Simplified Models for the Water Relations of Soilless Cultures: what they do or Suggest for Sustainable Water Use in Intensive Horticulture

Pardossi A., Malorgio F., Incrocci L., Carmassi G., Maggini R., Massa D., Tognoni F.
Dipartimento di Biologia delle Piante Agrarie, University of Pisa, Pisa, Italy.
(alberto.pardossi@agr.unipi.it)

Abstract

In intensive horticulture (including in this term both greenhouse cultivation and the outdoor production of containerised nursery stocks) there is an increasing application of closed-loop (no-drain) soilless cultures, in consideration of their positive environmental implications. In these systems, water use efficiency depends on how the mineral supply is controlled. Crop modelling and the use of recently-marketed devices (like chemo-sensors) are promising tools for the development of a sort of 'on-demand' fertigation strategy. The management of closed system is much more complicated when saline water is available to the grower, since the progressive accumulation of ions (such as sodium and chloride), that are scarcely taken up by the plants, makes it necessary to discharge, more or less frequently, the recycling nutrient solution, with consequent loss of water and fertilisers. The paper illustrates some simplified models for water relations of soilless culture and discusses what these models suggest, in terms of strategical, tactical or operational implementations, for a sustainable use of hydric resources, in particularly in cultivations conducted under saline conditions.

Keywords: hydroponics**,** closed systems, mineral uptake, modelling, salinity.

INTRODUCTION

The term 'soilless culture' includes all the techniques for cultivating plants without soil in artificial substrates or in pure nutrient solution (water culture, such as NFT, floating culture and aeroponics). These systems can be further classified according to the method to deliver the nutrient solution to the crop (drip irrigation or sub-irrigation; flowing, stagnant or mist nutrient solution), or the outcome of fertigation effluents: open (free-drain) or closed (recirculating water) systems. The application of water culture is scarce on a commercial scale and, with the exception of The Netherlands (where closed system are compulsory), free-drain substrate culture is commonly used for greenhouse production of vegetables, strawberry and cut flowers, or in the growing sector of outdoor production of containerised nursery stocks.

Although worldwide the diffusion of hydroponics is still limited, the growers' interest for this technology is increasing in consideration of its many advantages, including the higher use efficiency of resources like labour or water. Definitely, soilless culture may provide a valuable tool to save water and to minimize the environmental impact provoked by the large application of fertilisers and other agrochemical (soil fumigants, for instance), which is distinctive of intensive horticulture. However, the positive environmental implications of hydroponics are not implicit, since open soilless systems may be responsible for massive waste of water and nutrients.

In the last ten years, much attention has been paid to the quantitative description of water and mineral relations of greenhouse soilless cultivations, with the aim to improve their production efficiency. Several research (e.g. Van Kooten et al., 2004; Marcelis et al., 2005; Gieling et al., 2005) or review (Klaring, 2001; Savvas, 2002b) articles were published on the possible application of crop modelling for the management of fertigation in commercial hydroponics.

This paper illustrates a few simplified models (found in the literature or derived by experimental works conducted at University of Pisa) for the water requirements and the associated nutrient leaching in soilless culture and discusses what these models suggest, in terms of strategical, tactical or operational implementations, for a sustainable use of hydric resources in intensive horticulture.

OPEN SYSTEMS

A simple model may be used to estimate potential runoff (R) for both water and (dissolved) nutrients from free-drain soilless (soil too) culture:

$$R = I\ \ [(1 - IE) + (IE\ \ LF)] \qquad (1)$$

where I is irrigation volume (mm or m^3/ha), dependent on crop water demand for growth and evapotranspiration (E) , IE the irrigation efficiency (i.e., the ratio between the water available to root uptake and the one delivered by irrigation system) and LF is the leaching fraction. For I = 1, it takes

$$R = (1 - IE) + (IE\ \ LF) \qquad (2)$$

The value of IE ranges from 0.4 to nearly 1.0 depending on irrigation system, reaching the highest value in the case of drip irrigation or sub-irrigation. The loss of water includes both the seepage of irrigation system and the water that is not intercepted by the plant; in overhead irrigation, largely used in outdoor nurseries, it is the water that falls outside the containers.

Ross et al. (2001) proposed an index for the environmental risk of containerised crops in dependence on R, IE and LF (Table 1). Evidently, the use of drip irrigation (high IE) and closed system (LF close to zero) minimises R.

In an open, drip-irrigated substrate culture, with negligible evaporation, overall crop water consumption (W) is the following:

$$W = E + R \qquad (3)$$

If the term leaching requirements (LR), that is the R/E ratio, is introduced, then

$$W = E\ (1 + LR) \qquad (4)$$

The relationship between LF and LR is the following:

$$LF = LR\ /\ (1 + LR) \qquad (5)$$

Nutrient leakage (R_{NUT}) depends on R and the ion concentration in drain water (C_D):

$$R_{NUT} = R\ C_D \qquad (6)$$

On the basis of balance equation for water and nutrients in substrate culture, Sonneveld (2000) proposed the following equation for the relationship among C_D, LF and the ion concentration in irrigation water (C_I):

$$C_D = [C_I – (1\text{-}LF)\ C_U]\ /\ LF \qquad (7)$$

where C_U is the apparent nutrient uptake (or influx) concentration, i.e. the ratio between water and nutrients taken up by the crop.

Rearranging Eq. (7), one obtains:

$$LR = (C_I - C_U) / (C_D - C_I) \qquad (8)$$

Figure 1 reports the LR for open soilless culture as function of C_I and maximum C_D for Na, with the realistic assumption of a proportionality between C_U and C_I.

In Eqs. (7) and (8), electrical conductivity (EC) may be used instead of C, according to the following formula proposed by Sonneveld (2000):

$$EC\ (dS/m) = 0.19 + 0.095\ C^{CAT} \qquad (9)$$

where C^{CAT} is the sum of cation (or anions, assuming the electroneutrality of the nutrient solution) concentrations expressed in meq/L.

Typically, a watering dose in excess of at least 30-35% respect to crop E is necessary to avoid substrate salinization as well as to consider the unequal transpiration of individual plants and the uneven water distribution per plant that results from the difference in water flow of trickle nozzles. In horticultural areas without strict environmental legislation, or with poor compliance of it, the actual LR is often much higher, as over-irrigation is considered ‘safe and sound’, at least from the technical point of view. Consequently, in open system the runoff is massive, the water use efficiency (WUE) is reduced, the production costs increase and water sources are contaminated.

In order to reduce these drawbacks, precise irrigation scheduling must be adopted to minimise drain-off. For many important greenhouse crops, including tomato (e.g. Joilliet and Bailey, 1992; Carmassi, 2005), cucumber (Medrano et al., 2005) and rose (Kittas et al., 1999), it has been designed and validated a simplified (regression-based) version of Penman-Montheith formula, as follows:

was estimated using the following formula derived from the Penman–Monteith equation (Baille et al., 1994):

$$E=A(1-\exp(-K\ LAI))G+B\ LAI\ VPD \qquad (10)$$

where G is the inside solar radiation, VPD is the inside air vapour pressure deficit, LAI is the leaf area index, K is the light extinction coefficient and A, B are values being crop-specific constants. In irrigation scheduling, the application of a formula like Eq. (10) is coupled with the systematic measurement of both volume and EC of the drainage solution (more irregularly, of the substrate as well). If a rise in EC is observed, there is an increase in watering dosage and/or frequency, eventually with a concomitant reduction in EC of irrigation water (EC_I).

Stanghellini et al. (2003) reported that, on the basis of simultaneous measurement of both volumetric water content and EC of rockwool slabs (by means of electronic sensors), the dosage and salinity of the culture solution could be continuously adjusted to maintain a given set-point for root zone moisture and salinity. This procedure minimised drain fraction; it was only 10%, approximately.

CLOSED SYSTEMS

It is evident that only closed or virtually-closed (no-drain) growing systems can maximise WUE and minimise runoff-related environmental pollution. In closed-systems, the drainage water is collected and re-circulated after proper adjustment of pH and nutrient concentration and, eventually, disinfection (i.e. by heat or UV) to prevent the spread of root diseases. For optimal mineral supply, the management of recirculating nutrient solution requires frequent chemical analyses, which may be performed by means of usually time-consuming laboratory analyses or using low-cost, portable instruments that may provide fast and reliable analysis of the main nutrients.

The use of chemo-sensors of old (ISE) and new (ISFET) generation discloses new possibilities for the control of mineral supply in closed systems. The concentration of single nutrients could be monitored and corrected by means of multi-head injectors (Gieling et al., 2005) and this could prolong the use of the same solution, thus reducing the need for leaching. Till a few years ago, these systems were quite expensive and restricted to experimental applications, but recently some companies have developed and introduced into the market some devices for the control of commercial greenhouse hydroponics (Gieling et al., 2005; www.hydrion.nl).

Several procedures have been proposed for the management of recycling water in closed hydroponics (e.g. Klaring, 2001; Savvas, 2002a). These procedures may be simply grouped in two main categories: feed-back or feed-forward control of nutrient concentration in the culture solution. In the first case, the nutrient concentration is maintained a desired level, generally by automatic maintenance of an EC set-point. Alternatively, the concentration is modulated in order to feed the plant with the expected amount of nutrients required for growth, that may be estimated by mechanistic photosynthesis-driven models (Klaring., 2001; Marcelis et al., 2005). Models simulating crop growth and mineral nutrition could be implemented in expert systems for the management of soilless cultures (Bacci et al., 2005). Recently, Van Kooten et al. (2004) have illustrated the advantages and the scientific and technical basis of a sort of ‘on-demand' water and mineral supply to soilless-grown plants; the strategy is based on models for plant growth and mineral uptake and for the distribution of nutrients in the substrate.

An example of feed-forward strategy was reported by Pardossi et al. (2002). These authors compared two methods to control nutrient delivery to greenhouse melons grown with NFT using saline irrigation water (10 mM NaCl): 1) conventional EC-based control system, in which the recycling nutrient solution was periodically drained-out because of an excessive build-up of NaCl concentration; 2) a sort of programmed nutrient addition, which was based on a pre-established weekly mineral supply without any attempt to maintain constant values of EC. The second procedure proved to be quite efficient, as it did not affect fruit yield and, in comparison to the conventional method, reduced significantly the usage of water and fertilisers, and eliminated nutrient runoff.

The use of saline water in closed system

The major source of difficulties in the management of closed system is the salinity of raw water. When saline water is available, there is a more or less rapid accumulation of ions (Na, Cl,…) that are scarcely absorbed by the plants. This phenomenon may result in a concomitant increase in nutrient solution EC, if the management strategy aims to maintain constant nutrient concentration, or in a parallel depletion of nutrients, if the fertigation is based on a feed-back control of EC. In both cases, the crop is subjected to salinity stress, the severity of which augments over time. Under these conditions, the nutrient solution is normally recirculated till EC, or the concentration of some toxic ion, reaches a maximum acceptable threshold value (EC^{MAX} or C^{MAX}), after that it is replaced, at least partially. The term ‘semi-closed’ is used for this system. In Holland, growers are allowed to leach their systems whenever a crop-specific ceiling of Na concentration is reached: for example, 10 mM for tomato and 4 mM for cut roses (Baas and Berg, 1999).

A few models have been proposed for salinity build-up in closed soilless cultures (e.g. Silberbush and Ben-Asher, 2001; Kempkes and Stanghellini, 2003; Silberbush et al., 2004). Some of these models take into account a relevant number of parameters and their practical use appears difficult.

A simple model, recently designed and validated by Carmassi et al. (2005), predicts the (linear) change in concentration C over the period 0-1, as follows:

$$C_1 = C_0 + (C_R - C_U)\, E / V \qquad (11)$$

where V and C are, respectively, the volume and the ionic concentration of the recirculating solution (including the one in the mixing tank, in the irrigation lines and in the substrate) and C_R is the salt concentration of the water (raw water or nutrient solution) added to the system (i.e., to refill the mixing tank) for compensating crop E (C_U was defined previously).

If ion accumulation in the recirculating solution is not linear with crop water uptake, a different function may be used, taking into account the influence of external concentration on C_U, as follows:

$$C_U = p\, C \qquad (12)$$

Proper arrangement and integration of Eqs. (11) and (12) lead to the following expression:

$$C_1 = C_R/p + (C_0 - C_R/p) \exp(- p\, E/V) \qquad (13)$$

Directly from the integral of Eq. (13), it is possible to calculate the mean concentration (C_{AVG}) in the recyling water over the period with a given value of cumulative E, in order to estimate the severity of salinity stress to which the crop is exposed.

$$C_{AVG} = C_R/p + \{-1/p\ (C_R - C_R/p)\ [\exp(-p\, E/V) - 1]\ V/E\} \qquad (14)$$

For the linear model of Eq. (11), C_{AVG} is simply the mean between C_0 and C_1.

The LR of a semi-closed system can be estimated as the ratio between the volume of water discharged in occasion of each flushing event (V_F) and of the cumulated E for which EC (or C) reaches the ceiling threshold (E^{ECMAX}):

$$LR = VF / E^{ECMAX} \qquad (15)$$

V_F may be equal to the volume of the mixing tank (V_{TANK}) or higher, when it is repeated the procedure of refilling the tank with fresh water and recirculating it for a while before discharge, as it may occur in substrate culture. The following formula, validated experimentally (at least for rockwool slabs; unpublished data) may be used to calculate the salt concentration (C^N) in the system after N successive flushings:

$$C^N = C_I + \{(C^{MAX} - C_I)\, [(V - V_{TANK})/V]^N\} \qquad (16)$$

where C^N represents the lower limit of the salinity oscillation that typically occurs in semi-closed systems.

By integrating a transpiration formula like Eq. (10) and the salt accumulation models described by the equations reported previously, Carmassi (2005) was able to simulate the change in recycling water EC and the loss of both water and N in semi-closed rockwool culture of tomatoes conducted with saline water (NaCl concentration up to 20 mM). The aggregate model developed by Carmassi (2005) could be implemented in DDS for both off-line (prior-to-planting) estimate of crop W and on-line management of nutrient solution replenishment (Bacci et al., 2005).

STRATEGIES FOR EFFICIENT WATER USE IN SOILLESS CULTURE

Apart the direct use for the (automatic) control of fertigation, the models introduced previously give some suggestion how to manage soilless culture under the constraints imposed by the salinity of irrigation water.

With some realistic assumptions, the salt accumulation model proposed by Carmassi et al. (2005) may be further simplified and the following equation for W in semi-closed system can be derived (Stanghellini et al., 2004, 2005).

$$W = Ep\,[C^{MAX} / (C^{MAX} - C_I)] \qquad (17)$$

where Ep represents the potential crop evapotranspiration, and C_{MAX} is the maximum concentration of toxic ion (alternatively, EC) tolerated by the crop, that is the concentration at which the recycling nutrient solution is flushed out.

Considering the water cost or price (P, presumably dependent on salinity), the gross return (Y) of the crop and its sensitivity to salinity (as expressed by the slope s of the decrease in Y with increasing salinity; the higher is s, the greater is the yield loss due to salinity), Stanghellini et al. (2004, 2005) proposed this approximate equation for the optimal value for irrigation water salinity (C_I^{OPT}):

$$C_I^{OPT} = (P\,Ep) / (2\,s\,Y) \qquad (18)$$

From a simulation study conducted by these authors using realistic values for both P and Y, it was found that C_I^{OPT} was close to the value that allows the highest yield. This suggests that there is no benefit in using poor-quality water for high-value crops in closed systems and that, also to comply with the current environmental legislation (at least in some countries), growers should invest for improving the quality of raw water, by means of desalinisation and/or rainwater collection.

The salt accumulation model introduced in the previous paragraph also suggests that the LR may depend on the hydroponic technology adopted and on the physiological characteristics of the crop (they determine the rate of root uptake of both water and minerals).

Table 2 shows that, for a given value of C_U, C_I and the same oscillation in salinity, LR depends on the ratio between V_{TANK} and V. For hydroponic technique in which the water retained by the root zone is fairly low (NFT) or almost negligible (aeroponics), then with V_{TANK} close to V, leaching out the salts accumulated in the system is easier and LR is much lower compared to substrate culture, where more flushing cycles are necessary to decrease the salt concentration in the root zone (see Eq. 16). From the simulation it derives also that using a larger V_{TANK} may result in lower LR for the same substrate (rockwool, in Table 2).

The salinization rate of recycling water in closed system depends also on C_U, which considers both genuine root influx and salt accumulation in the substrate. Predictably, any ion contained in raw water that is not fully absorbed by the plants, accumulates in the recirculating water and in the growing medium, in a proportion that depends on the irrigation method. With sub-irrigation, in reasons of a nearly ascendant water movement, the salts in excess tend to accumulate in the substrate, in particular in the top layers (also as a consequence of selective root mineral uptake) and this results in a much slower salinization rate of the recirculating nutrient solution. Incrocci et al., (2006) recently reported that, in comparison to drip irrigation, subirrigation increased WUE and minimised the leaching of fertilisers in closed rockwool culture of tomato run with irrigation water containing up to 10 mM NaCl.

The procedure for nutrient replenishment may also affect water and nutrient runoff of semi-closed system.

Raviv et al. (1998) tested several control strategies for semi-closed substrate (tuff) culture of roses, which differ for the use of raw or rain water and for the values of EC at which drainage water was discharged. The strategy that minimized the use of water and fertiliser and led to pollution prevention was based on a larger use of rain water, the increase in EC level for drainage and the reduction of fertilisation dose.

In a more recent work (not yet published) with rockwool tomato culture, we tested different strategies to control the recirculating nutrient solution prepared with raw water containing 10 mM NaCl: 1) an EC set-point of approx. 3.0 dS/m was maintained and the nutrient solution was flushed out whenever Na concentration was higher than 20 mM and the concentration of N decreased below 1.0 mM; 2) the crop E was automatically compensated by refilling the mixing tank with fresh nutrient solution (EC = 2.5dS/m) and the recycling water was flushed out whenever EC exceeded 4.5 dS/m; 3) as strategy 2, but when EC reached 4.5 dS/m, the mixing tank was refilled with fresh water only in order to withdraw N from the nutrient solution before discharge. The experiment included also an open system, in order to verify the possible influence of Na accumulation and, in case of strategies 1 and 3, of nutrient depletion on crop performance. No effect of the adopted strategies was observed in terms of crop growth and fruit yield; on the other hand, tomato exhibits a moderate tolerance to salinity, which is further improved by soilless cultivation. As expected, strategies 1 and 3 appeared more sustainable than the other one, on account of much lower water and N losses.

Finally, Incrocci et al. (2003) proposed a sort of cascade cropping system to alleviate the environmental impact of semi-closed cultures. In this system, salt-tolerant crops (e.g. cherry tomato) could be cultivated with salt-enriched nutrient solutions flushed out of a culture with less tolerant species (e.g. round-table tomato). The drain water becomes progressively more saline as each successive species is grown and, in the end, it is drained out when the salinity is too high for profitable cultivation, but the nutrient content is negligible, then safe from the environmental point of view.

CONCLUSIONS

The need for sustainable use of water resources makes, or will make in the very next future, closed growing system compulsory for intensive horticulture. Compared to the open ones, closed systems require more skilful management, especially when the control of nutrient supply is considered. In this sense, the implementation in DSS of crop modelling and recently-invented devices for on-line monitoring of the root environment may provide a tools for effective and efficient cultures.

More tricky is the management of closed system when only saline water is available to the growers. The application of cascade cropping system seems feasible in very few cases, and probably the most valuable strategies is the improvement of water quality, by means of desalinisation or the use of rainwater. On a few species showing a moderate tolerance to salinity, like tomato and melon, the application of some particular procedures for the control of nutrient supply may have positive results in terms of both crop profitability and sustainability. Some of the models introduced in the paper also suggest that the type of hydroponic system adopted by the growers may influence the efficiency by which the crop uses water resources.

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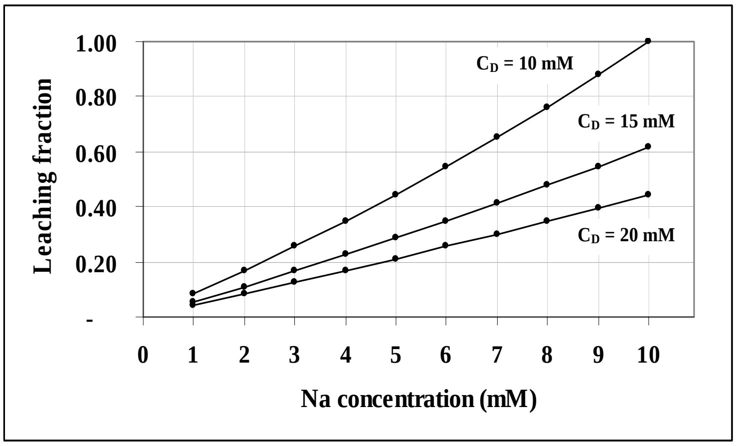

Fig. 1. Leaching fraction for open soilless culture as function of the Na concentration of irrigation water (C_I) and the maximum Na concentration in drainage water (C_D). Na influx concentration (C_U) was assumed to be dependent on irrigation water quality ($C_U = 0.2\ C_I$).

Tables

Table 1. Environmental risk as consequence of potential runoff (R; see Eq. 2 in the text) in substrate culture, in dependence of irrigation efficiency and leaching fraction (after Ross et al. 2001, modified).

Risk	Irrigation efficiency (IE)	Leaching fraction (LF)	Potential runoff
Low	>0.90	<0.15	<0.25
Moderate	>0.80	<0.35	<0.50
High	<0.80	>0.50	>0.60

Table 2. A simulation of the effect of hydroponic technique on leaching requirement (LR) and water loss in semi-closed system, in which the recycling water is periodically discharged by spilling out 1 or N times the mixing tank. Salinity build-up was considered to be a result of Na accumulation only. The simulation was performed using the Eqs. (9; 13-16) reported in the text with the following values: $p = 0.15$; $C_I^{Na} = 10$ mM; $EC_{NS} = 2.5$ dS/m. For calculating water runoff, a crop transpiration of 300 mm was used. See text for abbreviations.

	Rockwool	Rockwool I	Perlite	NFT	Aeroponics
V_{TANK} (mm)	5.0	10.0	5.0	5.0	5.0
V (mm)	15.0	20.0	10.0	6.0	5.2
V_{TANK} / V	0.33	0.50	0.50	0.83	0.97
Number of flushings (N)	8	5	5	2	1
Periodical drain-out at (mm)	40.0	50.0	25.0	10.0	5.0
EC^{MAX} (dS/m)	5.0	5.0	5.0	5.0	5.0
EC^{MIN} (dS/m)	3.4	3.40	3.40	3.4	3.4
$[Na]^{MAX}$ (mM)	36.5	36.5	36.5	36.5	36.5
$[Na]^{MIN}$ (mM)	11.0	10.8	10.8	10.7	10.8
Leaching requirement (LR)	0.65	0.61	0.61	0.40	0.24
Water runoff (mm)	196	183	183	121	71

Table 3. The influence of the strategy used to control mineral supply on some quantities of semi-closed rockwool culture of greenhouse tomato, in comparison with open (free-drain) system For each row, a different letter indicate a significant difference according to LSD test for $P < 0.05$. See text for details.

	Open system	Closed, str. A (constant EC)	Closed, str. B (rising EC)	Closed, str. A+B
Leaching events	-	14	11	8
LR	2.15 a	0.95 b	0.71 c	0.51 d
Water use (mm)	1042 a	574 b	512 c	480 c
Water runoff (mm)	712 a	279 b	212 c	162 d
E (mm)	331 a	295 b	300 ab	319 a
N leaching (g/m^2)	50.7 a	1.3 c	13.3 b	0.9 c
Mean EC (dS/m)	2.97 c	2.93 c	3.65 b	3.93 a
Mean [Na] (mM)	12.2 d	16.2 c	18.5 b	21.9 a
Fruit yield (Kg/m^2)	10.3 a	9.8 a	10.2 a	10.6 a
WUE (L/kg)	101.2 a	58.5 b	50.2 ab	45.2 a