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Extension and evaluation of a model for automatic drainage solution management in tomato crops grown in semi-closed hydroponic systems

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ABSTRACT

In the present paper, a model previously developed to simulate the course of Na^+ accumulation in closed hydroponic systems as a function of plant water consumption was further extended so as to be operative also in semi-closed and open systems, and evaluated in two experiments with hydroponic tomato. In the first experiment, the efficiency of the model to predict the Na^+ concentration in the recycled solution not only in a closed but also in an open and a semi-closed system was comparably tested. In the second experiment, the model was applied in two semi-closed systems differing in the target drainage fraction (0.3 or 0.6) and an open system used as control. The model proved to be functionally efficient in restricting nutrient and water discharge in semi-closed hydroponic systems, in comparison with open systems, as well as in mitigating salt accumulation in the root zone, in comparison with constantly closed systems. The semi-closed system did not improve yield in comparison with the closed system or water use efficiency in comparison with the open system because the Na concentration in the irrigation water used in the present study (2 mM) was relatively low, but improved appreciably the nutrient use efficiency in comparison with the open system. However, the model failed to accurately predict the course of Na^+ accumulation both in the closed and the semi-closed hydroponic system when applied in a different cultivar ('Belladona') than that used for model calibration ('Formula'). This failure is ascribed to marked differences in Na^+ exclusion efficiency between these two cultivars. Thus, when using this model in semi-closed hydroponic tomato crops, different calibration constants are needed for cultivars with strong genotypic differences in Na^+ exclusion efficiency. The model performance in a crop of the tomato cultivar used for its calibration (i.e. 'Formula') was acceptable for commercial crops, regardless of the applied drainage fraction. On-line monitoring of the actual drainage fraction instead of the use of a mean target value might further improve the ability of the model to predict the actual Na concentration in the root zone of semi-closed tomato crops.

1. Introduction

Soilless cultivation, especially in closed-loop hydroponic systems offers a great option for water saving in greenhouses (Kläring, 2001; Massa et al., 2011). Capture and recycling of the excess irrigation water that drains out of the root zone is possible in closed-cycle soilless growing systems and can considerably improve the water use efficiency in greenhouse crops (Savvas, 2002). This technique might additionally restrict groundwater pollution by nitrates and phosphates (Thompson et al., 2007). The recycling of excess irrigation water applied to greenhouse crops is feasible, since soilless growing systems are becoming increasingly popular among Mediterranean growers.

Irrigation water in Mediterranean countries is characterized by high salt concentrations, including not only Na^+ and Cl^- but also Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Sonneveld and Voogt, 2009). Hence, in most cases, the quality of the available irrigation water in terms of mineral composition is incompatible with the application of completely closed hydroponic systems (Savvas, 2002; van Os et al., 2008). Consequently, to enable Mediterranean growers to adopt cropping systems with recycling of the excess irrigation water, henceforth termed drainage solution (DS), efficient technologies have to be developed to minimize salt accumulation.

To overcome the problem of salt accumulation, two alternative options are possible: The first option is the desalination of poor

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List of symbols and abbreviations

Abbreviations

CLS	closed system
DATI	days after treatment initiation
DF	drainage fraction
DS	drainage solution
EC	electrical conductivity
IS	irrigation solution
NS	nutrient solution
NSCS	nutrient solution for closed hydroponic systems
OPS	open system
SCS	semi-closed system
SS	nutrient solution retained by the substrate (substrate solution)
WUE	water use efficiency

Symbols

a	constant referred to in Eq. (1), dimensionless
b	constant referred to in Eq. (1), dimensionless
C_{Nar}	concentration of Na^+ in the DS and the NS retained in the root zone, mmol L^{-1}
C_{Nau}	Na^+/water uptake ratio, commonly termed uptake concentration, mmol L^{-1}
C_{Naw}	Na^+ concentration in the irrigation water used to prepare NS, mmol L^{-1}
i	number of irrigation events starting from treatment initiation ($i = 1 \ldots n$)
V_d	volume of collected DS after an irrigation event, L
V_s	total volume of NS included in the closed system (sum of DS and SS), L
V_w	net volume of water (excluding reused DS) supplied at the *i*th irrigation event, L
V_{wc}	cumulative net volume of water (excluding reused DS) supplied up to a particular time, L
V_x	volume of water input to a SCS or an OPS supplying as much Na^+ as the Na^+ output through the rejection of V_d liters of DS, L

quality irrigation water, e.g. by means of reverse osmosis technology. The second option is the intermittent opening of the systems (application of semi-closed systems) which considerably restrict the waste of irrigation water (Carmassi et al., 2005; Massa et al., 2010). The second option is much cheaper and therefore much more likely to be adopted by greenhouse growers in the Mediterranean countries. However, to efficiently apply a semi-closed soilless cultivation system, reliable knowledge and technology specifically adapted to the Mediterranean types of irrigation water (rich in NaCl but also in calcium bicarbonates) and climatic conditions is required (Pardossi et al., 2006).

Proper automated management of the recycling process by using suitable techniques and models may minimize the need to discharge DS (Massa et al., 2011). A standard method of DS recycling involves as a first step the preparation of a nutrient solution (NS) with a composition corresponding to the estimated nutrient to water uptake ratios (de Kreij et al., 1999). This solution is termed 'nutrient solution for closed hydroponic systems' (NSCS) and its composition is species-specific. Subsequently, the NSCS is blended with the DS to be recycled. The NS obtained by blending NSCS and DS constitutes the irrigation solution supplied to the crop. The mixing process is automatically adjusted in real time to a ratio resulting in a constant target electrical conductivity (EC) in the outgoing irrigation solution (IS). However, if the EC in the IS is maintained constant, the increase of the EC in the DS due to salt accumulation imposes a decrease in the percentage of DS that is mixed with NSCS and a corresponding increase in the discharged DS (Raviv et al., 1998). Furthermore, if the EC of the IS is kept constant while the concentrations of salt ions increase, the concentration of nutrients will inevitably decrease (Kim et al., 2013). To minimize DS discharge and to prevent a progressive decrease of nutrient concentrations in the IS, the target EC of the latter should be gradually elevated up to a maximum acceptable level (Carmassi et al., 2005).

The adjustment of the target EC might be performed automatically depending on the rate of salt accumulation, thereby optimizing the nutrient supply and minimizing the discharge of DS. However, automation of this process requires either online measurement or model-based prediction of the salt concentrations in the DS (van Os et al., 2008; Kim et al., 2013). On-line monitoring of individual ion concentrations in hydroponic nutrient solutions is an interesting approach but the currently available equipment is expensive and not reliable in the long term (Gieling et al., 2005; Massa et al., 2011). The development of reliable and inexpensive ion-selective electrodes is currently at an experimental level (Kim et al., 2013; Rius-Ruiz et al., 2014). The development of mass-balance models that can be used to simulate concentrations of individual salt ions in the recirculating nutrient solution is a cheaper alternative (Massa et al., 2011). Therefore, in this paper, an automatically managed semi-closed hydroponic system was evaluated in terms of nutrient and water use efficiency, based on a previously developed model that can be used to simulate the course of Na^+ accumulation in closed hydroponic systems as a function of the cumulative plant water consumption (Savvas et al., 2008; Varlagas et al., 2010).

The primary objective of the research reported in this paper was to evaluate the performance of an extended version of a model previously developed by Savvas et al. (2005) when used to manage DS discharge in semi-closed hydroponic systems through simulation of Na^+ accumulation. However, also the impact of the drainage fraction (DF), i.e. volume ratio of the nutrient solution that drains out of the root zone to the total supplied solution, was evaluated in the present paper, because previous research has indicated that it may influence the rate of Na and Cl accumulation in the root zone of hydroponically-grown plants (Sonneveld and Voogt, 2009). Maintaining a higher volume of nutrient solution per plant in closed hydroponic systems is possible by increasing either the volume of substrate per plant or the total volume of DS stored in tanks (Savvas et al., 2006). The latter strategy can be combined with an increased DF, achieved by increasing the volume of IS per irrigation event while not altering the standard irrigation frequency, to maximize salt leaching from the root zone. The increased leaching of salts from the root environment could reduce the mean Na concentration in the root zone during the intervals between two irrigation events, thereby mitigating the impact of NaCl accumulation due to recycling on yield performance. This strategy is feasible when the DS is recycled, since an increased DF in closed hydroponic systems does not increase waste of nutrients and water (Katsoulas et al., 2006). Taking this into consideration, the extended model version that can be used also in semi-closed hydroponic systems to minimize discharge of nutrients and water, was additionally evaluated in an experiment with two distinctly different target drainage fractions.