Deliverable n. 6

Models for salt accumulation in recirculating nutrient solution culture

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Introduction

In closed-loop hydroponics a complete nutrient solution is prepared with water that generally contains non-essential ions, and recirculated until chemical characteristics (namely EC and the concentration of potentially-harmful ions) are below a given threshold that is dependent on many factors, first of all on the crop's tolerance to salinity.

Tipically, when poor-quality irrigation water is used, there is a rapid increase in EC due to the accumulation of ions such as sodium, chloride, and sulphate and, in case of hard water, calcium and magnesium. Bicarbonate ions, which are often contained in underground water, are neutralised by acid injection for pH control and do not represent a relevant problem. Instead, micronutrients, such as B or heavy metals, may accumulate to toxic levels; however, their concentrations are in order of micromoles per litre and, at variance with other ions that can be indirectly determined by measuring EC, these ions have to be monitored through expensive and time-consuming laboratory analysis.

A simple mathematical model is proposed to estimate how fast the concentration of a given ion increases or decreases in dependence on the relevant factors that influence plant mineral relations in closed-loop hydroponics.

Model description and assumptions

The model is derived by the balance equation for nutrient uptake by the crop.

The uptake (U) over the period between n and n-1 (days or weeks) can be calculated as follows:

$$\textbf{1)}\quad U = (V\ C_{n-1}) + (E\ C_{ns}) - (V\ C_n)$$

where C_{ns} and V are the ion concentration (mM) and volume (l/plant) of the recirculating solution. V includes the water inside the substrate, if any, and in case of NaCl C_{ns} corresponds to the concentration of irrigation water).

Uptake concentration C_U is the following:

$$\textbf{2)}\quad C_U = U / E$$

where E is the crop evapotranspiration (l/p).

Then,

$$\textbf{3a)}\quad C_U = (V\ C_{n-1})/E + (E\ C_{ns})/E - (V\ C_n)/E$$

$$\textbf{3b)}\quad C_U = C_{ns} + (C_{n-1} - C_n)\ V / E$$

Rearranging equation 3b, it is possible to predict C_n on the basis of C_{n-1} , E, V and C_U, as follows:

4) $$C_n = C_{n-1} + [(C_{ns} - C_u)] E / V$$

Therefore, the model simulates the changes in ion concentration and *EC* of recirculating nutrient solution in dependence on the relevant factors that influence mineral relations in hydroponics, such as the volume of recycling solution (the system buffer), crop transpiration and the quality of irrigation water as well as the uptake concentration of the ion C^I_U, i.e. the ratio between the ion and water uptake by the crop. C^I_U which includes both genuine root uptake and nutrient loss by uncontrolled leaching and precipitation in the substrate.

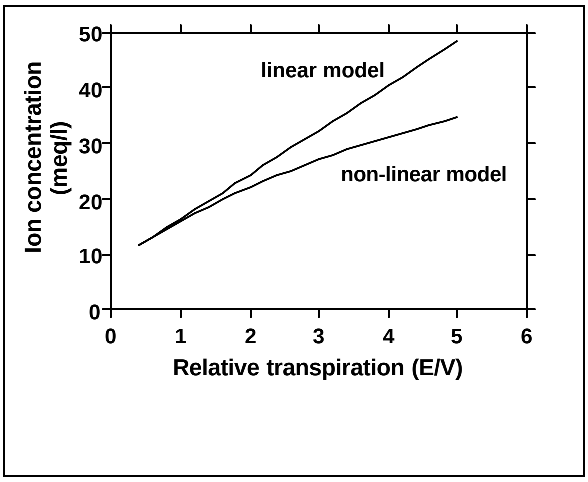
Indeed, for non-essential ions, such as *Na* and *Cl*, a different model could be used taking account of the influence of external concentration on C_U . A linear function can be used to describe the relationship between C_U for *Na* and its external concentration (Sonneveld, 2000; Silberbush and Ben-Asher, 2001):

5) $$C_U^{Na} = p\, C^{Na}$$

After substitution, the following formula can be derived:

6) $$C^{Na}_n = (C^{Na}_{n-1} - C^{Na}_{ns}/p)\, e^{-(E/V)\, p} + C^{Na}_{ns}/p$$

Nevertheless, for the typical range of values for E/V and p in commercial greenhouses, linear and non-linear models produce similar results in term of simulation of the changes in the concentration of non-essential ions in the recirculating solution.



Simulation of the change in the concentration of non-essential in the recirculating nutrient solution of closed-loop hydroponics. The simulation was performed using both linear (C_U = 2 mM) and non-linear model (p = 0.20); the value of NaCl concentration in the irrigation water is 10 mM.

Linear model for the change in ion concentration can also be used to predict the volume of supplied nutrient solution for which EC exceeds a given value (EC^{max}), as follows:

7) $$E = V (C^{max} - C_{ns}) / (C_{ns} - C_U)$$

If E is compensated by filling the mixing tank with complete nutrient solution with a given nutrient concentration of C_{ns}, the model can be used to calculate nutrient accumulation or depletion, if C_U for that nutrient is known.

The salt accumulation model is based on several assumptions, which seem reasonable:

1) the difference between the concentration of the nutrient solution in the mixing tank and the one in the root zone (substrate) is negligible; the assumption is valid in case of nutrient

film technique or large drainage percentage in substrate culture;

2) the volume of recirculating solution is the sum of the solution in the mixing tank and in the root zone; therefore, it depends on water retention of the substrate;

3) the uptake concentration refers to the genuine, net (influx minus efflux) uptake by the roots together with the amount of ions that are lost by salt precipitation in the root zone (substrate, gullies,…).

The uptake concentration depends on crop species and growing conditions as well; in general this parameter is less variable than the nutrient uptake rate (Savvas and Lenz, 1995; Sonneveld, 2000). Moreover, under the typical non-limiting nutrition condition of hydroponics, the rate of nutrient uptake and then C_U are not greatly affected by the external ion concentration.

The models of equation 4 and 6 identify clearly what are the strategies to reduce salt build-up:

1) increasing V, i.e. the buffer of the system (hydroponic technology);

2) decreasing salt concentration of irrigation water, namely C_{ns} (water treatment technology);

3) decreasing E (climate control technology);

4) increasing C_U (hydroponic technology[1] and breeding).

[1] Subirrigation-based hydroponics could be adopted to increase salt accumulation in the growing media

Calibration and validation of the model

The salt accumulation model was calibrated and validated for tomato crop in semi-closed loop substrate culture using data collected in previous experiments or reported in the literature.

The experiments were conducted in spring and in summer of 2001 using irrigation water of different NaCl concentration: approximately 10 (treatment S1) and 20 mM (treatment S2) which corresponded to 3.0 and 3.9 mS/cm of the nutrient solution supplied to the crop.

In both treatments the following macronutrient composition (meq/l) was adopted: $N\text{-}NO_3$ 12.5, *P* 1.1, *K* 8.5, *Mg* 4.8, *Ca* 6.8.

Plants were grown in rockwool slabs with high percentage of drainage solution (70-80%) in order to avoid differences in *EC* between the solution in the mixing tank and the one retained by the substrate. Irrigation was controlled by a PC on the basis of measurement of indoor global radiation.

The solution tank was automatically refilled with complete nutrient solution. In this system, EC gradually increases as a result of the accumulation of macro-elements and, principally, of non-essential ions (Na and Cl) contained in the irrigation water, as shown in Figure 1.

The figure 1 also shows the close relationship among the increase in EC, the accumulation of Na and crop transpiration. The recirculating solution was daily checked for EC and discharged when EC exceeded 6.0 and 8.0 mS/cm in S1 and S2 treatment, respectively; the mean values at which the recycling solution was discharged were actually 6.2 and 8.3 mS/cm in T1 and T2, respectively.

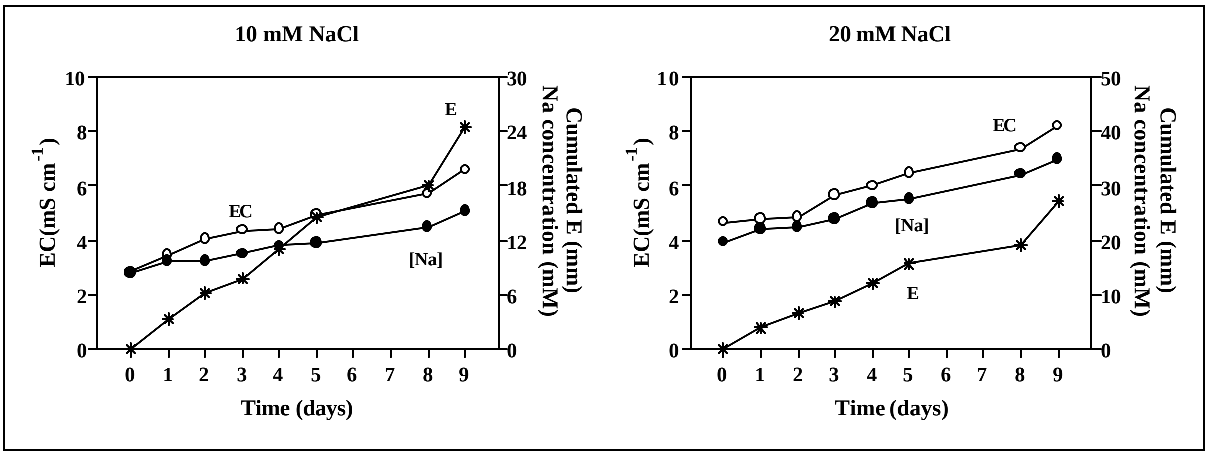


Figure 1. Changes in crop evapotranspiration (E), EC and Na concentration of the recycling nutrient solution in two closed-loop rockwool cultures of tomato conducted using irrigation water with different NaCl concentration (10 and 20 mM). Data refer to plants grown between 48 (9 April 2001) and 57 (18 April 2001) days from planting.

Ion accumulation model was used to simulate the change in the concentration of both Na (C^{Na}) and other cations (C^{C}) (K, Ca and Mg); non-linear model was used for Na with a *p* value of 0.25, while linear model and a C_U^{C} value of 16 (spring) or 13 (autumn) meq/l was used for macro-cations. Thus, EC was calculated on the basis of the sum of cations using the following model (after Sonneveld et al., 1999):

8) $EC = 0.19 + 0.095\ (C^{C} + C^{Na})$.

The comparison between simulated and measured values of EC and Na concentration of the recirculating nutrient solution in the four experimental crops is reported in Figures 1, while in Figure 2 the simulated and measured changes in EC in spring experiments are reported in details.

Using linear model for both macronutrients and non-essential ions it was calculated the runoff of water and nitrogen due to periodic flushing; the estimated were compared with the measured values (Table 1). Water runoff was calculated on the basis of leaching fraction that in turn was estimated on the basis of the cumulated value (E_{fl}) of crop transpiration for which EC reaches EC^{max}, as follows:

9) $LF = V_{fl} / (E_{fl} + V_{fl})$

E_{fl} is determined according to the equation 7 (E_{fl} = E):

The leakage of N was estimated on the basis of the mean N concentration in runoff water. To model the change in $N\text{-}NO_3^-$ concentration in the recycling culture solution, the value of uptake concentration was assumed to be 11 and 9 meq/l in spring and autumn, respectively.

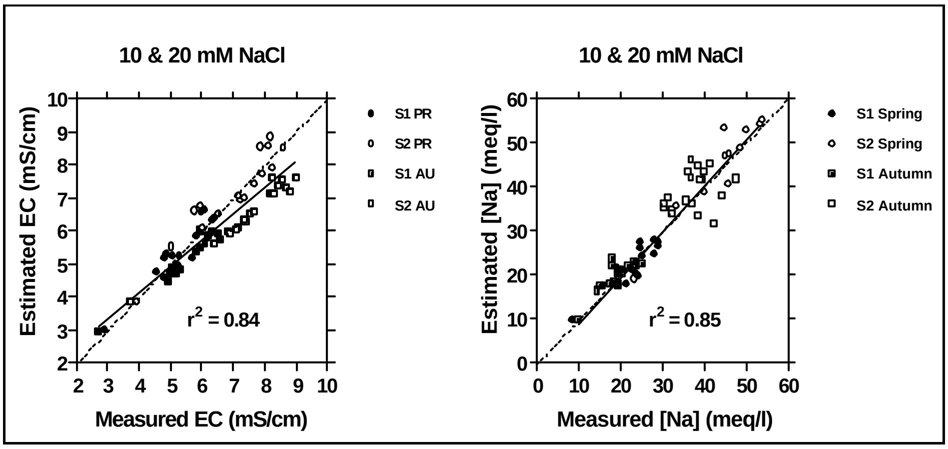


Figure 2. Comparison between measured and predicted values of EC and Na concentrations in the recirculating nutrient solutions of different tomato substrate (rockwool) cultures conducted in spring or in summer using irrigation water with two different Na concentrations (S1, 10 mM; S2, 20 mM). Solid line represents linear regression relationship while dotted line is the 1:1 line.

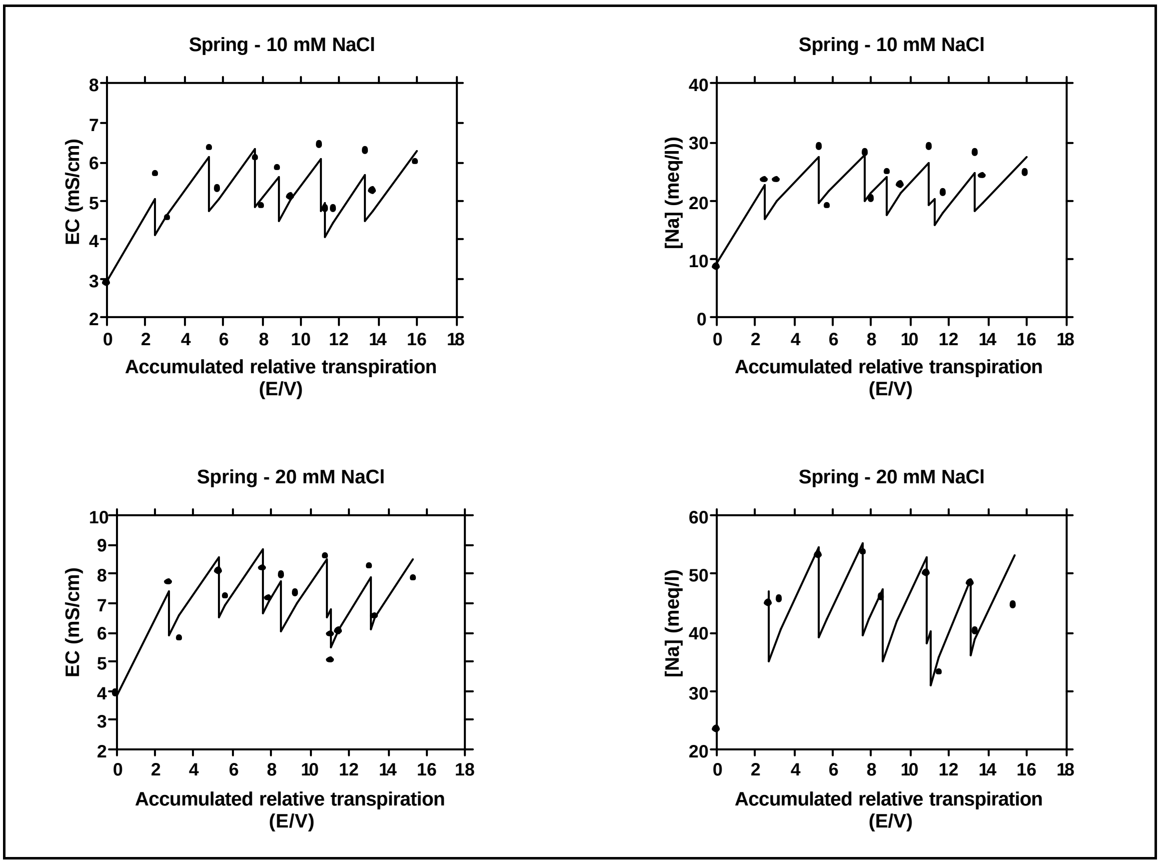


Figure 3. Comparison between measured (symbols) and simulated (line) values of EC and Na concentration in the recirculating nutrient solution of tomato substrate (rockwool) cultures conducted in spring using irrigation water with two different Na concentrations (S1, 10 mM; S2, 20 mM).

Table 1. Comparison between the measured and predicted values of water and nitrogen runoff due to periodic flushing for different tomato substrate (rockwool) cultures conducted in spring or in summer using irrigation water with two different Na concentrations (S1, 10 mM; S2, 20 mM).

		Irrigation water EC (mS/cm)	EC^{max} (mS/cm)	E (mm)	Water runoff (mm)	Leaching fraction	Drainage water $[N\text{-}NO_3]$ (mM)	N leaching kg/ha
SPRING S1	Measured	3.0	6.0	258	49	16	17.5	120
	Simulated	*3.0*	*6.0*	*258*	*71*	*22*	*14.3*	*146*
SPRING S2	Measured	3.9	8.2	248	49	16	19.6	134
	Simulated	*3.9*	*8.2*	*248*	*64*	*20*	*14.3*	*126*
FALL S1	Measured	3.0	6.2	188	63	25	23.8	210
	Simulated	*3.0*	*6.2*	*188*	*65*	*26*	*23.3*	*213*
FALL S2	Measured	3.9	8.4	169	70	29	21.0	206
	Simulated	*3.9*	*8.4*	*169*	*62*	*27*	*21.6*	*186*

Conclusions

The simple model developed in this work simulates rather well the fast salt accumulation which tipically occurs in recycling nutrient solution culture when irrigation water of poor quality is available; the model seems to be valid over a wide range of growing conditions, since it was validated with data from tomato cultures conducted in different seasons and using irrigation waters of different salinity.

The model may be a tool for the management of closed-loop hydroponics, in particular I) to predict the amount of crop evapotranspiration that leads to a given value of *EC* or concentration of toxic ion and, then, to estimate runoff in semi-closed systems, that is with periodic flushing of exhausted solution); II) to adjust the concentration of nutrient solution used to refill the mixing tank, in order to avoid undesired variations of nutrient concentration.

The models could be employed in both on-line (daily management of irrigation) and off-line (simulation study to define best strategies to manage efficiently water and nutrient supply) subroutines of the Decision Support System (DSS) that Hortimed Project is developing.

References

1) Savvas D. and Lenz F. 1995. Nährstoffaufnahme von Aubergine (Solanum melongena L.) in Hydrokultur. Gartenbauwissenschaft 60: 29-33.

2) Silberbush M. and Ben-Asher J. 2001. Simulation study of nutrient uptake by plants from soilless cultures as affected by salinity buildup and transpiration. Plant and Soil 233: 59-69.

3) Sonneveld C. 2000. Effect of salinity on substrate grown vegetables and ornamentals in greenhouse horticulture. Ph.D. Thesis, Wageningen University.

4) Sonneveld C., Voogt W. and Spaans L.. 1999. An universal algorithm for calculation of nutrient solutions. Acta Horticulturae 481: 331-339.