

# Simulhydro, a Simulation Tool for Water and Mineral Relations of Greenhouse Soilless Culture

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**Cover photos:** Left, Basil grown in a floating system (soilless) in a plastic greenhouse; right, a soilless rose cultivation in a plastic greenhouse.

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# **SIMULHYDRO, A SIMULATION TOOL FOR WATER AND MINERAL RELATIONS OF GREENHOUSE SOILLESS CULTURE**

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## Abstract

SIMULHYDRO is an EXCEL™ spreadsheet developed only for expert users: it could be used to calculate the water and nutrient use efficiency using different water sources, fertilization strategies and water wasting options of a semi-closed and open soilless greenhouse crop.

SIMULHYDRO contains a composite model developed for calculating water and mineral relations of greenhouse crops grown in semi-closed or open substrate culture. The model simulated on a daily basis: i) the evolution of crop leaf area index and water uptake using empirical equations; ii) the variations of ion concentrations and electrical conductivity the recirculating or drainage nutrient solution using a mass balance equation based on the concept of ion uptake concentration. The model was calibrated and validated using results from a series of experiments conducted with tomato at University of Pisa using saline water and different fertigation strategies. The model could be used for operative management of soilless culture, assessment of water use and nutrient leaching, and scenario analysis of different cropping practices. The model is currently implemented in an Excel spreadsheet that is freely available to interested users. In this document, the rationale and the structure of the proposed model is illustrated along with quick guide to the use of software.



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## INTRODUCTION

Awareness of the pollution associated with intensive agriculture forces greenhouse growers to adopt more environment-friendly cultivation methods, such as closed soilless culture and biological control of pests and diseases. Closed soilless growing systems, in which drainage water is captured and recirculated, reduce water consumption and nutrient leaching. However, commercial application of these systems is scarce, as their management is more difficult compared with open (free-drainage) cultivation systems.

Alongside the possible diffusion of root-borne diseases, the salinity of irrigation water is the main difficulty for the management of closed systems. In fact, non-essential (ballast) ions (e.g.  $Na^+$  and  $Cl^-$ ) dissolved in the irrigation water at concentration higher than uptake concentration ( $C_U$ , the ratio between the ions and the water taken up by the plants; see Nomenclature for abbreviations) accumulates in the root zone. This makes it necessary to discharge, more or less frequently, the recirculating nutrient solution, thus resulting in water and nutrient losses. The term 'semi closed' is used for these systems. In the Netherlands, where closed growing systems are compulsory, the discharge of recirculating nutrient solution is allowed whenever  $Na^+$  concentration reaches a crop-specific threshold, for example:  $8 \text{ mol m}^{-3}$  for tomato and  $5 \text{ mol m}^{-3}$  for lettuce (Stanghellini et al., 2007). In semi-closed systems, leaching fraction ( $LF$ , the percent ratio between supply and drainage water) may range from 20% to 30%, as it occurs commonly in well-managed open systems.

Closed growing systems are commonly operated by adjusting the composition of the refill water based on continuous measurements of  $EC$  and  $pH$ , and on irregular chemical analysis of the recirculating nutrient solution. These analyses can be performed in the laboratory by time-consuming methods or in situ using expensive chemo-sensors or quick tests. Alternatively, simulation models can contribute to improved fertigation control by considering variations in the ionic composition of the recirculating nutrient solution.

A composite model was designed for water and mineral relations of greenhouse tomato grown in substrate (rockwool) culture using different fertigation strategies. The composite model uses a mass balance equation based on the concept of  $C_U$  (Savvas, 2002; Sonneveld, 2000) to estimate the composition of the nutrient solution recirculated in closed-systems or drained out from open system. Crop leaf area index ( $LAI$ ) and water uptake ( $W_U$ ) are predicted using the empirical models reported by Carmassi et al. (2007). In addition, original equations are used to estimate: i) the amount of nutrients supplied according to fertigation control strategy; ii) salt leaching due to free-drainage irrigation applied to semi-closed systems in occasion of nutrient solution discharge (flushing).

In compliance with standard requirements of crop modelling (Robson et al. 2008), the model was calibrated with data collected in previous works and validated in two independent experiments conducted in 2005 and 2007 (Massa et al., 2010, 2011). In these experiments, different fertigation strategies were tested and nutrient solutions were prepared using saline ( $9.5 \text{ mol m}^{-3} \text{ NaCl}$ ) water.

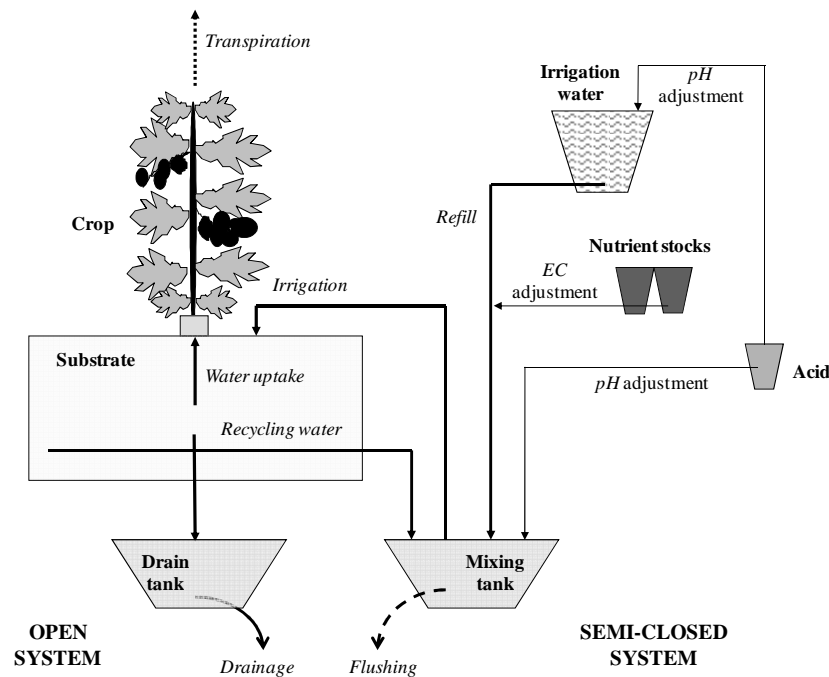
The composite model could be implemented in a decision support system (DSS) for fertigation management in soilless culture management (e.g. Bacci et al., 2005; Elings et al., 2004; van Straten et al., 2006). In addition, the model could enable local assessment of water withdrawal and fertiliser leaching in greenhouse crops or scenario analysis of different cropping practices. In The

Netherlands, the current legislation imposes limits to the amount of irrigation water that may be applied to greenhouse crops (for instance, 1140 Lm<sup>-2</sup> in tomato culture; Stanghellini et al., 2007). Simulation models of both water uptake ( $W_U$ ) and  $W_L$  may be useful tools for both growers (for efficient water management at the farm gate) and policy makers (for instance, for establishing limits to water and fertiliser application). The model could be also used to estimate emission of plant protection products applied to the crop through recirculating nutrient solution. These emissions depend on dissipation kinetics and root uptake of the substance under consideration, and on the frequency of discharging recirculation water (van der Linden, 2009; Vermeulen et al., 2010).

The model is currently implemented in an Excel spreadsheet and work in progress to develop a user-friendly executable program is underway. This paper reports both model structure and quick user guide.

## GROWING SYSTEM AND FERTIGATION STRATEGY

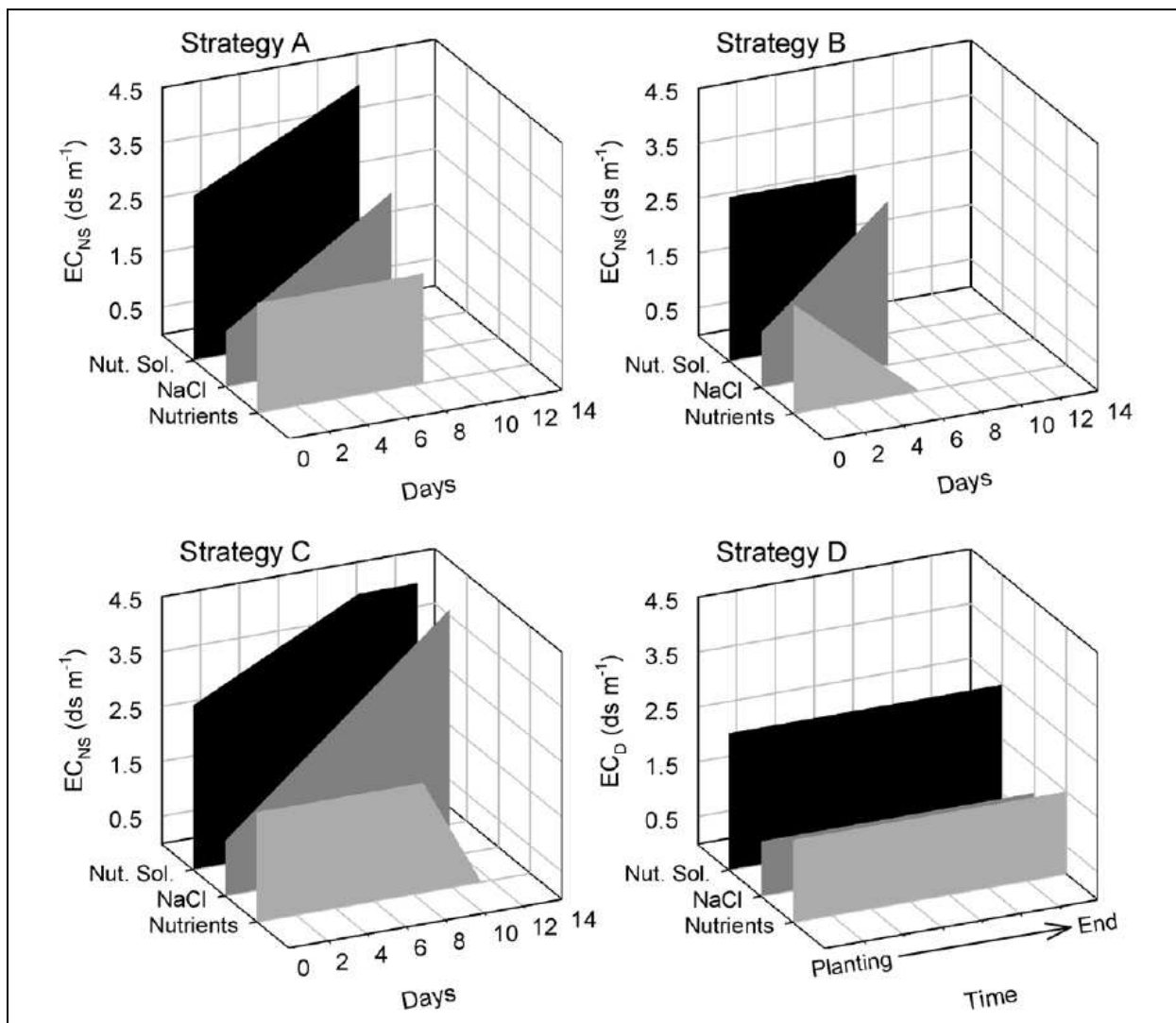
In the growing system considered by the composite model, (Figure 1), total volume of nutrient solution ( $V_{NS}$ ) is the sum of the one contained in the substrate ( $V_S$ ) and in the mixing tank ( $V_T$ ) collecting drainage water. The mixing tank was refilled with newly-prepared nutrient solution to compensate for crop water uptake ( $W_U$ ). Both ion concentration ( $C_{RNS}$ ) and  $EC$  ( $EC_{RNS}$ ) of the refill nutrient solution depended on fertigation strategy, which also defined the conditions for flushing in semi-closed systems. Open system was identical to the semi-closed ones, without the capture of drainage water.



**Fig. 1.** Schematic description of the substrate growing systems used for greenhouse experiments and model simulation. Plants are irrigated with the nutrient solution contained in the mixing tank, which was automatically refilled with nutrient solution or raw water (depending on the fertigation strategy). In semi-closed systems, the recirculating nutrient solution is periodically discharged (flushing). In open system, the drainage water from the substrate is not recirculated.

In all systems, reference (full-strength) nutrient solution is prepared by dissolving appropriate volumes of two stock solutions in pH-controlled irrigation water. The dilution ratio ( $r$ ) of stock solutions is generally 1 to 100 or 200 1:100 ( $r = 0.01$  or  $0.02$ ). Ion composition and  $EC$  of reference nutrient solutions ( $C_{NS}^{REF}$  and  $EC_{NS}^{REF}$ ) and irrigation water ( $C_{IW}$  and  $EC_{IW}$ ) used in the validation experiments are given in Table 2. In these experiments, different  $EC_{NS}^{REF}$  and  $C_{NS}^{REF}$  were used during early developmental stage (Stage I) and in the following period (Stage II), which initiated after the plants were top cut above the fifth truss (i.e. 54 days after planting; (Table 2).

The strategies under investigation are illustrated below and in Fig. 2; the values of some parameters used for each strategy in the validation experiments are also presented in Table 1.



**Fig.2.** Schematic illustration of the four fertigation strategies simulated by SIMULHYDRO. The graphs show the contribution of nutritive ions and  $Na^+$  to the electrical conductivity of the recirculating nutrient solution ( $EC_{NS}$ ) or of the drainage ( $EC_D$ ) in semi-closed systems (strategies A,B,C) or in open system (Strategy D).



**Table 1.** Basic parameters of the fertigation strategies used in semi-closed (Strategies A, B; C and E) or open (Strategy D) soilless cultures of greenhouse tomato conducted in 2005 and 2007 for model validation. See Nomenclature for abbreviations.

	Experiment I (2005)			
	Strategy A	Strategy B	Strategy C	Strategy D
$EC_{NS}^{REF}$ (dS m <sup>-1</sup> )	2.64/2.31*	2.64/2.31*	2.64/2.31*	2.64/2.31*
$EC_{NS}^{SP}$ (dS m <sup>-1</sup> )	3.00	3.00	3.00	-
$EC_{NS}^{MAX}$ (dS m <sup>-1</sup> )	4.50	-	4.50	-
$C_{NS}^{F,NO_3^-}$ (mol m <sup>-3</sup> )	-	<1.0	<1.0	-
$V_W$ (L m <sup>-2</sup> )	12.0	12.0	12.0	-
$V_D$ (L m <sup>-2</sup> )	18.0	18.0	18.0	-
$EC_D$ (dS m <sup>-1</sup> )	-	-	-	3.00/2.70*
	Experiment II (2007)			
	Strategy C(1)	Strategy (C2)		
$EC_{NS}^{REF}$ (dS m <sup>-1</sup> )	2.68	2.68		
$EC_{NS}^{SP}$ (dS m <sup>-1</sup> )	4.50	3.50		
$EC_{NS}^{MAX}$ (dS m <sup>-1</sup> )	6.50	7.50		
$C_{NS}^{F,NO_3^-}$ (mol m <sup>-3</sup> )	<1.0	<1.0		
$V_W$ (L m <sup>-2</sup> )	3.0	9.0		
$V_D$ (L m <sup>-2</sup> )	9.0	15.0		

\* The values refer to crop stage I and II, respectively.

*Strategy A.* The mixing tank is replenished with reference nutrient solution (Table 2) in order to maintain a constant  $C_{NS}$  of the macronutrients. Because of the accumulation of  $NaCl$ ,  $EC$  of the recirculating nutrient solution ( $EC_{NS}$ ) tends to rise up. When a ceiling value ( $EC_{NS}^{MAX}$ ) is reached, the nutrient solution in the mixing tank is discharged. Then, the plants are irrigated with a pre-definite volume ( $V_W$ ) of acidified water without drainage recirculating, with the aim of leaching the salts accumulated in the substrate. Therefore, the volume of water discharged ( $V_D$ ) on each occasion is the sum of  $V_T$  and  $V_W$ . After flushing,  $EC_{NS}$  is adjusted to a target  $EC$  ( $EC_{NS}^{SP}$ ) by adding proper doses of stock solutions to the mixing tank.

*Strategy B.* In order to maintain a given  $EC_{NS}^{SP}$ ,  $W_U$  is compensated with refill nutrient solution having variable  $EC_{RNS}$ . In this system,  $EC_{RNS}$  tends to decrease with time because of  $NaCl$  accumulation, thus resulting in progressive depletion of macronutrient content until  $C_{NS}^{NO_3^-}$  drops below a critical concentration, when the nutrient solution was discharged in the same way as in

Strategy A. In the validation experiments, a value of  $1.0 \text{ mol m}^{-3}$  was selected because  $20 \text{ mgL}^{-1}$  ( $1.42 \text{ mol m}^{-3}$ ) is the limit imposed to the  $\text{NO}_3^-$  concentration of wastewater discharged into surface water by the current Italian legislation (Decree 152/2006) associated with the implementation of European Nitrate Directive (The Council of the European Communities, 1991).

Strategy C. The mixing tank is refilled with reference nutrient solution until  $EC_{NS}^{MAX}$  (Table 1) is reached; afterwards, it is filled up with acidified water for a few days. When  $C_{NS}^{NO_3^-}$  decreases below  $1.0 \text{ mol m}^{-3}$ , the nutrient solution is discharged as previously described.

Strategy D. The crop is irrigated with reference nutrient solution and without recirculating drainage water. A large  $LF$  ( $>50\%$ ) should be used to maintain the  $EC$  of drainage water ( $EC_D$ ) close to the value of fertigation water.

## MODEL OUTLINE

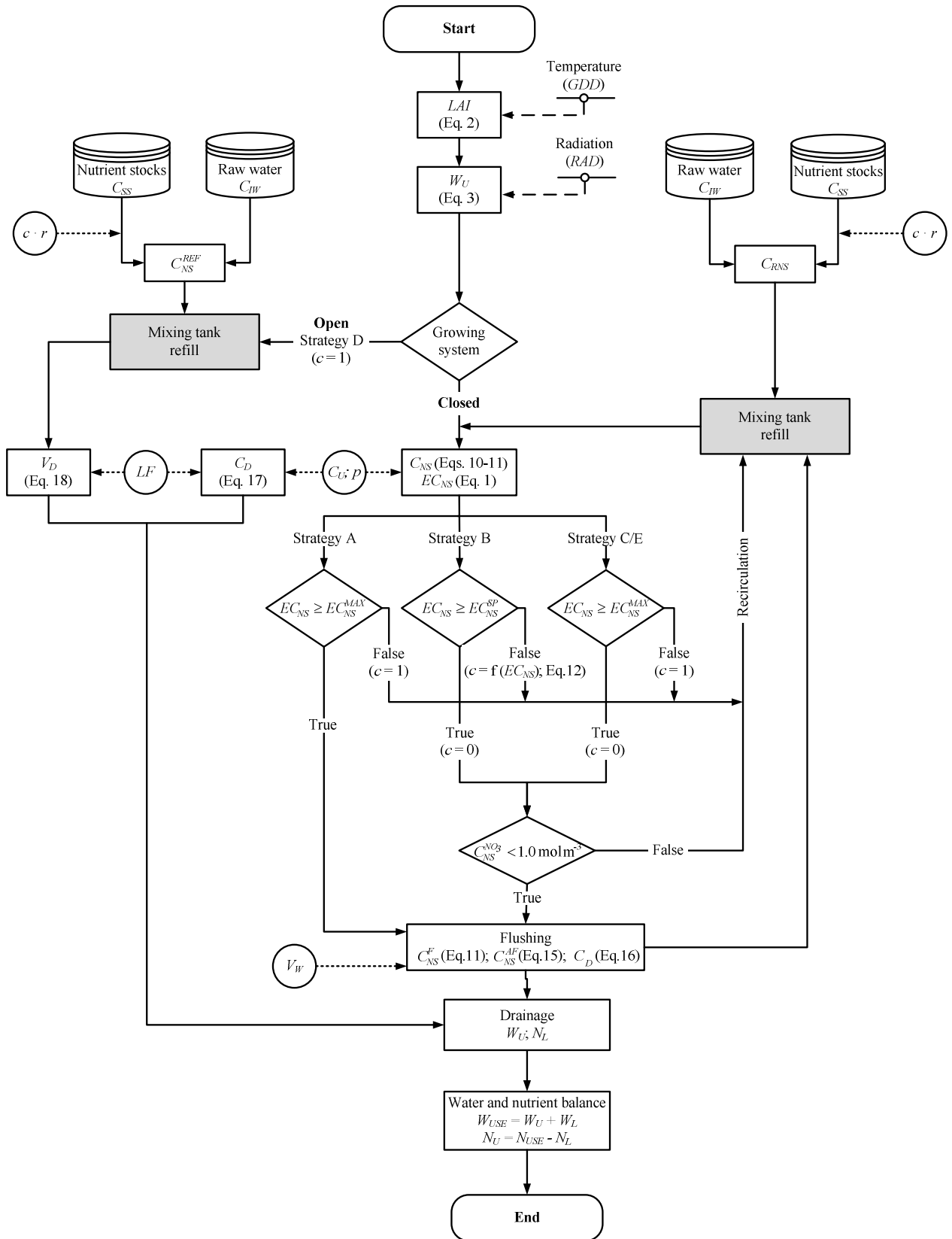
The model consists of some modules that estimate, on a day to day basis,  $LAI$ ,  $W_U$  and the concentrations of both nutritive and ballast ions in the nutrient solution that is recirculated in semi-closed systems or drained out from open system (Figure 2). Seasonal balance sheets for water and nutrients are also computed (Figure 2). The model involves some inherent assumptions, which were verified in some experiments at University of Pisa (Carmassi et al., 2005, 2007; Incrocci et al., 2006; Massa et al., 2011):

- i) leaf growth, plant transpiration and nutrient uptake are not affected by the salinity levels considered by simulation.
- ii) In all growing systems,  $V_T$ ,  $V_S$  and thereby  $V_{NS}$  remain fairly constant due to frequent tank replenishment and over-irrigation ( $LF > 50\%$ ). For the same reasons, the differences between  $C_S$  and  $C_{NS}$  (semi-closed systems) or  $C_D$  (open system) is negligible.
- iii) Irrigation water is the only source of ballast ions (e.g.  $\text{Na}^+$ ,  $\text{Cl}^-$  and  $\text{HCO}_3^-$ ), because high-purity soluble fertilisers are used.
- iv) The cationic-anionic balance maintains the electro-neutrality of irrigation water and nutrient solution (Sonneveld and Voogt, 2009). Therefore,  $EC$  of nutrient solution samples can be calculated from the sum of valences ( $CAT$ ,  $\text{mol m}^{-3}$ ) of  $\text{Ca}^{2+}$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$  and  $\text{Na}^+$  according to the formula proposed by Sonneveld (2000) and validated by Carmassi et al. (2005):

$$EC = 0.19 + 0.095 \cdot CAT \quad (1)$$

- v) The contribution of trace elements (Table 2) and  $\text{H}^+$  to  $EC$  is negligible because their concentrations are of the order of  $10^{-2} \text{ mol m}^{-3}$  ( $pH$  was invariably higher than 5.0).

In the validation experiments,  $C_{NS}^{REF}$  of individual macronutrients (Table 2) was equal or close to the corresponding  $C_U$ , which were determined in previous experiments with the same tomato cultivar grown in comparable conditions (L. Incrocci and D. Massa, unpublished data). The values of  $C_U^{NO_3^-}$ ,  $C_U^{H_2PO_4^-}$ ,  $C_U^{K^+}$ ,  $C_U^{Ca^{2+}}$  and  $C_U^{Mg^{2+}}$  were, respectively, the following: 10.00, 1.00, 6.70, 3.55 and  $0.60 \text{ mol m}^{-3}$ , in Stage I; 7.00, 0.70, 4.70, 2.80 and  $0.45 \text{ mol m}^{-3}$ , in Stage II.



**Fig. 3.** Relational diagram of the composite model used for simulating water and mineral relations of greenhouse tomato plants grown in semi-closed (Strategies A, B, C and E) or open substrate cultures (Strategy D). See Nomenclature for the list of symbols and abbreviations.

### Leaf area index and crop water uptake

Leaf area index is assumed to obey a sigmoid function of accumulated thermal time (expressed as growing degree days, *GDD*):

$$LAI = a_1 + \frac{(a_2 - a_1)}{1 + e^{\left(\frac{a_3 - GDD}{a_4}\right)}} \quad (2)$$

where  $a_1$  (-0.335),  $a_2$  (4.803),  $a_3$  (755.3) and  $a_4$  (134.7) are regression coefficients.

Thermal time is computed from  $T$  using a basal temperature of 8°C for tomato (Thornley and Johnson, 1990). Eq. 2 is valid for *GDD* ranging from 400 (approximately the value at transplanting) to 1600 and for *LAI* up to 4.8.

Crop water uptake is modelled as a function of *LAI* and *RAD* intercepted by the crop canopy:

$$W_U = b_1 \cdot (1 - e^{-k \cdot LAI}) \cdot \frac{RAD}{\lambda} + b_2 \quad (3)$$

where  $b_1$  (0.946, dimensionless) and  $b_2$  (0.188 L m<sup>-2</sup>) are empirical constants,  $k$  is the canopy light extinction coefficient (0.69; Carmassi et al. 2007), and  $\lambda$  (2.45 MJ Kg<sup>-1</sup>) is the latent heat of water vaporization.

**Table 2.** The concentration (mol m<sup>-3</sup>) of individual ions and electrical conductivity (*EC* ; dS m<sup>-1</sup>) of irrigation water and reference (full-strength) nutrient solutions used in two experiments conducted in 2005 and 2007 with greenhouse tomato grown in soilless culture. Stage II initiated after the plants were cut above the fifth truss, that is 54 (2005) or 76 (2007) days after planting. Concentrations of  $NO_3^-$ ,  $H_2PO_4^-$  and  $K^+$  of irrigation water were below the detection limits. Nutrient solutions contained the following concentrations of micronutrients: 40.6 mmol m<sup>-3</sup>  $Fe^{3+}$ ; 35.0 mmol m<sup>-3</sup>  $H_2BO_3^-$ ; 4.6 mmol m<sup>-3</sup>  $Zn^{2+}$ ; 3.6 mmol m<sup>-3</sup>  $Cu^{2+}$ ; 10.9 mmol m<sup>-3</sup>  $Mn^{2+}$ .

	$NO_3^-$	$H_2PO_4^{-*}$	$SO_4^{2-}$	$HCO_3^-$	$K^+$	$Ca^{2+}$	$Mg^{2+}$	$Na^+$	<i>EC</i>
Experiment I (2005)									
Irrigation water	-	-	0.04	4.52	-	1.50	0.80	9.50	1.53
Nutrient solution (stage I)	10.00	1.00	2.37	0.56	6.70	4.00	0.80	9.50	2.64
Nutrient solution (stage II)	7.00	0.70	2.27	0.56	4.70	3.25	0.80	9.50	2.31
Experiment II (2007)									
Irrigation water	-	-	0.04	4.92	-	1.50	1.00	9.50	1.57
Nutrient solution (stage I and II)	10.0	1.00	2.51	0.61	6.70	4.00	1.00	9.50	2.68

\*In the weakly-acid nutrient solutions used in soilless culture,  $HPO_2^-$  is the prevalent form of phosphate.

### *Ion concentration of recirculating nutrient solution in semi-closed systems*

A mass balance approach is used to predict the change in  $C_{NS}$  of each ion over the period  $n$  and  $n-1$  (day):

$$\Delta C = C_{NS,n} - C_{NS,n-1} = (C_{RNS} - C_U) \cdot \frac{W_U}{V_{NS}} \quad (4)$$

Then:

$$C_{NS,n} = C_{NS,n-1} + (C_{RNS} - C_U) \cdot \frac{W_U}{V_{NS}} \quad (5)$$

In Eq. 5, the initial condition for  $\frac{W_U}{V_{NS}} = 0$  is  $C = C_{NS}^{REF}$  at the beginning of cultivation and  $C = C_{NS}^{SP}$  after each flushing.

If  $C_U$  of a given ion is not constant, it does not accumulate linearly with  $W_U$ , as predicted by Eq. 4, and thereby a different function must be used.  $C_U^{Na^+}$  is assumed to be proportional to its  $C_{NS}$ :

$$C_U = p \cdot C_{NS} \quad (6)$$

The value of  $p$  used for model validation was 0.18 (Carmassi et al., 2005).

As  $C_{RNS}^{Na^+}$  is equal to  $C_{IW}^{Na^+}$ , substituting Eq. 6 in Eq. 4 yields the following equation, after rearrangement:

$$\frac{(C_{NS,n} - C_{NS,n-1})}{\frac{W_U}{V_{NS}}} = C_{IW} - p \cdot C_{NS} \quad (7)$$

Eq. 7 can be written in a differential form for small increments of  $C_{NS}$  ,:

$$\frac{dC_{NS}}{d\left(\frac{W_U}{V_{NS}}\right)} = C_{IW} - p \cdot C_{NS} \quad (8)$$

The integration of Eq. 8, with the initial conditions  $C_{NS} = C_{IW}$  for  $\frac{W_U}{V_{NS}} = 0$ , leads to the following expression:

$$C_{NS,n} = \left( C_{IW} - \frac{C_{IW}}{p} \right) \cdot e^{\left( -p \cdot \frac{W_U}{V_{NS}} \right)} + \frac{C_{IW}}{p} \quad (9)$$

where  $C_{NS,n}$  is ion concentration in the recirculating solution at step  $n$ .

Ion concentrations at steps  $n-1$  and  $n$  can be estimated using Eq. 9; 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:

$$C_{NS,n} = \left( C_{NS,n-1} - \frac{C_{IW}}{p} \right) \cdot e^{\left( -p \cdot \frac{W_U}{V_{NS}} \right)} + \frac{C_{IW}}{p} \quad (10)$$

For  $NO_3^-$  and other nutrients,  $C_{NS}$  is calculated with Eq. 5. In this equation, the term  $C_{RNS}$  has two components:  $C_{IW}$ , which is assumed to be constant; the ion concentration ( $r \cdot C_{SS}$ ) resulting from stock solution injection.

The correction factor ( $c$ ) for dilution of nutrient stocks depends on fertigation strategy. Hence, Eq. (5) can be rewritten as:

$$C_{NS, n} = C_{NS, n-1} + (c \cdot r \cdot C_{SS} + C_{IW} - C_U) \left( \frac{W_U}{V_{NS}} \right) \quad (11)$$

In Strategy A, where  $W_U$  is compensated with reference nutrient solution (i.e.  $C_{RNS} = C_{RNS}^{REF}$ ),  $c$  is 1. In Strategy C and E,  $c$  is 1 and 0, respectively, before and after  $EC_{NS}^{MAX}$  is reached. In Strategy B,  $c$  is calculated for each replenishment of the mixing tank using

$$c = \begin{cases} \frac{(EC_{NS}^{SP} - EC_{NS, n-1})}{(EC_{NS}^{REF} - EC_{IW})} & \text{if } EC_{NS, n-1} \leq EC_{NS}^{SP} \\ 0 & \text{if } EC_{NS, n-1} > EC_{NS}^{SP} \end{cases} \quad (12)$$

where the  $EC_{NS, n-1}$  is computed from  $C_{NS, n-1}^{CAT}$  with Eq. 1.

As  $EC_{NS, n-1}$  increased due to progressive accumulation of ballast ions,  $c$  tended to 0 in Strategy B.

#### *Ion concentration of the recirculating water after flushing*

In semi-closed systems, ion concentration in the recirculating nutrient solution after flushing ( $C_{NS}^{AF}$ ) is estimated using

$$C_{NS}^{AF} = C_{IW} \cdot \frac{V_T}{V_{NS}} + C_S^{AF} \cdot \frac{V_S}{V_{NS}} \quad (13)$$

where  $C_S^{AF}$  is the ion concentration of the water remaining in the substrate after washing.

The latter quantity is calculated from the concentration in the substrate before flushing ( $C_S^F$ ) and  $V_W$ :

$$\frac{dC}{dV_W} + \frac{C_S^F}{V_S} = \frac{C_{IW}}{V_S} \quad (14)$$

The integration of Eq. 14, with  $C = C_S^{Fl}$  for  $\frac{V_W}{V_S} = 0$ , leads to:

$$C_S^{AF} = C_{IW} + (C_S^F - C_{IW}) \cdot e^{\left( \frac{-V_W}{V_S} \right)} \quad (15)$$

Thus, the model estimates the volume ( $V_{SS}$ ) of stock solutions used to adjust  $EC_{NS}^{AF}$  to  $EC_{NS}^{SP}$  and ion composition of the new nutrient solution.

### *Ion concentration in the drainage nutrient solution from semi-closed or open system*

Ion concentration ( $C_D$ ) in the water drained from semi-closed systems is calculated as follows:

$$C_D = \frac{V \cdot (C_{NS}^F - C_{NS}^{AF})}{V_D} \quad (16)$$

Instead, in open culture  $C_D$  is calculated as reported by Sonneveld (2000):

$$C_D = C_U + \left( \frac{C_{NS} - C_U}{LF} \right) \quad (17)$$

The value of  $C_U^{Na^+}$  is calculated as the product of  $C_{IW}^{Na^+}$  times  $p$  (0.18).

### *Water and nutrient balance*

In open system, daily  $V_D$  is estimated from  $LF$  and  $W_U$ :

$$V_D = W_U \cdot \frac{LF}{1 - LF} \quad (18)$$

A balance sheet for water and macronutrients are computed for each fertigation strategy (Figure 2).

In semi-closed systems,  $W_U$  corresponds to the nutrient solution (or water) used daily to refill the mixing tank. Evaporation from the substrate, which is commonly wrapped in plastic bags, and water loss due to accidental seepage are considered negligible. In each growing system, water drainage ( $W_L$ ) is calculated as the number of discharges times  $V_D$ . In open culture, daily  $W_U$  is determined as the difference between water supply and  $V_D$ . In semi-closed systems, seasonal water use ( $W_{USE}$ ) is computed as the sum of cumulative  $W_L$  and  $W_U$ , while in open system  $W_{USE}$  corresponds to the volume of nutrient solution supplied during the growing season. In all systems, total  $N$  supply ( $N_{USE}$ ) is determined from volume and  $NO_3^-$  content of the nutrient solution fed to the crop.  $N$  loss ( $N_L$ ) is estimated by cumulating the amount of  $NO_3^-$  that is leached daily from open system or in occasion of flushing from semi-closed systems. Calculation of  $W_L$  and  $N_L$  considers the nutrient solution remaining in each growing system at the end of cultivation. Crop  $N$  uptake ( $N_U$ ) is calculated by subtracting  $N_L$  from  $N_{USE}$ .

## **SOFTWARE DESCRIPTION AND USE**

The use of SIMULHYDRO is available to interested users free of charge; it can be requested by email to Dr. Luca Incrocci (incrocci@agr.unipi.it) or downloaded (SYMULHYDRO.zip) from the Euphoros project WEB site (<http://www.euphoros.wur.nl/UK/Deliverables/>).

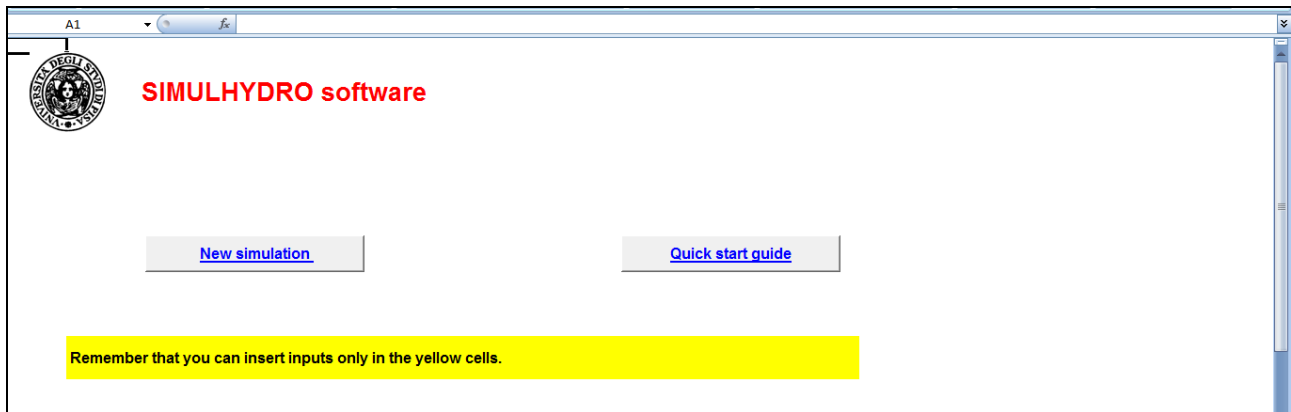
The software Zip folder contains two versions of same spreadsheet, which are compatible to Excel™ 2007 or Excel™ 1997-2003 along with complete reference manual (pdf).

SIMULHYDRO does not require any particular hardware and operating system; it can be run in Windows 7, Windows Vista or Windows XP SP3 environment.

**SIMULHYDRO contains macros.** Before to starting, be sure that Excel™ is able to activate the macros contained in this file. Please consult on-line guide for more information on Excel macros activation.

*Use*

Open the file SIMULHYDRO (.xltm for Excel™ 2007, .xlt for the older version) and activate macros. When Start window will appear (see fig. 4), click on New Simulation button.



**Fig. 4.** The home page of SIMULHYDRO software. For a new simulation, user must click on the New simulation button

User can restore previous simulations that had been saved in .xltm files by opening them directly.

User can consult the Quick Start Guide from every page.

For new simulation, user has to provide original sets of input variables or parameters. SIMULHYDRO already contains all inputs necessary to simulate a tomato rockwool soilless culture under the growing conditions that occurred during the validation experiment carried out in the spring of 2006 at the University of Pisa (Massa et al. 2011). User navigates among five successive windows using the Next or Back buttons.

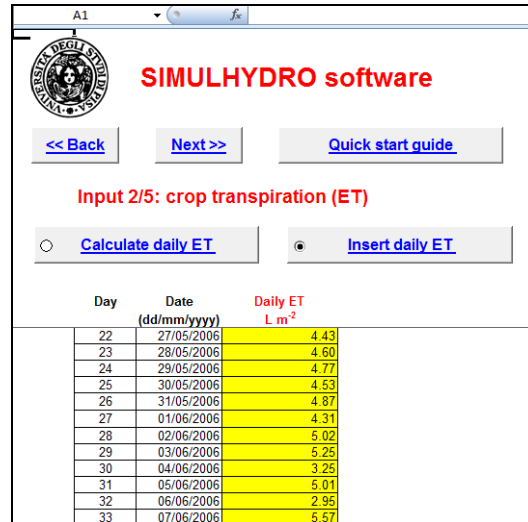
The system requires the input parameters divided in five different windows. Please compile all data input required before to move to the following window parameters:

1) **Crop chronology** (Fig. 5): dates (between 1/01/1900 to 1/01/2030) of planting, the onset of fruiting stage and the end of cultivation (last harvest).

**Fig. 5.** The crop chronology window of SIMULHYDRO software.

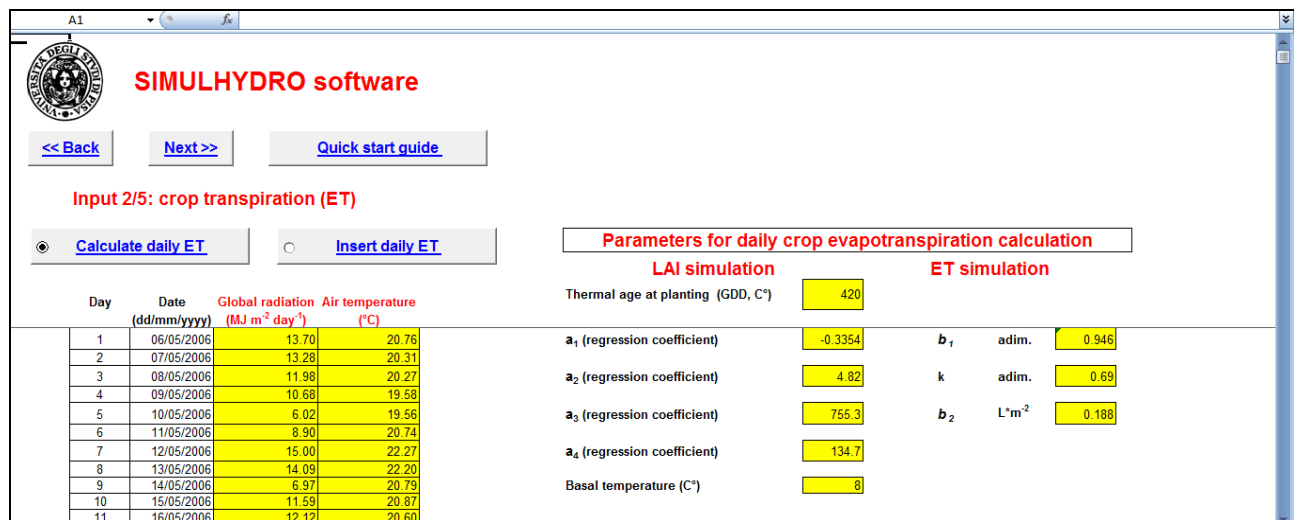


2) **Daily transpiration ( $ET$ )**. Two options are available (Fig. 6). Users may insert measured daily  $ET$  (Fig. 6) or calculate using the composite model proposed by Carmassi et al. (2007) (Fig. 7). This model simulates the evolution of leaf area index ( $LAI$ ) based on crop thermal time (i.e. growing degree days,  $GDD$ ) and then daily  $ET$  from  $LAI$  and the radiation ( $R_{int}$ ) intercepted by the crop.  $LAI$  is modeled using the Boltzmann sigmoid equation (Motulsky and Christopoulos, 2003) (see eq. 2). User can change model parameters, including the basal temperature for  $GDD$  computation and the light extinction coefficient required to calculate  $R_{int}$  from incident  $R$ , and insert new values of environmental variables (Fig. 7).



Day	Date (dd/mm/yyyy)	Daily ET $L\ m^{-2}$
22	27/05/2006	4.43
23	28/05/2006	4.60
24	29/05/2006	4.77
25	30/05/2006	4.53
26	31/05/2006	4.87
27	01/06/2006	4.31
28	02/06/2006	5.02
29	03/06/2006	5.25
30	04/06/2006	3.25
31	05/06/2006	5.01
32	06/06/2006	2.95
33	07/06/2006	5.57

**Fig. 6.** The daily transpiration window of SIMULHYDRO software: in this case user had selected to insert measured daily  $ET$ .



Day	Date (dd/mm/yyyy)	Global radiation ( $MJ\ m^{-2}\ day^{-1}$ )	Air temperature ( $^{\circ}C$ )
1	06/05/2006	13.70	20.76
2	07/05/2006	13.28	20.31
3	08/05/2006	11.98	20.27
4	09/05/2006	10.68	19.58
5	10/05/2006	6.02	19.56
6	11/05/2006	8.90	20.74
7	12/05/2006	15.00	22.27
8	13/05/2006	14.09	22.20
9	14/05/2006	6.97	20.79
10	15/05/2006	11.59	20.87
11	16/05/2006	12.12	20.60

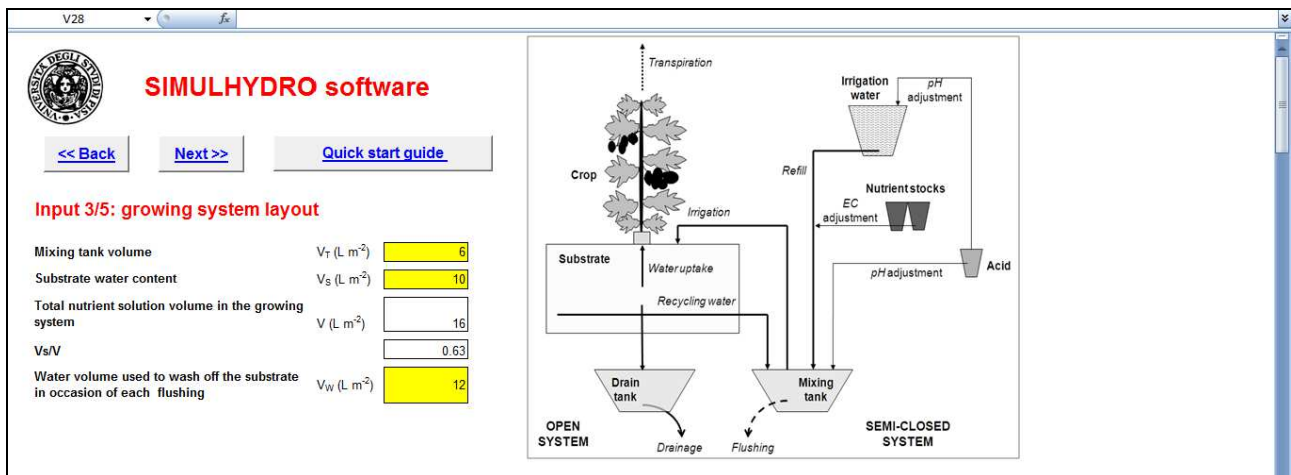
Parameters for daily crop evapotranspiration calculation			
LAI simulation		ET simulation	
Thermal age at planting ( $GDD, ^{\circ}C$ )	420		
$a_1$ (regression coefficient)	-0.3354	$b_1$ adim.	0.946
$a_2$ (regression coefficient)	4.82	$k$ adim.	0.69
$a_3$ (regression coefficient)	755.3	$b_2$ $L\ m^{-2}$	0.188
$a_4$ (regression coefficient)	134.7		
Basal temperature ( $^{\circ}C$ )	8		

**Fig. 7.** The crop transpiration window of SIMULHYDRO software: in this case, user had selected to simulate the daily  $ET$  by the Carmassi  $ET$  model, inserting the daily average air temperature and the daily global radiation (see. Eq. 2 and 3).

3) **Growing system layout** (Fig. 8): the capacity of mixing tank, the volume of nutrient solution retained by the substrate at water container capacity and the amount of water used to wash off the substrate in occasion of each flushing event.


4) **Ion composition** of irrigation water and reference nutrient solution, and ion uptake concentration (Fig. 9). Ion concentration is expressed in  $mol\ m^{-3}$  or  $mmol\ m^{-3}$  for macronutrients and

micronutrients, respectively. For ballast ions such as Na and Cl, the coefficient of proportionality between uptake concentration and external concentration ( $p$ ; it ranges from 0 to 1) is required. SIMULHYDRO computes automatically the total concentration of cations and anions, which must be equal, otherwise the user is warned by the appearance of red colour in the cell with “Electro-neutrality test”. The composition of the reference nutrient solution depends on the ion concentration of irrigation water and of the ideal nutrient recipe selected by the user. User may use the nutrient solution calculator (SOLNUTRI) for calculating the composition of reference nutrient solution. SOLNUTRI can be downloaded from Euphoros project WEB site (<http://www.euphoros.wur.nl/UK/Deliverables/>). In the Appendix, the ion composition of ideal nutrient recipe and ion uptake concentrations are reported for some greenhouse crops.



**Fig. 8.** The growing system layout window of SIMULHYDRO software: user must insert the main parameters that characterized the soilless system that will be simulated.

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# SIMULHYDRO software

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Quick start guide

Input (4/5): ion composition of irrigation water and reference nutrient solution, and crop uptake concentration

	HCO <sub>3</sub> <sup>-</sup>	N-NO <sub>3</sub> <sup>-</sup>	N-NH <sub>4</sub> <sup>+</sup>	P-H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	K	Ca	Mg	S-SO <sub>4</sub> <sup>-</sup>	Na	Cl	Σ C <sup>+</sup>	Σ A <sup>-</sup>	EC	Electro-chemical neutrality test
	mol m <sup>-3</sup>										eq m <sup>-3</sup>		dS m <sup>-1</sup>	
Irrigation water (1 <sup>st</sup> stage)	3.70	0.00	0.00	0.00	0.00	1.50	0.80	0.60	9.50	9.20	14.10	14.10	1.53	
Irrigation water (2 <sup>nd</sup> stage)	3.70	0.00	0.00	0.00	0.00	1.50	0.80	0.60	9.50	9.20	14.10	14.10	1.53	
Reference nutrient solution (1 <sup>st</sup> stage)	0.56	10.00	0.00	1.00	6.70	4.00	0.80	2.52	9.50	9.20	25.80	25.80	2.64	
Reference nutrient solution (2 <sup>nd</sup> stage)	0.56	7.00	0.00	0.70	4.70	3.25	0.80	2.42	9.50	9.20	22.30	22.30	2.31	

	N-NO <sub>3</sub> <sup>-</sup>	N-NH <sub>4</sub> <sup>+</sup>	P-PO <sub>4</sub> <sup>-</sup>	K	Ca	Mg	S-SO <sub>4</sub> <sup>-</sup>	Na	Cl	Σ C <sup>+</sup>	Σ A <sup>-</sup>	EC	Electro-chemical neutrality test
	mol m <sup>-3</sup>							p	eq m <sup>-3</sup>		dS m <sup>-1</sup>		
Ion uptake concentration (1 <sup>st</sup> stage)	10.00	0.00	1.00	6.70	3.55	0.60	1.50	0.18	0.18	15.18	15.66	1.63	
Ion uptake concentration (2 <sup>nd</sup> stage)	7.00	0.00	0.70	4.70	2.80	0.45	1.50	0.18	0.18	11.38	10.88	1.27	

**Fig. 9.** The fourth input window of SIMULHYDRO software: user must insert the ion composition of irrigation water, the reference nutrient solution for the first and second stage, as well as the uptake nutrient concentration for each growing stage.

**5) Fertigation control parameters** (Fig. 10). Simulation can be run using different strategies for fertigation management and user must insert specific parameters such as:

- Maximum EC ( $\text{dS m}^{-1}$ ): it is the maximum value of the EC of recirculating nutrient solution (in semi-closed systems) or drainage nutrient solution (in open system) that the crop tolerates without any significant yield reduction.
- Set-point EC ( $\text{dS m}^{-1}$ ): it is the EC to which the recirculating nutrient solution in semi-closed system is adjusted after each flushing event by injection of nutrient stocks.
- Minimum N concentration in the recirculation nutrient solution ( $\text{N-NO}_3^-\text{MIN}$ ,  $\text{mol m}^{-3}$ ): it is a parameter required by Strategies B and C (see second section of this document). It represents the  $\text{N-NO}_3$  concentration that allows the discharge of recirculating nutrient solution because it is lower than crop physiological requirement or the maximum allowed concentration established by legislation to  $\text{N-NO}_3$  content in wastewater.
- Total fruit yield ( $\text{Kg m}^{-2}$ ): this quantity is used to calculate water and nutrient use efficiency.

		Strategy A (variable EC)	Strategy B (constant EC)	Strategy C (variable EC and nutrient depletion)	Strategy D (Free-drain system)	
					1 <sup>st</sup> stage	2 <sup>nd</sup> stage
Maximum EC	$\text{EC}_{\text{MAX}}$ ( $\text{dS m}^{-1}$ )	4.50	3.00	4.50	3.48	2.59
Set-point EC	$\text{EC}_{\text{SP}}$ ( $\text{dS m}^{-1}$ )	3.00	3.00	3.00		
Minimum N concentration in the recirculation nutrient solution	$\text{N-NO}_3^-\text{MIN}$ ( $\text{mol m}^{-3}$ )		1.00	1.00		
Total fruit yield (optional)	( $\text{kg m}^{-2}$ )	11.25	11.25	11.25	11.25	

**Fig. 10.** The fifth input window of SIMULHYDRO software: user must insert some specific parameters for each fertigation strategies (A-C) simulated the closed-loop cycle system and for the open system.

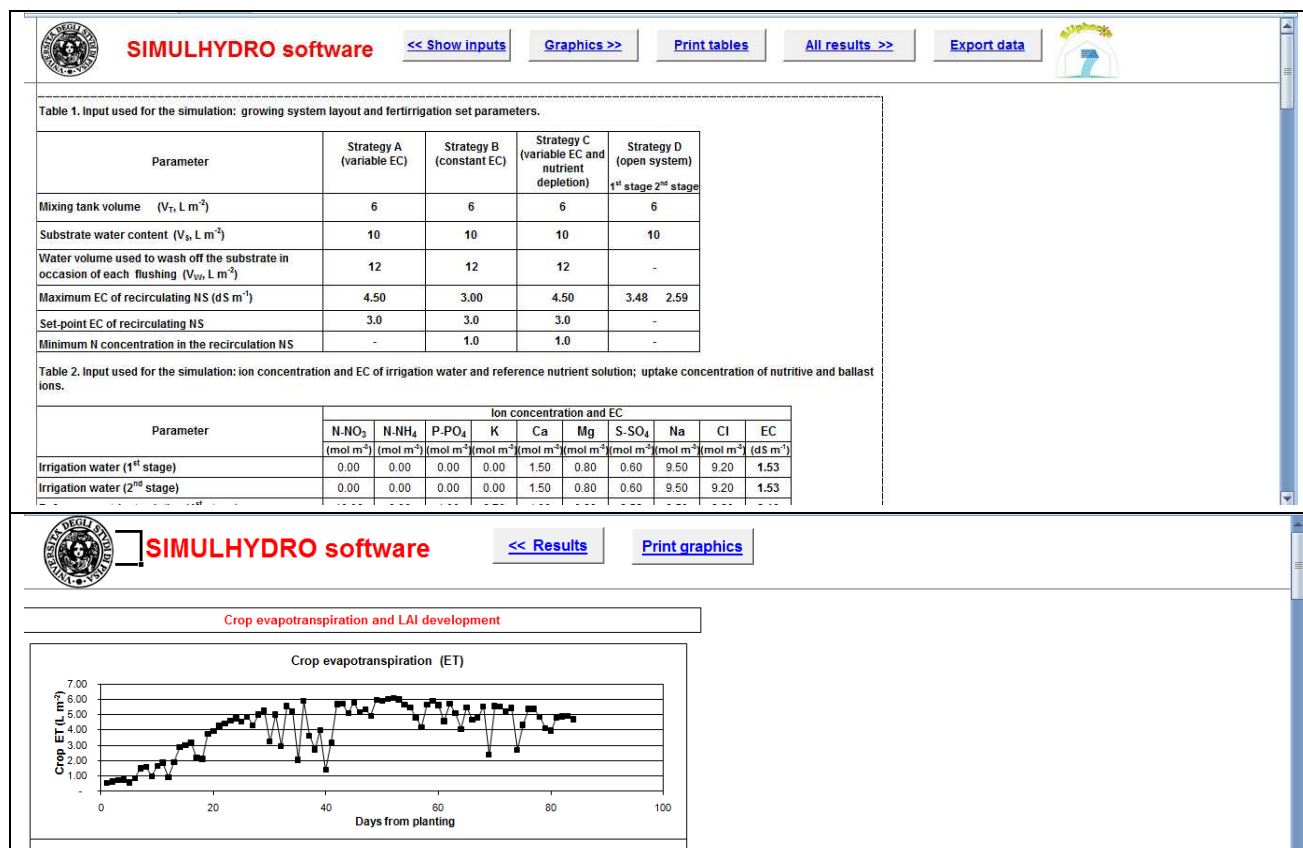
Input summary table	
<b>Input 1/5: Crop chronology</b> <a href="#">Edit</a>	
Planting date (dd/mm/yyyy)	06/05/2006
End of 1 <sup>st</sup> growth stage (dd/mm/yyyy)	29/06/2006
End of cultivation (dd/mm/yyyy)	28/07/2006
Duration of 1 <sup>st</sup> growth stage (days)	54
Growing period (days)	84
<b>Input 2/5: daily crop transpiration (ET)</b> <a href="#">Edit</a>	

**Fig. 11.** The input summary table of SIMULHYDRO software: user could check the inserted input, and eventually could be edited. Finally could start the simulation clicking the [calculate](#) button. insert some specific parameters for each fertigation strategies (A-C) simulated the closed-loop cycle system and for the open system.

SIMULHYDRO shows a summary table, where all inputs provided by the user are shown and can be edited (Fig. 11).

Finally, user can launch the simulation by clicking the Calculate button. This operation will require 1 to 3 minutes depending on computer characteristics. Calculation progress is shown in progress bar. The main results of simulation are reported in printable graphics and tables (see an example in Fig. 11) and can be exported in a spreadsheet (.xls) containing daily values of crop ET, water runoff, nutrient leaching and the ion composition of recirculating or drainage nutrient solution. The total parameter simulated could be checked in the “all results” section

Each simulation can be saved with its own name in a specific folder.



**Fig. 12.** Output of SIMULHYDRO: tables and graphics obtained after the simulation of the four different fertilization strategies.

## Nomenclature

Symbol or abbreviation	Description	Unit
$\lambda$	latent heat of water vaporization	MJ Kg <sup>-1</sup>
$A, B$	water uptake model coefficients	dimensionless
$a_1, a_2, a_3, a_4$	leaf area model coefficients	dimensionless
$C$	molar concentration	mol m <sup>-3</sup>
$CAT$	the sum of valences of the cations ( $Ca^{2+}$ , $Mg^{2+}$ , $K^+$ , $Na^+$ )	mol m <sup>-3</sup>
$c$	correction factor of the dilution ratio ( $r$ ) of the stock nutrient solutions	dimensionless
$EC$	electrical conductivity	dS m <sup>-1</sup>
$GDD$	growing degree days	°C
$k$	light extinction coefficient	dimensionless
$LAI$	leaf area index	dimensionless
$LF$	leaching fraction	%
$N$	mass of nitrogen ( $NO_3^-$ )	g m <sup>-2</sup>
$p$	coefficient of proportionality between $Na^+$ uptake concentration and sodium concentration in the root (nutrient solution) zone	dimensionless
$r$	dilution ratio of the stock nutrient solutions in the irrigation water	dimensionless
$RAD$	daily global radiation	MJ m <sup>-2</sup> day <sup>-1</sup>
$T$	air temperature	°C
$V$	volume of nutrient solution	L m <sup>-2</sup>
$W$	volume of water in crop water balance	L m <sup>-2</sup>
Superscripts		
$AF$	in the recirculating nutrient solution after flushing	
$F$	in the recirculating nutrient solution when the conditions for flushing were fulfilled in semi-closed cultures	
$I$	ion ( $NO_3^-$ , $Ca^{2+}$ , $Mg^{2+}$ , $K^+$ , $Na^+$ )	
$MAX$	ceiling value for the $EC$ of recirculating nutrient solution in semi-closed cultures	
$REF$	reference (full-strength) nutrient solution	
Subscripts		
$D$	The nutrient solution discharged daily from open culture or in occasion of flushing from semi-closed cultures	
$IW$	irrigation (raw) water	
$L$	water drainage or nitrogen leaching	
$NS$	nutrient solution in the growing system (contained in the mixing tank and in the substrate), which was recirculated in semi-closed cultures	
$RNS$	nutrient solution used to refill the mixing tank in both semi-closed and open systems	
$S$	in the substrate	
$SP$	target $EC$ of recirculating nutrient solution in semi-closed cultures	
$SS$	stock nutrient solutions	
$T$	in the mixing tank	
$U$	crop uptake of water or nitrogen; uptake concentration of individual ions	
$USE$	seasonal consumption of water or nitrogen	
$W$	water used to wash off the substrate in occasion of flushing in semi-closed cultures	

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