted by Eq. (7), and a different function should be used. For $Na^+$, $C_U$ was assumed to be proportional to its concentration in the recycling nutrient solution ($C$):

$$C_U = pC \quad (8)$$

By substituting Eq. (8) in Eq. (7) and after rearrangement, the following equation is obtained:

$$(C_n - C_{n-1})\frac{V}{W_U} = C_R - pC \quad (9)$$

For small increments, Eq. (9) can be written in a differential form:

$$\frac{dC}{d(W_U/V)} = C_R - pC \quad (10)$$

The integration of Eq. (10), with the initial condition $C = C_R$ for $W_U/V = 0$, leads to the following expression:

$$C_i = \left(C_R - \frac{C_R}{p}\right)\exp\left(-p\frac{W_U}{V}\right) + \frac{C_R}{p} \quad (11)$$

where $C_i$ is the ion concentration in the recirculating solution at step $i$.

The ion concentrations at steps $n-1$ and $n$, respectively, can be expressed by means of Eq. (11); thus, the comparison of the two expressions gives the ion concentration at step $n$ as a function of its concentration at step $n-1$, as follows:

$$C_n = \left(C_{n-1} - \frac{C_R}{p}\right)\exp\left(-p\frac{W_U}{V}\right) + \frac{C_R}{p} \quad (12)$$

Solving Eq. (12) for $W_U$, it takes:

$$\frac{C_n - C_R/p}{C_{n-1} - C_R/p} = \exp\left(-p\frac{W_U}{V}\right) \quad (13)$$

After rearrangement:

$$W_U = -\frac{V}{p}\ln\left(\frac{C^n - C_R/p}{C - C_R/p}\right) \quad (14)$$

According to Eq. (12), $Na^+$ tends to accumulate in the recirculating water as long as $C_U$ is appreciably lower than $C_R$; afterwards, as $C_U$ approaches $C_R$, $Na^+$ concentration stabilizes at values close to $C_R/p$, the asymptote of $C$. Hence, the absolute value of the denominator on the left-hand side of Eq. (13) represents the largest increment one could observe for the $Na^+$ concentration of recycling water.

For $C_{n-1} = C^{min}$, it is possible to predict the value of cumulated $W_U$ ($W_U^{max}$) for which $Na^+$ concentration reaches a given threshold for flushing ($C^{max}$; 30 or 55 mol m$^{-3}$ in T10 and T20, respectively), as follows:

$$W_U^{max} = -\frac{V}{p}\ln\left(\frac{C^{max} - C_R/p}{C^{min} - C_R/p}\right) \quad (15)$$

$C^{min}$ is the $Na^+$ concentration after flushing, which can be calculated as

$$C^{min} = \frac{C_R V_T + C^{max} V_S}{V} \quad (16)$$

LR was computed as

$$LR = \frac{V_T}{W_U^{max}} \quad (17)$$

Finally, for the growing period considered in each experiment (Table 1), $W_U$ was calculated as the sum of daily values and then, by definition of LR, $W_R$ was

$$W_R = LRW_U = \frac{V_T}{W_U^{max}} W_U \quad (18)$$

### 2.7. Statistical analysis

The influence of irrigation water NaCl concentration on crop growth and fruit yield was assessed by means of *t*-Student test. The values reported in tables and figures are reported as means of three replicates; the variation coefficient of the mean ranged from 4 to 16%. The correlation analysis for the considered parameters was performed with Statgraphics Plus 5.1 (Manugistic, Rockwille, USA); the correlation matrix is reported in Table 2.

The statistical program IRENE (Integrated Resources for Evaluating Numerical Estimates) v. 1.00, a MS-Windows software developed by the Research Institute for Industrial Crops (ISCI, Bologna, Italy; http://www.isci.it/tools) (Fila et al., 2003), was used for model validation. IRENE provided several statistical parameters based on the relationship between predicted (*P*) and measured (*M*) values: the Relative Root Mean Square Error (RMSE); the Modelling Efficiency (EF); the Coefficient of Residuals Mass (CRM). For a perfect *M*–*P* correspondence, RMSE is 0, EF is 1 and CRM is 0.

### 2.8. Sensitivity analysis

The sensitivity analysis of the model was performed for a hypothetical spring culture considering the following reference conditions: growing period of 70 d with constant values of daily mean *T* (21.8 °C) and *R* (9.6 MJ m$^{-2}$); $C_R$, 15 mol m$^{-3}$; $C^{max}$, 50 mol m$^{-3}$; $V_S$, 9 mm; $V_T$, 5 mm. The effects of a change in model input parameters were investigated by calculating the relative partial sensitivity of the model output, as described by Heuvelink (1999):

$$\frac{\delta O/O}{\delta I/I} \quad (19)$$

in which $\delta O/O$ is the relative change in model output, and $\delta I/I$ is the relative change in the input value or input data.

Sensitivity was calculated as the average sensitivity to a change in parameter or input data by −40, −20, 20, and 40%. Temperature sensitivity was calculated as the average sensitivity to changes of −3, −1, 1 and 3 °C. Model outputs examined were: maximum value of LAI, LR, $W_U$ and *W*.

## 3. Results and discussion

### 3.1. Plant response to NaCl concentration of irrigation water

In the literature it is reported that tomato is a crop moderately sensitive to salinity (Maas and Hoffman, 1977). According to these authors, the maximum salinity (expressed as the EC of soil saturated paste extract) without yield reduction is 2.5 dS m$^{-1}$, with a reduction of approximately 10% in the fruit production for each unit increase of EC above the threshold. On the other hand, the influence of salinity on crop development and yield depends on cultivar, climatic conditions and growing technique as well (e.g. Shannon and Grieve, 1999; Romero et al., 2001). For reasons of improved water relations and mineral nutrition, hydroponics may reduce the susceptibility to salinity in crop plants (e.g. Navarro et al., 1999). Adams (1987) found that the $Na^+$ concentration in the root environment of a tomato soilless culture could increase up to 37 mol m$^{-3}$, with a correspondent nutrient solution EC of 6.2 dS m$^{-1}$, without any yield reduction. In rockwool culture, Li and Stanghellini (2001) observed a reduction of tomato leaf expansion only at EC higher than 6.5 dS m$^{-1}$.

Since the $Na^+$ concentration and the EC in the nutrient solution oscillated between a minimum and maximum value, in this work the plants were not exposed to a constant salinity in the root zone. Fig. 1 illustrates the typical changes in EC and

**Table 2 – Correlation coefficients between daily crop water uptake ($W_U$), leaf area index (LAI), indoor solar radiation (*R*), vapour pressure deficit (VPD), air temperature (*T*), growing degree days (GDD) and crop age (AGE, days from sowing), as recorded in the experiments conducted in 2000 with semi-closed rockwool cultures of greenhouse tomato**

| | $W_U$ (mm d$^{-1}$) | LAI | R (MJ m$^{-2}$) | VPD (kPa) | T (°C) | GDD | AGE (d) |
|---|---|---|---|---|---|---|---|
| LAI | 0.48 | – | | | | | |
| R | 0.98 | 0.48 | – | | | | |
| VPD | 0.57 | 0.31 | 0.59 | – | | | |
| T | 0.56 | 0.63 | 0.57 | 0.38 | – | | |
| GDD | 0.31 | 0.83 | 0.32 | 0.11 | 0.78 | – | |
| AGE | 0.35 | 0.88 | 0.35 | 0.16 | 0.77 | 0.99 | – |

The coefficient not significant at least at $P \leq 0.05$ ($n$ = 158) is reported in italics.

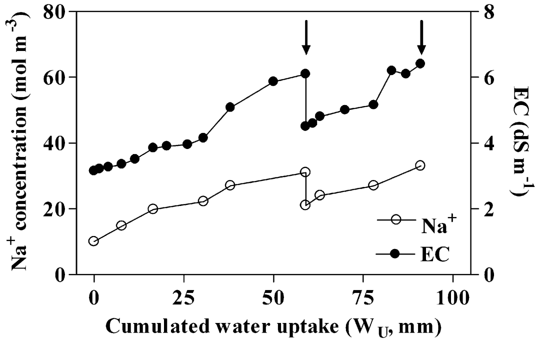


**Fig. 1 – Changes in the electrical conductivity (EC) and $Na^+$ concentration in the recycling nutrient solution of a semi-closed rockwool culture of greenhouse tomato, as a function of cumulated crop water uptake ($W_U$). The data refer to the culture conducted in spring 2001 using a nutrient solution with a NaCl concentration of 10 mol m$^{-3}$ (Experiment II-3). The arrows indicate when the recycling water was partially discharged and replaced by fresh nutrient solution. The values are means of three replicates.**

$Na^+$ concentration that took place in the recirculating nutrient solution, as a function of cumulative $W_U$; T10 treatment was chosen as an example. The progressive increase in the EC of the recycling water was associated with a concomitant rise in the concentration of $Na^+$ and, to a much lesser extent, of $Ca^{2+}$ and $Mg^{2+}$ (data not shown). As a matter of fact, the salinity buildup in the recycling water was mostly due to the accumulation of NaCl, since the molar concentrations of these ions were almost identical (data not shown). In the example illustrated in Fig. 1, the increase in NaCl concentration accounted for more than 70% of the increment measured in the EC, as estimated on the basis of the relationship between EC and molar concentration of NaCl (U.S. Salinity Laboratory Staff, 1954).

These results are in agreement with those found by Savvas et al. (2005) in closed substrate cultures of greenhouse cucumber conducted using irrigation water with NaCl concentration ranging from 0.8 to 15 mol m$^{-3}$; these authors observed similar kinetics for the accumulation of $Na^+$ and $Cl^-$ in the recycling nutrient solution, with a mutual molar ratio close to 1.0.

In the system under investigation, only the water in the mixing tank (i.e. $V_T$) was discharged. Therefore, after the first flushing event, which generally occurred 2–6 weeks after the beginning of the experiment, the values of EC and $Na^+$ concentration ($C^{min}$ in Eqs. (14) and (15)) were inevitably higher than the values in the refill nutrient solution (3.0 or 3.9 dS m$^{-1}$; 10 or 20 mol m$^{-3}$), on account of the salts retained by the substrate. On average, the measured EC and $Na^+$ concentration after flushing were around 4.5 and 6.0 dS m$^{-1}$ or 20 and 40 mol m$^{-3}$, in T10 and T20 treatment, respectively.

The composition of the nutrient solution influenced neither biomass accumulation nor fruit yield, as indicated by the results of Experiment I (Table 3); similar results were found in other experiments (data not shown). Moreover, a slight, but significant increment in the dry residue and total soluble solids of the fruits picked from the plants grown in T20 treatment was found (Table 3), as it was also observed in the spring cultures in 2001 and 2002 (data not shown).

No differences between T10 and T20 treatments were found for both LAI (Fig. 2) and $W_U$ (Fig. 3). $W_U$ was quite variable with a tendency to increase throughout the growing period as a consequence of LAI development and increasing $R$, at least in spring cultures.

In consideration of the absence of any important physiological effect of the two NaCl-enriched nutrient solutions, the data collected in both T10 and T20 treatments were grouped for model calibration and validation.

### 3.2. *LAI development and crop light interception*

The Boltzmann sigmoid equation was used to simulate the evolution of LAI as a function of GDD in Experiment I (Fig. 2). The derived equation was the following ($r^2 = 0.994$; $n = 11$):

$$\mathrm{LAI} = -0.335 + \frac{4.803 + 0.335}{1 + \exp[(755.3 - \mathrm{GDD})/134.7]} \tag{20}$$

This equation, which is valid for GDD values ranging from roughly 400 to 1600 GDD and for LAI up to 4.8, was used to estimate the daily values of LAI in validation experiments.

**Table 3 – Shoot (leaves and stems) dry biomass and fruit yield in semi-closed rockwool cultures of greenhouse tomato conducted in spring 2000 using two nutrient solutions differing for the concentration of NaCl: 10 mol m$^{-3}$ (T10) and 20 mol m$^{-3}$ (T20)**

| | T10 (10 mol m$^{-3}$ NaCl) | T20 (20 mol m$^{-3}$ NaCl) | Significance[a] |
|---|---|---|---|
| Shoot dry biomass (g plant$^{-1}$) | 366.0 ± 3.5 | 356.7 ± 5.0 | NS |
| Fruit yield (kg m$^{-2}$) | 10.1 ± 0.5 | 9.6 ± 0.3 | NS |
| Fruit number per square meter (Fruits m$^{-2}$) | 61.3 ± 2.4 | 65.2 ± 1.6 | NS |
| Average fruit weight (g) | 164.7 ± 2.1 | 147.2 ± 2.8 | * |
| Fruit dry residue (%) | 5.3 ± 0.2 | 5.8 ± 0.2 | * |
| Fruit total soluble solids (°Brix) | 4.3 ± 0.2 | 5.0 ± 0.2 | * |

The significance of the difference between means is reported (t-Student). The values are means ± S.D. of three replicates.
[a] NS, not significant.
* Significant ($P \le 0.05$).

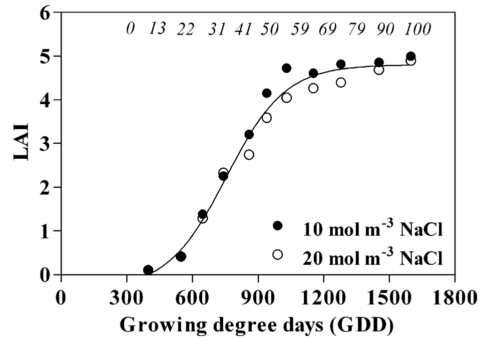


**Fig. 2 – The development of leaf area index (LAI) in semi-closed rockwool cultures of greenhouse tomato as a function of growing degree days (GDD). The experiment was conducted in spring 2000 using two nutrient solutions differing for the concentration of NaCl: 10 mol m$^{-3}$ (T10) and 20 mol m$^{-3}$ (T20). The values inside the graph indicate the time (days after transplanting) of sampling. The solid line represents the simulation model (Boltzmann sigmoid equation) developed for both sets of data, while the symbols are the measurements (means of three replicates).**

The measurements of light extinction within the crop canopy produced a value of $0.690 \pm 0.014$ ($n = 74$) for $k$ to be used in Eq. (6). This value is close to those reported for tomato by other authors (0.64, after Stanghellini, 1987; 0.70, after Marcelis et al., 1998).

### 3.3. Model calibration and validation

The relationship between crop $E$ and climate parameters in greenhouse crops was investigated by many authors (e.g. De Villele, 1974; Stanghellini, 1987; Jolliet and Bailey, 1992; Fernandez et al., 2001). The $W_U$ model considered in this study is a simplification of the $E$ model proposed by Baille et al. (1994) for ornamental crops, which was based on the $R$

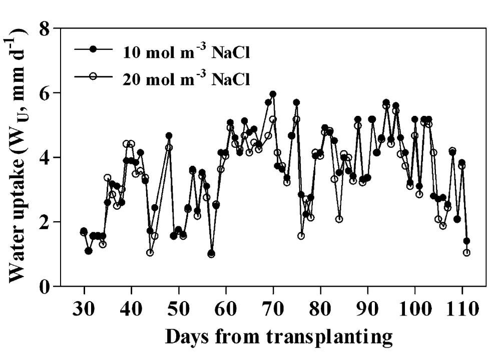


**Fig. 3 – The evolution of daily crop water uptake ($W_U$) in semi-closed rockwool cultures of greenhouse tomato. The experiment was conducted in spring 2000 using two nutrient solutions differing for the concentration of NaCl: 10 mol m$^{-3}$ (T10) and 20 mol m$^{-3}$ (T20). The values are means of three replicates.**

intercepted by the canopy and VPD. In fact, the model did not include VPD, which was significantly correlated to $R$ (Table 2). In the development of empirical regression model, it is a normal practice to limit the number of variables by omitting those that are closely correlated to others. Furthermore, the most likely application of the proposed model is the off-line (prior to greenhouse planting) estimate of crop water requirements and, in that case, only $R$ data may be available.

$W_U$ was closely correlated with $R$, $T$, LAI and VPD (Table 2). The values of parameters $A$ and $B$ in Eq. (6), as determined by regression analysis, were $0.946 \pm 0.016$ and $0.188 \pm 0.059$ mm d$^{-1}$, respectively; the determination coefficient was 0.980 ($n = 158$) and the standard error of the model ($\sigma_M$) was 0.259 mm. Therefore, the model considered an appreciable night-time $W_U$ (the intercept of Eq. (6)), which indeed reached values up to 10% of 24 h accumulated value (data not shown).

$W_U$ model was validated using the data from the experiments conducted in 2001 and 2002. The comparison between $P$ and $M$ values for the daily $W_U$ is reported in Fig. 4. The residuals, not shown for the sake of brevity, were distributed randomly with respect to the measures. The determination coefficient for the linear regression between $P$ and $M$ was 0.853 ($n = 581$), with the slope (0.963) and the intercept (−0.053) not significantly different, respectively, from 1 and 0. The value of EF was satisfactory (0.808), while CRM was 0.018, thus indicating a slight underestimation of $W_U$; RMSE was 0.25. Fig. 5 illustrates the results of simulation of $W_U$ for the experiments conducted in 2002. In general, there was a good agreement between $P$ and $M$ values.

In the $W_R$ model developed in this study, a linear relationship was supposed between the $C_U$ and the root zone concentration of $Na^+$. A linear dependence of $C_U$ on the external concentration was also observed by Sonneveld (2000) and Silberbush and Ben-Asher (2001), whereas an exponential relationship between these parameters was reported in other papers (Sonneveld, 2000; Savvas et al., 2005). The precise knowledge of how external concentration affects the plant uptake of non-essential ions, like $Na^+$ and $Cl^-$, may be important to improve any model designed to simulate the rate of salinity buildup in recirculating water soilless culture.

Using the data collected in previous or parallel works (some of them were published: Malorgio et al., 2001; Incrocci et al., 2006) with tomato plants grown in closed hydroponics using different substrates (rockwool, pumice and peat-perlite) or the nutrient film technique, the parameter $p$ was calculated, for intervals of 5–14 d during the same experiment, on the basis of the ratio between the $C_U$ of $Na^+$ and its concentration in the recycling nutrient solution. The ratio ranged from 0.10 to 0.30 and a value of 0.18 was selected for model validation, since it resulted in the best prediction of the $Na^+$ concentrations measured in the calibration experiments in both T10 and T20 treatment (data not shown). This value is roughly twice the one reported for tomato by Sonneveld (2000), but it is within the range (0.01–0.23) that the same author indicated for a number of greenhouse species cultivated in soilless culture.

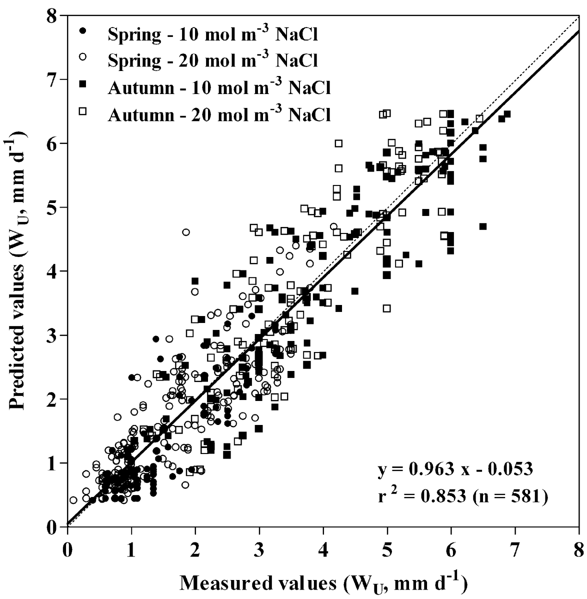


**Fig. 4 – Comparison between measured and predicted values of the daily water uptake ($W_U$) in different semi-closed rockwool cultures of greenhouse tomato conducted in spring or in autumn of two subsequent years (2001–2002) using two nutrient solutions differing for the concentration of NaCl: 10 mol m$^{-3}$ (T10) and 20 mol m$^{-3}$ (T20). Solid line represents linear regression, while dotted line is the 1:1 relationship. The values are means of three replicates.**

Table 4 reports the comparison between P and M values of LR and cumulative $W_U$, $W_R$ and W; for the experiments I-1 and I-2, P values of $W_U$ refer to the same data sets used for calibration. The expected LR, as calculated with Eq. (11), was compared with the LR determined as the ratio between the cumulative measurements of $W_R$ and $W_U$.

There was a good agreement between P and M values of $W_U$, with a mean deviation between P and M of $2 \pm 10\%$. The modelling of LR was less satisfactory, especially when spring crops were considered; the average value for P and M values of LR was 0.30 and 0.28, respectively. The P–M residual averaged (±S.D.) $11 \pm 25\%$ for LR and $13 \pm 26\%$ for $W_R$. Nevertheless, the aggregated model accounted well for W with an average deviation of $4 \pm 11\%$ between P and M.

### 3.4. *Sensitivity analysis*

The sensitivity analysis (Table 5) showed that R has the greatest influence on W, as it determines $W_U$. $W_U$ model also considers T, which affects the development of LAI. W decreases with increasing p, which is a measure of the plant's affinity for $Na^+$. However, the quality of irrigation water is more relevant than crop physiology. In fact, approximately a 10% increase in the $Na^+$ concentration of raw water results in a LR increase by 26%, whereas the same increase in p corresponds to a reduction of 11%. Finally, model outputs were slightly dependent on k and $V_T$.

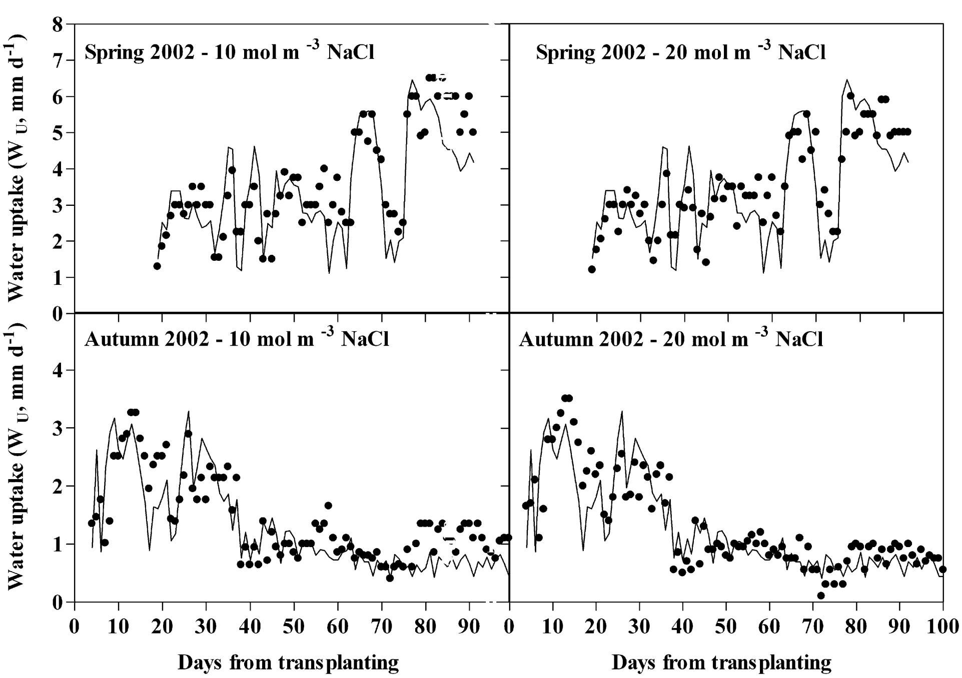


**Fig. 5 – Comparison between measured (symbols) and predicted (line) values of daily water uptake ($W_U$) in different semi-closed rockwool cultures of greenhouse tomato conducted in 2001 and 2002 using two nutrient solutions differing for the concentration of NaCl: 10 mol m$^{-3}$ (T10) and 20 mol m$^{-3}$ (T20). The values are means of three replicates.**

**Table 4 – Comparison between the measured (*M*) and predicted values (*P*) of water uptake ($W_U$), leaching requirement (LR), water runoff ($W_R$) and total water use (*W*) for different semi-closed rockwool cultures of greenhouse tomato conducted in spring 2000 and in spring or autumn 2001 and 2002 using two nutrient solutions differing for the concentration of NaCl: 10 mol m$^{-3}$ (T10) and 20 mol m$^{-3}$ (T20)**

| Experiment | NaCl concentration (mol m$^{-3}$) | $W_U$ (mm) | | | LR | | | $W_R$ (mm) | | | W (mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P | M | P–M (%) | P | M | P–M (%) | P | M | P–M (%) | P | M | P–M (%) |
| I-1 | 10 | 323 | 283 | 14.1 | 0.27 | 0.25 | 6.1 | 87 | 72 | 21.1 | 410 | 355 | 15.6 |
| I-2 | 20 | 323 | 269 | 20.1 | 0.33 | 0.32 | 3.2 | 107 | 86 | 23.9 | 430 | 355 | 21.0 |
| II-3 | 10 | 272 | 274 | −0.7 | 0.27 | 0.18 | 51.0 | 73 | 49 | 49.9 | 345 | 323 | 6.9 |
| II-4 | 20 | 272 | 264 | 3.0 | 0.33 | 0.24 | 38.3 | 90 | 63 | 42.5 | 362 | 327 | 10.6 |
| III-5 | 10 | 237 | 231 | 2.6 | 0.27 | 0.33 | −19.0 | 64 | 77 | −16.9 | 301 | 308 | −2.3 |
| IV-6 | 10 | 252 | 267 | −5.6 | 0.27 | 0.21 | 28.7 | 68 | 56 | 21.5 | 320 | 323 | −0.9 |
| IV-7 | 20 | 252 | 257 | −1.9 | 0.33 | 0.27 | 21.2 | 83 | 70 | 18.8 | 335 | 327 | 2.5 |
| V-8 | 10 | 122 | 136 | −10.3 | 0.27 | 0.31 | −12.6 | 33 | 42 | −21.6 | 155 | 178 | −13.0 |
| V-9 | 20 | 122 | 127 | −3.9 | 0.33 | 0.39 | −14.5 | 40 | 49 | −17.8 | 162 | 176 | −7.8 |
| | Mean (±S.D.) | 242 ± 74 | 234 ± 60 | 2 ± 10 | 0.30 ± 0.03 | 0.28 ± 0.07 | 11 ± 25 | 72 ± 24 | 63 ± 15 | 13 ± 26 | 313 ± 97 | 297 ± 70 | 4 ± 11 |

For the experiments I-1 and I-2, P values of $W_U$ refer to the same data sets used for calibration.

**Table 5 – Sensitivity analysis for the models of water requirements of a semi-closed rockwool culture of greenhouse tomato**

| | $W_U$ model | | LR model | W model |
|---|---|---|---|---|
| | Maximum LAI | $W_U$ (mm) | LR | W (mm) |
| Reference output | 4.82 | 238.9 | 0.20 | 287.1 |
| Partial sensitivity | | | | |
| *T* | 0.018 | – | – | 0.054 |
| *k* | – | 0.182 | – | 0.182 |
| *R* | – | 0.955 | – | 0.955 |
| $V_T$ | – | – | 0.053 | 0.009 |
| $C_R$ | – | – | 2.586 | 0.434 |
| *p* | – | – | −1.144 | −0.192 |

The values represent the outputs of the model in reference conditions and their partial sensitivity [δO/O/δI/I, see Eq. (19)] to a change in inputs. The reference conditions were the following: growing period of 70 d with constant values of *T* (21.8 °C) and *R* (9.6 MJ m$^{-2}$); $C_R$, 15 mol m$^{-3}$; $C^{max}$, 50 mol m$^{-3}$; $V_S$, 9 mm; $V_T$, 5 mm.

## 4. Conclusions

Using both empirical and mechanistic approach, an aggregated model was built, calibrated and validated to simulate how much water is needed for recycling water culture of greenhouse tomato carried out under saline conditions.

In spite of its simplicity, the model appeared suitable for the simulation of $W_U$, $W_R$ and then *W* in tomato cultures conducted in different seasons and with different NaCl concentrations of irrigation water. As expected, the sensitivity analysis showed the great influence of radiation on *W* and suggested that the quality of irrigation water (namely, NaCl concentration) is more relevant for crop water use efficiency than any other factor considered by the LR model, including the affinity of the plant for the ballast ions contained in the nutrient solution, which is represented by *p* (Eqs. (8)–(14)).

The method proposed in this paper could be applied to any crop for which a suitable transpiration model is available and/or to any ion in the raw water that is scarcely absorbed by the crop. The implementation of LAI and $W_u$ equations valid for a wider range of growing conditions may improve the generality of the model and extend its appliance to the assessment of the water use efficiency and runoff of semi-closed soilless culture.

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## REFERENCES


Adams, P., 1987. The test of raised salinity. Grower 107 (2), 23–27.
Baas, R., Berg, D., 1999. Sodium accumulation and nutrient discharge in recirculation systems: a case study with roses. Acta Hort. 507, 157–164.
Baille, M., Baille, A., Laury, J.C., 1994. A simplified model for predicting evapotranspiration rate of nine ornamental species vs climate factors and leaf area. Sci. Hort. 59, 217–232.
Carmassi, G., Incrocci, L., Maggini, R., Malorgio, F., Tognoni, F., Pardossi, A., 2005. Modelling salinity buildup in recirculating nutrient solution culture. J. Plant Nutr. 28, 431–445.
De Villele, O., 1974. Besoins en eau des cultures sous serres. Essai de conduite des arrosages en fonction de l'ensoleillement. Acta Hort. 35, 123–135.
Fernandez, M.D., Orgaz, F., Fereres, E., Lopez, J.C., Cespedes, A., Perez-Parra, J., Bonachela, S., Gallardo, M., 2001. Programacion del riego de cultivos horticolas bajo invernadero en el sudeste español. Cajamar (Caja Rural Intermediterranea), Almeria, España, 78 pp.
Fila, G., Bellocchi, G., Acutis, M., Donatelli, M., 2003. IRENE: a software to evaluate model performance. Eur. J. Agron. 18, 369–372.
Heuvelink, E., 1999. Evaluation of a dynamic simulation model for tomato crop growth and development. Ann. Bot. 83, 413–422.
Incrocci, L., Malorgio, F., Della Bartola, A., Pardossi, A., 2006. The influence of drip irrigation and subirrigation on tomato grown in closed-loop substrate culture with saline water. Sci. Hort. 107, 365–372.
Jolliet, O., Bailey, B.J., 1992. The effect of climate on tomato transpiration in greenhouse: measurements and models comparison. Agr. Forest Meteorol. 58, 43–62.
Li, Y.L., Stanghellini, C., 2001. Analysis of the effect of *EC* and potential transpiration on vegetative growth of tomato. Sci. Hort. 89, 9–21.
Maas, E.V., Hoffman, G.J., 1977. Crop salt tolerance. Current assessment. J. Irrig. Drain. Div. 103 (IR2), 115–134.
Malorgio, F., Incrocci, L., Carmassi, G., Pardossi, A., Tognoni, F., 2001. Accumulo di sali (NaCl) e consumo minerale in pomodoro coltivato in sistemi idroponici a ciclo chiuso. Italus Hortus 8 (6), 43–48.
Marcelis, L.F.M., Heuvelink, E., Goudrian, J., 1998. Modelling biomass production and yeld of horticultural crops: a review. Sci. Hort. 74, 83–111.
Motulsky, H., Christopoulos, A., 2003. Fitting models to biological data using linear and nonlinear regression. A practical guide to curve fitting. GraphPad Software Inc., San Diego, CA http://www.graphpad.com.
Navarro, J.M., Botella, M.A., Martinez, V., 1999. Yield and fruit quality of melon plants grown under saline conditions in relation to phosphate and calcium nutrition. J. Hort. Sci. Biotechnol. 74 (5), 573–578.
Nobel, P.S., Long, S.P., 1985. Canopy structure and light interception. In: Coombs, J., Hall, D.O., Long, S.P., Scurlock, J.M.O. (Eds.), Techniques in Bioproductivity and Photosynthesis. Pergamon Press, Oxford, pp. 41–49.
Pardossi, A., Malorgio, F., Incrocci, L., Tognoni, F., 2005. Hydroponic technologies for greenhouse crops. In: Ramdane, D. (Ed.), Crops: Quality, Growth and Biotechnology. WFL Publisher, Helsinki, pp. 360–378.
Romero, A.R., Soria, T., Cuartero, J., 2001. Tomato plant water uptake and plant water relationships under saline growth conditions. Plant Sci. 160 (2), 265–272.
Savvas, D., Meletiou, G., Margariti, S., Tsirogiannis, I., 2005. Modelling the relationship between water uptake by Cucumber and NaCl accumulation in a closed hydroponic system. Hortscience 40, 802–807.
Shannon, M.C., Grieve, C.M., 1999. Tolerance of vegetables crops to salinity. Sci. Hort. 78, 5–38.
Silberbush, M., Ben-Asher, J., 2001. Study of nutrient uptake by plants from soilless cultures as affected by salinity buildup and transpiration. Plant Soil 233, 59–69.
Sonneveld, C., 2000. Effect of salinity on substrate grown vegetables and ornamentals in greenhouse horticulture. Ph.D. Thesis. Wageningen University, 151 pp.
Stanghellini, C., 1987. Transpiration of greenhouse crops. An aid to climate management. PhD Thesis. Wageningen Agricultural University, the Netherlands, 150 pp.
Thornley, J.H.M., Johnson, I.R., 1990. Plant and Crop Modelling. A Mathematical Approach to Plant and Crop Physiology. Clarendon Press, Oxford, 670 pp.
United States Salinity Laboratory Staff, 1954. Diagnosis and improvement of saline and alkali soils, Agricultural Handbook No. 60. US Department of Agriculture, US Government Printer, Washington.