Modeling the Relationship between Water Uptake by Cucumber and NaCl Accumulation in a Closed Hydroponic System

Dimitrios Savvas,¹ Gerasimos Meletiou, Spiridoula Margariti, and Ioannis Tsirogianis

Faculty of Agricultural Technology, TEI of Epirus, P.O. Box 110, 47100 Arta, Greece

Anastasios Kotsiras

Agricultural Institute of Filiatra, Agrokipion, 24300 Filiatra, Greece

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Abstract. In a completely closed hydroponic system, Na and Cl commonly accumulate in the root zone, at rates depending on the concentration of NaCl in the irrigation water (rate of Na and Cl inlet) and the Na to water and Cl to water ratios at which they are taken up by the plants (rates of Na and Cl outlet). However, while the concentration of NaCl in the irrigation water is commonly a constant, the Na to water and Cl to water uptake ratios are variables depending on the concentrations of Na and Cl in the root zone and, hence, on the rates of their accumulation. To quantify this feed-back relationship, a differential equation was established, relating the rate of Na (or Cl) accumulation to the rate of water uptake. This equation was solved according to the classical Runge-Kutta numerical method using data originating from a cucumber experiment, which was conducted in a fully automated, closed-loop hydroponic installation. Four different NaCl concentrations in the irrigation water, 0.8, 5, 10 and 15 mM, were applied as experimental treatments. The theoretically calculated curves followed a convex pattern, with an initially rapid increase of the Na and Cl concentrations in the root zone and a gradual leveling out as the cumulative water consumption was rising. This was ascribed to the gradual approaching of the Na to water and Cl to water outlet ratios via plant uptake, which were increasing as NaCl was accumulating in the root zone, to the constant NaCl to water inlet ratio (NaCl concentration in irrigation water). The model could predict the measured Na and Cl concentrations in the drainage water more accurately at 10 and 15 mM NaCl than at 0.8 and 5 mM NaCl in the irrigation water. Possible explanations for these differences are discussed. Plant growth and water uptake were restricted as salinity was increasing, following a reverse pattern to that of Na and Cl accumulation in the root zone. The leaf K, Mg and P concentrations were markedly restricted by the increasing salinity, while that of Ca was less severely affected.

Closed hydroponic systems enabling recycling of the fertigation effluents in greenhouses are becoming increasingly important, due to limitations in irrigation water availability and environmental concerns (Savvas, 2002a; Van Os, 1999). However, accumulation of NaCl originating from the irrigation water may impose a partial discharge of drainage water (Carmassi et al., 2005; Raviv et al., 1998), thereby reducing the efficiency of closed systems to prevent groundwater contamination with nitrates and phosphates. The use of intelligent automation systems based on mass balance models in closed hydroponic systems could minimize the need to discharge drainage water, thereby reducing groundwater contamination (Le Bot et al., 1999). Since

NaCl originates from irrigation water used to compensate for transpiration losses, a relationship may be established between NaCl accumulation and water uptake, which might considerably contribute to the development of such intelligent systems.

Silberbush and Ben-Asher (2001) have proposed a theoretical model to simulate nutrient uptake and salt accumulation in closed hydroponic systems. This model provides a theoretical understanding of the complexity of factors influencing the uptake and accumulation of ions in a closed system with time. However, factors such as leaf area index, root length density and root surface area, which are involved in the above model, seem to affect the rate of water uptake in a similar way with that of nutrient uptake, since both rates fluctuate much more strongly with time than their ratio (Savvas and Lenz, 1995; Sonneveld, 2002). This response originates from the sharing of transport pathways by CO₂ and water vapour as they pass through leaf stomata, which imposes a nearly constant transpiration to assimilation ratio for a particular plant species, as expressed

in terms of water use efficiency (Hopmans and Bristow, 2002). Also, this is in response to the dominant control of leaf-intercepted radiation on both assimilation and transpiration (Hsiao, 1993). Consequently, relationships between ion to water uptake ratios and the concentrations of these ions in the root zone may be established, by neglecting the impact of any other variable. The above consideration regarding the ion to water uptake ratios is valid also for Na and Cl, since their active exclusion depends on the availability of energy derived from assimilation (Munns, 2002). Sonneveld et al. (1999) used the term “uptake concentrations” to describe the ion to water uptake ratios and showed that for Na and Cl these are exponential functions of their concentrations in the root zone.

In the present paper, we attempt to establish a relationship between Na or Cl concentration in the root zone and cumulative water uptake using a previously established equation between uptake concentrations and concentrations in the root zone (Savvas et al., 2005). The effects of progressively increasing salinity in closed hydroponic systems on plant growth and yield have been studied for few crop species (Bar-Yosef et al., 1999, 2000; Raviv et al., 1998). However, there is no information on the effects of a progressive salinity build-up in the root zone due to recycling of the drainage solution on cucumber grown hydroponically. Therefore, the impact of NaCl accumulation in a closed system on cucumber growth, nutrient uptake, and water consumption, are also addressed in this study.

Materials and Methods

Cucumber (*Cucumis sativus* L. ‘Camaron’) seedlings grown in peat cubes (4×4×4 cm) were transferred at the stage of the third true leaf into channels connected to fully automated hydroponic installations, which enabled complete recycling of the drainage solution (Savvas, 2002b). The experiment was conducted in a glasshouse located in Arta (lat. 39°7’N, long. 20°56’E), Greece. The channels were distributed over 12 independently operating hydroponic systems, which constituted the experimental units. Each experimental unit consisted of two channels, 5 m in length, accommodating 20 plants (10 plants/channel). Porous polyurethane slabs (100×20×6 cm) were used as substrate. The crop density was 1.6 plants per m². The plants were pruned according to the umbrella training system (Klieber et al., 1993). Excessively high summer temperatures were controlled by passive ventilation and automatically operated shading screens. Trickle irrigation was automatically applied by means of a suitable computer program, at intervals depending on solar radiation intensity, which was monitored using a solar energy sensor. All channels were covered with polyethylene sheets and thus water evaporation was negligible. Furthermore, no drainage water was deliberately discharged and any losses due to technical failures were negligible.

Four different nutrient solution treatments were established in a randomized block design, with three blocks. In all treatments, the entire

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¹To whom reprint requests should be addressed; e-mail savvas@teiep.gr.

Table 1. Initial Na and Cl concentrations (mM), and EC (dS·m⁻¹) in drainage solution sampled from the 12 experimental units on the date of recycling initiation (day 0).

NaCl concn in irrigation water (mM)	Na			Cl			EC		
	Replication			Replication			Replication		
	1	2	3	1	2	3	1	2	3
0.8	1.83	1.68	1.77	1.69	1.55	1.46	2.32	2.28	2.28
5.0	7.15	7.36	7.19	6.85	6.90	6.65	2.90	2.95	2.94
10.0	13.56	13.17	13.79	12.82	13.41	13.89	3.65	3.61	3.71
15.0	21.28	20.15	20.49	19.35	19.01	18.82	4.54	4.42	4.49

quantity of drainage water after each application of nutrient solution (irrigation cycle) was captured and recycled in the next watering cycle, regardless of its volume. Nevertheless, the drainage fraction was maintained within the range 0.35 - 0.45 by properly manipulating the cumulative sum of solar energy at which an irrigation events was triggered off. The supply of nutrients was in all treatments identical and could be maintained roughly constant throughout the experiment by means of a previously developed model based on frequent determination of the nutrient concentrations in the drainage water (Savvas, 2002b). The concentration of NaCl in the fresh irrigation water was 0.8 mM. To obtain irrigation water containing 5, 10, and 15 mM NaCl in the salinity treatments, the required quantity of NaCl was automatically computed and injected whenever fresh nutrient solution was prepared, as described in a previous paper (Savvas et al., 2004).

The cucumber seedlings were planted on June 13. Immediately after planting, the seedlings were supplied with nutrient solutions of different NaCl concentrations, depending on the irrigation water used in each treatment. Recycling of the drainage solution was initiated on 18 June (day 0) and the experiment was terminated on 16 Oct. The volume of fresh nutrient solution supplied to the crop at each irrigation event, as well as that of the drainage water collected thereafter and recycled, were automatically recorded in a Microsoft Access database and used to calculate the cumulative uptake of water by the crop. The effect of the increasing NaCl salinity on plant growth was investigated by sampling the vegetative shoot of two plants per experimental unit 0, 9, 23, 57, 91, and 125 d after planting and measuring its dry weight. Furthermore, samples of drainage solution were collected 0, 8, 22, 38, 56, 78, 100, and 120 d after treatment (recycling) initiation and analysed to determine the Na and Cl concentrations. The volume of drainage water was similar in all sampling dates. To study the effects of the increasing salinity on the nutrient status of the plant, samples of young leaves (5th leaf from the apex) were collected 31, 64, 96 and 120 d after treatment initiation, and used to determine the concentrations of K, Ca, Mg and P.

The concentration of Na in the drainage solution was measured by atomic absorption spectrophotometry (GBC 932A/A), while that of chloride was determined by titration with AgNO₃ in the presence of K₂CrO₄ (Eaton et al., 1995). All leaf samples were dried at 80 °C to constant weight, ground, and used to extract K, Ca, Mg, and P by means of 1 M HCl after dry ashing at 550 °C for 5 hours.

The concentrations of K, Ca, and Mg in the obtained extract were determined by atomic absorption spectrophotometry. Phosphorus was measured in the same extract by the vanadomolybdophosphoric acid colorimetric method at 460 nm (Eaton et al., 1995) using a Hitachi U-2001 spectrophotometer.

The data regarding water consumption, yield, and tissue nutrient concentrations were subjected to single factor analyses of variance and plotted in graphs using the PlotIT3.2® work package. The significance of differences between the treatment means in Figures 1, 4 and 5 is indicated by vertical bars depicting ± standard errors.

Model outline

Assuming that water losses via evaporation or discharge of drainage water were negligible, the total volume of water introduced into the closed system, henceforth denoted by V_w , was equal to that removed via transpiration. The nutrient solution remaining into the closed system, henceforth denoted by the subscript s , comprises the solution retained by the substrate and that collected as drainage water. Its volume (V_s) fluctuated only slightly with a mean value of 5.25 L/plant throughout the cropping period, depending on the drainage fraction, which ranged between 0.35 to 0.45, and can, thus, be considered constant. We assume that the concentrations of Na and Cl (mM) in the nutrient solution remaining into the closed system, which are denoted by C_{xs} ($x = \text{Na, Cl}$), are approximately equal with those measured in the drainage solution. The only source of Na and Cl input into the closed system was the NaCl of the irrigation water, whose concentration (mM) is denoted by C_{xw} . This value was constant throughout the cropping period. Since the system was completely closed, the only outlet for Na and Cl was the absorption by the plant, at uptake concentrations (mmol·L⁻¹) denoted by C_{xu} . Any NaCl impurities originating from fertilizers, or solid NaCl depositions on emitters etc. due to evaporation of nutrient solution, are considered negligible. Under these conditions, any increase of C_{xs} is proportional to the increase of V_w and to the difference between the rates of NaCl inlet and NaCl outlet ($C_{xw} - C_{xu}$), and inversely proportional to V_s . Mathematically, this relationship is written as follows:

$$dC_{xs}/dt = dV_w(C_{xw} - C_{xu})/V_s \quad [1]$$

Rearranging Eq. [1], one obtains the following differential equation:

$$dC_{xs}/dV_w = (C_{xw} - C_{xu})/V_s \quad [2]$$

According to Sonneveld et al. (1999), C_{xu} may be expressed as a function of C_{xs} :

$$C_{xu} = aC_{xs}^b \quad [3]$$

where a and b are constant values depending on the crop species. Eq. [3] may be used in a generalized form by introducing an additional constant c to model Na or Cl uptake as a function of its concentration in the root zone:

$$C_{xu} = aC_{xs}^b + c \quad [4]$$

Replacing [4] in [2] one obtains:

$$dC_{xs}/dV_w = (C_{xw} - aC_{xs}^b - c)/V_s \quad [5]$$

In a previous paper concerning cucumber (Savvas et al., 2005), we applied nonlinear regression analysis by using Eq. [4] as a model and we found that a was 0.021 and 0.074, b was 1.652 and 1.302, and c was -0.014 and 0.191, for Na and Cl, respectively. Hence, Eq. [5] can be written as

$$dC_{Na}/dV_w = (C_w - 0.021(C_{Na})^{1.652} + 0.014)/5.25 \quad [6]$$

for sodium, and

$$dC_{Cl}/dV_w = (C_w - 0.074(C_{Cl})^{1.302} + 0.191)/5.25 \quad [7]$$

for chloride.

Eq. [5] is of the type:

$$(dy/dx) = py^a + r \quad [8]$$

In the general case there is no explicit formula $y = g(x)$ (analytical solution) satisfying [8]. Numerical methods have to be used. We use the classical Runge-Kutta method of order four (Butcher, 1987). The independent variable V_w (cumulative water uptake in liters per plant) ranged within the interval [0, 200] in our experimental treatments. Therefore, Eq. [3] is going to be approximated within the interval [0, 200]. The values $C_{xs,0}$ for $V_{w,0} = 0$ (Table 1), which were measured in the drainage solution on the date of recycling initiation (day 0) are used as starting values. We define:

$$F(C_{xs}) = (C_w - aC_{xs}^b - c)/V_s \quad [9]$$

Hence, Eq. [5] becomes

$$(dC_{xs}/dV_w) = F(C_{xs}) \quad [10]$$

According to the Runge-Kutta method, the solution of Eq. [10] consists of number pairs $(C_{xs,0}, V_{w,0}), (C_{xs,1}, V_{w,1}), (C_{xs,2}, V_{w,2}), \dots$, etc., which can be computed as follows:

$V_{w,0} = 0, V_{w,1} = h, V_{w,2} = 2h, V_{w,3} = 3h, \dots$, where h is the step, a small positive number (Butcher, 1987). We use the auxiliary variables K_1, K_2, K_3, K_4 and get $K_1 = hF(C_{xs,0})$, $K_2 = hF(C_{xs,0} + (K_1/2))$, $K_3 = hF(C_{xs,0} + (K_2/2))$, $K_4 = hF(C_{xs,0} + K_3)$, and finally $C_{xs,(n+1)} = C_{xs,n} + (1/6)(K_1 + 2K_2 + 2K_3 + K_4)$ for $n = 1, 2, 3, \dots$

The size of the error of this method is $O(h^5)$. We choose $h = 0.005$, which rendered a good approximation.

Results and Discussion

After continuous recycling of the drainage water for 120 d, the cumulative uptake of water by cucumber was 194 L/plant, when the NaCl concentration in the irrigation water used to compensate for transpiration losses was 0.8 mM. The use of irrigation water containing 5, 10 or 15 mM NaCl, which resulted in much

Fig. 1. Cumulative water consumption during 120 d of drainage solution recycling in a cucumber crop grown in a completely closed hydroponic system as influenced by the NaCl concentration in the irrigation water used to compensate for transpiration losses. Data are presented on a relative basis as a percentage of the treatment with the highest water consumption.

Fig. 2. Sodium concentrations in the drainage water as relationships of the cumulative water consumption during 120 d of drainage solution recycling. Data originate from cucumber crops grown in completely closed hydroponic systems with four different NaCl concentrations in the irrigation water used to compensate for transpiration losses. In each graph, lines indicate the values obtained by solving Eq. [6], while symbols depict measured values in three independent replications.

higher NaCl concentrations in the root zone (see below), restricted significantly the uptake of water to 71.7%, 57%, and 46%, respectively, of that consumed when the NaCl concentration

in water was 0.8 mM (Fig. 1). The suppression of water consumption is a well known effect of salinity, which is associated with decreased shoot growth and hence with restriction of the

transpiring leaf area (Greenway and Munns, 1980). Partial closure of stomatal aperture, which is a well known response of cucumber to salinity (Drew et al., 1990) may have additionally restricted the total water consumption.

Solving Eqs. [6] and [7] according to the Runge-Kutta method rendered the curves shown in Figs. 2 (Na) and 3 (Cl), respectively. These curves predict the courses of Na and Cl concentrations (C_{xy}) in the root zone of cucumber grown in closed hydroponic systems as functions of the water consumption when the NaCl concentration in the irrigation water used to compensate for transpiration is 0.8, 5, 10, or 15 mM (C_{xy}). The actual pairs of values for water consumption and the corresponding Na and Cl concentrations measured in the drainage water during the experiment, are depicted by symbols in Figs. 2 and 3, respectively.

Since all drainage solution was recycled, the volume of irrigation water introduced into the system was equal to that consumed by the plants. The Na to water and Cl to water outlet ratios, which were exclusively due to plant uptake, were enhanced as water consumption was increasing, because NaCl was accumulating in the root zone with time. However, the NaCl to water inlet ratio (NaCl concentration in irrigation water) was constant. Consequently, the differences between inlet and outlet in the Na to water and Cl to water ratios were decreasing as the cumulative water consumption was increasing and this resulted in a convex pattern of Na and Cl increase in the root zone. The obtained curves provided excellent prediction of the actual Na and Cl concentrations in the root zone at 10 and 15 mM NaCl in the irrigation water used to compensate for transpiration losses (Figs. 2c and d, and 3c and d, respectively). At 5 mM NaCl in the irrigation water, the ultimate concentration of Na in the root environment, as predicted by the model, was slightly underestimated, but the divergence from the measured values was still satisfactorily short (Fig. 2b). However, at 0.8 mM NaCl in the irrigation water, the predicted Na concentrations were rather overestimated (Fig. 2a). With respect to Cl, the course of its accumulation could be only roughly predicted by Eq. [7] when the NaCl concentration in the irrigation water was 0.8 and 5 mM (Figs. 3a and 3b, respectively).

The data shown in Figs. 2 and 3 reveal that the model described by Eq. [5] may be used to relate the rate of salt accumulation in the root zone of cucumber grown in closed hydroponic systems to the cumulative water consumption. However, the ability of Eq. [5] to accurately predict the concentrations of Na and Cl in the root zone depends also on the determination of good estimates for a , b , c , as well as on a precise measurement of V_s . The parameters a , b , and c , which may vary considerably among different crop species, are determined by empirical means using nonlinear regression analysis (Savvas et al., 2005; Sonneveld et al., 1999). It is well known that the ability of the plants to minimize the net accumulation of sodium and/or chloride ions is a multigenic trait (Flowers, 2004) and hence each gene can be expressed at different external NaCl

Fig. 3. Chloride concentrations in the drainage water as relationships of the cumulative water consumption during 120 d of drainage solution recycling. Data originate from cucumber crops grown in completely closed hydroponic systems with four different NaCl concentrations in the irrigation water used to compensate for transpiration losses. In each graph, lines indicate the values obtained by solving Eq. [7], while symbols depict measured values in three independent replications.

10 and 15 than at 0.8 and 5 mM NaCl in the irrigation water. Hence, it is reasonable to conclude that the values of a , b , and c used in the present study fitted better at high than at low external NaCl concentrations.

Another aspect to consider with respect to the efficiency of the model described by Eq. [5] to predict the Na and Cl concentrations in the root environment is the validity of a , b , and c under various climatic conditions. It has been stated that the coupling between ion uptake and transpiration rates may disappear at very high transpiration rates (Hopmans and Bristow, 2002), thereby imposing variable uptake concentrations at different dates, even if the concentrations of the corresponding ions in the external solution remain identical (Adams, 2002). Consequently, the high transpiration rates occurring during the summer in our experiment (approximately up to day 80 from treatment initiation) may have occasionally led to higher Na and Cl uptake concentrations than those corresponding to the values of a , b , and c used in the present study, which were based on data partly gained in autumn (Savvas et al., 2005). As a result, the concentrations of Na and Cl in the root zone, which were computed by setting the same values of a , b , and c in Eq. [5] throughout the experiment, may appear overestimated during the summer period when compared with the measured values. This consideration is in agreement with the results shown in Fig. 3 but not with those in Fig. 2, which indicates that such seasonal effects may have influenced mainly the uptake of chloride.

Carmassi et al. (2004) proposed also a model relating the ionic concentration in the nutrient solution comprised in a closed hydroponic system with the ionic and the water uptake. However, these researchers supposed a linear relationship between uptake concentration and concentration of the respective ion in the root environment. With most plant species, exponential relationships between uptake concentrations of Na and Cl and their concentrations in the root environment seem to fit better to experimental data, especially in case of Cl (Baas et al., 1995; Sonneveld et al., 1999).

The progressive increase of NaCl concentration in our closed hydroponic systems due to the presence of 5, 10, and 15 mM NaCl in the irrigation water suppressed significantly the shoot dry weight of cucumber to 76.6%, 59.6%, and 45%, respectively (Fig. 4a). In particular, the dry weight of the shoot (stem and leaves) at the end of the experiment was 350, 247, 183, and 158 g per plant when the transpiration losses were compensated for by using irrigation water with 0.8, 5, 10, and 15

Fig. 4. Development of shoot dry weight during 120 d of drainage solution recycling in a cucumber crop grown in a completely closed hydroponic system as influenced by the NaCl concentration in the irrigation water used to compensate for transpiration losses. Data are presented as (a) a percentage of the treatment with the highest shoot dry weight and (b) in grams per plant. In b, symbols depict measured values while lines correspond to best fit equations.

concentration. Hence, the mechanisms underlying exclusion of Na and Cl from the photosynthetically active leaves of glycophytes may change as the external concentration of NaCl increases. Such changes may not fit well in one and the same regression curve, which means that different estimates for a , b , and c may be required for the low and high range of external NaCl concentrations usually occurring in closed hydroponic systems. In the present study, we used the same values of a , b , and c throughout the studied range of external NaCl concentrations (about 0 to 60 mM NaCl). However, Eq. [5] could predict more accurately the Na and Cl levels in the root zone at

Fig. 5. Concentrations of P, K, Ca and Mg during 120 d of drainage solution recycling in the 5th leaf from the apex of shoots of cucumber grown in a completely closed hydroponic system as influenced by the NaCl concentration in the irrigation water used to compensate for transpiration losses.

mm NaCl, respectively (Fig. 4b). Significant differences between the treatments were first observed 23 d after planting (18 d after recycling initiation), and were further enlarged on day 57, but remained constant thereafter. It has been shown that a gradual exposure of plants to salinity is less detrimental than a rapid increase of the salt concentration, because in the former case the plants can adjust their osmotic status (El-Shourbagy and Ahmed, 1975; Slatyer, 1961). However, this may be of minor significance under conditions of long-term exposure to salinity, since the growth reduction observed in our experiment is comparable with that reported for cucumber by other investigators at similar NaCl levels in the rhizosphere (Drew et al., 1990; Sonneveld and de Kreij, 1999), which were not as gradually imposed as in the present study.

Cucumber is considered a salt sensitive plant species (Drew et al., 1990; Jones et al., 1989). The appreciable suppression of cucumber shoot growth at NaCl levels in the root environment up to 55 to 60 mM (Fig. 4) is in agreement with the above statement. According to Sonneveld (2000), cucumber is specifically sensitive to sodium chloride. Consideration of Figs. 1 and 4a reveals that the impact of salinity on water uptake and plant growth followed a similar pattern. This

is reasonable, since plant transpiration and plant assimilation are physically connected by the concurrent diffusion of water vapor and carbon dioxide through the stomata. However, the suppression of shoot dry mass was stronger than that of water consumption. This indicates that growth may have been inhibited not only due to stomatal limitations. Drew et al. (1990) found that both chlorophyll content and net photosynthesis were adversely affected by salinity in cucumber, while water use efficiency decreased too. Based also on measurements of net assimilation as a function of the substomatal CO_2 concentration, they concluded that the growth of cucumber was suppressed mainly due to impairment of the photosynthetic apparatus at chloroplast level.

The concentration of P in the leaf of cucumber was not influenced as the Na and Cl concentration increased to approximately 30 mM in the external solution, but was suppressed as the levels of Na and Cl in the root zone were further raised to values above 40 mM (Fig. 5a). Diminished leaf P concentrations due to NaCl salinity have been found predominantly in experiments with soil grown crops, and were attributed to reduced activity of P in soil solution (Grattan and Grieve, 1999). In contrast, in soilless grown crops the leaf P concentration is either not affected or increased

by NaCl salinity (Grattan and Grieve, 1999; Kawasaki et al., 1983), presumably because Cl^- and H_2PO_4^- are not competitive in terms of plant uptake (Champagnol, 1979). Cucumber seems to be one of the exceptions, since in the present experiment the leaf P level was markedly reduced when the NaCl concentration in the external solution was higher than 25 mM (10 and 15 mM NaCl in the irrigation water).

The translocation of K to the leaves of cucumber was not significantly reduced after gradual exposure of the plant to external concentrations up to 30 mM NaCl but was markedly restricted at higher salinity levels (Fig. 5b). Reduced K concentrations in cucumber leaf due to NaCl-salinity have been reported also by Drew et al. (1990). Potassium is the most prominent inorganic solute contributing to the maintenance of turgor pressure in cell protoplast (Marschner, 1995). Hence, a restricted K availability may affect physiological procedures depending on turgor maintenance in tissues and cell compartments where a substitution of K by Na is not possible due to the high sodium toxicity (e.g., phloem loading).

The leaf Ca concentration was significantly diminished when the external Na and Cl levels were about 55 and 60 mM, respectively (Fig. 5c). However, in August the leaf Ca concentration was significantly restricted even with

nearly 30 mM NaCl in the root environment. Reduced Ca translocation to the leaf is a common response of many plants to salinity and seems to originate predominantly from the suppression of transpiration rates (Ho and Adams, 1994). The leaf Mg concentration of cucumber exhibited the highest sensitivity to NaCl salinity, since it was diminished on all sampling dates even with about 30 mM Na and Cl in the root zone (Fig. 5d). Nevertheless, the decrease of the leaf Mg concentration was not proportional to the level of salinity as the latter was further increasing. Increased salinity is not always associated with decreases in leaf Mg (Grattan and Grieve, 1999). Hence, the appreciable suppression of leaf Mg even with salinity levels up to 30 mM NaCl, as well as those of K and P, may indicate a specific inability of cucumber to maintain optimal nutrient levels under salt stress conditions. Nevertheless, the leaf K, Ca, and Mg concentrations measured in cucumber leaf in this study were within the corresponding ranges of adequacy (Marschner, 1995) even in the treatments resulting in high salinity levels in the rhizosphere. Hence, it is reasonable to conclude that the restricted translocation of P, K, Ca, and Mg to leaf was a consequence and not a cause of the high salt sensitivity of cucumber.

Conclusions

Cucumber is susceptible to gradual accumulation of Na and Cl in completely closed hydroponic systems. Plant growth, water consumption, and uptake of P, K, and Mg are severely restricted as the Na and Cl concentrations in the root environment increase. The course of Na and Cl accumulation may be predicted as a function of cumulative water uptake and this may be used to create intelligent automation systems enabling a better management of fertigation effluents in closed hydroponic systems. However, the empirically determined parameters linking the Na to water and Cl to water uptake ratios with the Na and Cl concentrations in the root zone may alter to some extent as the latter rise above a threshold, as well as at different seasons of the year. Hence, to obtain a more accurate estimation of the Na and Cl concentrations in the rhizosphere as functions of the cumulative water uptake, further research is needed for each plant species. Such research should be aimed at establishing special relationships between root zone and uptake concentrations of Na and Cl for low and high NaCl concentrations in the irrigation water as well as for different seasons of the year.

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