Development and evaluation of a DSS for fertilisation management in a hydroponic cucumber crop grown in the Mediterranean region

Nikolaos Katsoulas*, Sofia Faliagka, Anastasia Bari, Yiannis Naounoulis

Laboratory of Agricultural Constructions and Environmental Control, Department of Agriculture Crop Production and Rural Environment, University of Thessaly, Fytokou Street, 38446 Volos Magnesia, Greece

*Correspondence: nkatsoul@uth.gr; Tel.: +30-24210-93249

Abstract

The Precimed simulation model was developed to estimate the daily crop potassium (K) and calcium (Ca) uptake and its efficiency was evaluated in a greenhouse soilless cucumber crop grown in the Mediterranean basin. The model simulates crop nutrient needs without requiring complex data. More specifically, the model simulates dry matter production (DMP) taking into account climatic data such as temperature and solar radiation, and in combination with crop evapotranspiration, predicts the actual nutrient uptake of such a crop. Despite some discrepancies, the model performance was adequate as it simulated DMP, K, and Ca uptake sufficiently, resulting in an increased nutrient use efficiency without significantly affecting fruit yield. The model will be further incorporated into a user-friendly Decision Support System (DSS) to provide growers with a weekly nutrient solution recipe for integrated nutrient management in soilless greenhouses.

Keywords: K, and Ca uptake; cucumber; dry matter production; Decision Support System

1. Introduction

Providing nutrients in precise concentrations based on the crop's daily needs is essential in hydroponics, as significantly less nutrient depletion could be achieved especially in open- and semi-open loop systems. The notion of "zero emissions" has been widely studied in the agricultural sector; however, the optimization of water and nutrient inputs remains of high importance in the Mediterranean region, an area characterized by relatively poor quality water that prevents continuous recycling of the nutrient solution used in hydroponics (Katsoulas and Voogt, 2014). Precision irrigation and fertilisation practices decrease leaching losses resulting in more efficient water and nutrient use and lower groundwater contamination (Pratt, 1984). Simulation models and their further incorporation into DSS have been extensively proposed for the Mediterranean area as an indirect method of assessing crop water and nutrient needs in soilless cultivations (Pardossi et al., 2004; Marcelis et al., 2005; Gimenez et al. 2012). Indeed, nowadays, simulation models are being developed using a range of algorithms to be further integrated into DSS to provide the end-users with some valuable information in terms of fertigation management (Katsoulas Stanghellini, 2019). However, the majority of these models require a large dataset to run properly, making their use complicated for growers and advisors (Gimenez et al. 2012). The ultimate purpose of this work was to develop a user-friendly simulation model for precision fertigation and assess its ability to predict the daily K, and Ca demands of a soilless cucumber crop to be further integrated into a DSS to provide greenhouse growers with a weekly nutrient recipe based on the crop's growth stage as an alternative method to the conventional-current fertigation approach followed by the majority of the growers.

2. Materials and Methods

2.1. Model description

A simulation model has been developed to estimate the daily nutrient needs of a crop by correlating crop's DMP with nutrient uptake (K, and Ca). Several climatic data are required for the model to function properly, such as the daily maximum and minimum temperature and solar radiation (SR) inside the greenhouse.

Three main components have to be simulated in order the model to run properly, which are the fraction of intercepted photosynthetically active radiation ($f_{i\text{-PAR}}$), the DMP, and the nutrient uptake. At first, the cumulative thermal time of a certain day (CTT_i) can be calculated by adding the thermal time (TT_i), that is calculated as the average of the maximum and minimum air temperature recorded for that day, to the CTT accumulated up to that date. Moreover, the relative thermal time (RTT_i) for a certain day is calculated as the ratio between the CTT_i to the CTT at the maximum PAR interception (CTT_f), i.e. at the full canopy growth stage. Using all the above parameters, the model simulates the $f_{i\text{-PAR}}$ for each of the RTT values (Eq. 1) as follows:

$$f_{i-PAR} = f_o + \frac{f_f - f_o}{1 + B * \exp^{(-a*RTT_i)}} \quad \text{(Eq. 1)}$$

where f_o and f_f represent the initial and the maximum $f_{i\text{-PAR}}$ at the transplantation and full growth stage, respectively. The f_o value is considered to be close to zero (f_o=0.02). The coefficient a, is the equation fitting coefficient and is equal to 12 when it comes for cucumber crops (Gallardo et al. 2016). In Eq.1, B is a coefficient expressed as a function of the half relative thermal time period ($RTT_{0.5}$) and it is equal to the inverse of $\exp^{(-a*RTT_{0.5})}$ representing the RTT at which $f_{i\text{-PAR}} = 0.5 * (f_f + f_o)$.

To simulate the DMP of a crop, a series of coefficients correlated with solar SR need to be calculated. The mean daily PAR inside the greenhouse (RAR_{ins}) is expressed as the product of the mean daily solar radiation ($SR_{in\text{-}i}$) multiplied by the duration (seconds day^{-1}) of the sunlight from the sunrise to the sunset of a given day and the ratio of PAR/SR for plastic greenhouses that is 0.43, according to Kittas et al. (1999). Thus, the daily PAR interception ($PAR_{int\text{-}i}$) is expressed as the product of the $f_{i\text{-PAR}}$ for a given day, and the RAR_{ins}. $SR_{in\text{-}i}$ is calculated after the multiplication of the integral of the external solar radiation with the transmissivity of the cladding material used to cover the roof of the greenhouse, as suggested by Gallardo et al. (2016). The daily increment of the DMP (ΔDMP_i) can be calculated as the product of the daily $PAR_{int\text{-}i}$ and the radiation use efficiency (RUE) for a given day. Thus, the DMP of a given day is the sum of the ΔDMP_i and the total DMP accumulated up to that date. Dry matter production concerns the aboveground plant material, exclusively. However, it is important to note that the notion of the dry matter production includes the total biomass produced by the plant up to the tested date, together with the pruned or harvested materials that may have been removed from the crop.

As shown in Eq.2, after calculating the DMP, the simulated critical nutrient content (% Nutrient) is calculated using the critical nutrient dilution curve of Greenwood et al. (1990):

$$\text{Simulated crop nutrient content } (\%\ \text{Nutrient}_i) = a * DMP_i^b \quad \text{(Eq. 2)}$$

, where "a" is the nutrient content accumulated in the dry biomass and "b" the statistical parameter affecting curve's degree of the relationship (dimensionless) when DMP_i=1 t ha^{-1}. The a and b coefficients derived from literature, and calibrated by Gallardo et al. (2016, 2021) for tomato crops when DMP_i>1 t ha^{-1} and they are presented in Table 1. In case DMP_i values are less than 1 t ha^{-1}, the simulated nutrient content equals to the constant "a" coefficient.

Table 1. Coefficients a, and b derived from the nutrient dilution curves power equations.

	K	Ca
a	4.51	2.32
b	-0.157	-0.227

Finally, crop's nutrient uptake (g m^{-2}) for a given day is determined after Eq.3 using Eq.2, and is calculated as the product of ΔDMPi and the estimated critical nutrient content (% Nutrient) for that day:

$$\text{Crop Nutrient uptake} = \%\text{Nutrient}_\text{i} * \Delta\text{DMP}_\text{i} \qquad \text{(Eq. 3)}$$

After calculating all the aforementioned coefficients, a weekly nutrient recipe is recommended to the end-user after dividing crop's nutrient uptake (Eq.3) by the evapotranspiration values predicted for that period.

2.2. Experimental setup

An experiment was conducted at the Laboratory of Agricultural Constructions and Environmental Control of the University of Thessaly in Velestino (latitude 39°44', longitude 22°79', altitude 85 m), Greece. The experiment was performed in a greenhouse compartment with a total ground area of 240 m^2. Plants were irrigated either through a standard nutrient solution (NS) comprising the conventional treatment (CT) or through a simulated NS provided by the Precimed model comprising the improved treatment (IT). Contrary to the CT, the NS corresponding to the improved treatment was produced once per week based on the nutrient uptake forecast provided by the model.

Climatic data from the greenhouse facilities were collected using a climate control computer (Sercom, Netherlands) from October to December and used as input to the simulation model. The duration of the experiment was 77 days. During that period, a soilless cucumber crop (*Cucumis sativus* cv. Columbia) was grown inside the greenhouse compartment that is consisted of 6 hydroponic channels (3 channels/treatment). In total, 216 (108 plants/treatment) cucumber plants with a density of 1.1 plants m^{-2} were grown on perlite substrates (Hydroperl, NORDIAAGRO, Athens, Greece). Three of these non-adjacent hydroponic lines were used as the control treatment of the experiment, comprising 3 replications per treatment, where the CT were applied, whilst the remaining lines of the greenhouse compartments were used to assess the efficiency of the improved treatment.

Table 2. Mean values of the maximum and minimum temperature (°C) and the integral of solar radiation (MJ m^{-2} day^{-1}) during the experimental period

Experimental Months	Maximum Temperature (°C)	Minimum Temperature (°C)	Average Solar Radiation (MJ m^{-2} day^{-1})
October	29.5 ± 1.00	14.1 ± 0.27	6.2 ± 0.50
November	25.4 ± 0.93	13.3 ± 0.19	3.4 ± 0.33
December	23.1 ± 0.72	15.1 ± 0.62	3.3 ± 0.27

2.3. Measurements

Measurements concerning the DMP were performed to validate the accuracy of the model. For this reason, several plants were marked inside the greenhouse compartment from the beginning of the experimental setup. At each pruning or harvesting practice, the aboveground plant material that is the leaves, stems and fruits were collected, weighted and then oven-dried at 70°C to constant weight. Moreover, 10 destructive measurements (n=4, per treatment) took place during which whole marked plants were cut aboveground, and separated into leaves, stems and fruits following the same drying procedure as described for the agronomic practices. Thus, the total DMP was calculated as the sum of the dry biomass resulting from each destructive measurement and the dry matter of all pruned and harvested plant material up to that date.

3. Results and discussion

3.1. Model calibration

Several coefficients were used to calibrate the Precimed model and start the simulation process and they are presented in Table 3.

Table 3. Calibration coefficients of the simulation model

Calibration coefficients	**Value**
Fraction of intercepted PAR at the stage of transplantation (f_o)	0.02
Maximum fraction of intercepted PAR (f_f)	0.95
Equation fitting coefficient (shape coefficient, a)	12.0
Half relative thermal time ($RTT_{0.5}$) when $f_{i\text{-}PAR} = 0.5 * (f_f + f_o)$	0.53
Radiation use efficiency (RUE, *g MJ^{-1} PAR*)	5.00

The relationship between the simulated and measured dry matter production values is presented in Fig. 1. A good correlation of simulated and measured DMP values was observed, as confirmed by the relatively high values of the determination coefficient (R^2=0.89). These results are in line with those of Gimenez et al. (2012), who proved a very accurate simulation of DMP for pepper crops cultivated in a plastic soil-based greenhouse. However, in the present work, the Precimed simulation model underestimated the DMP from 28 to 46 days after transplantation (DAT) by approximately 35%. This can be explained by emphasising the dependence of the simulation model on the solar radiation, as the recorded SR was very low during the range of the aforementioned DAT.

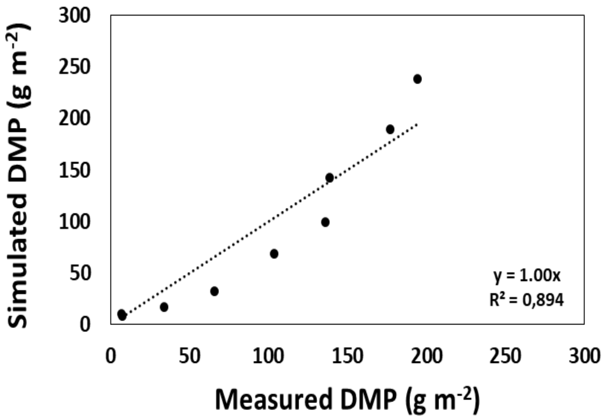

Figure 1. Scatter plot of linear regression analysis for measured and simulated DMP (g m^{-2}) values.

3.2. K and Ca simulation

As shown in Fig. 2 (a), the model simulated crop's K uptake accurately, as most of the measured and simulated values demonstrated a similar trend and were significantly close to the 1:1 line. A good correlation between the measured and simulated values was recorded, showcasing a good determination coefficient (R^2=0.93) and a root mean square error (RMSE) of 1.79 g m^{-2}. Moreover, in the case of the Ca uptake simulation, a significant linear correlation was found when plotting the simulated versus the measured values which is also confirmed by the high determination coefficient (R^2=0.91) (Fig. 2 (b)). This good agreement is also reflected by the statistical parameter RSME which was 1.86 g m^{-2}. The results of the present work are consistent with those of Gallardo et al. (2021), who accurately simulated the K, and Ca uptake of a soil-grown tomato crop and a soilless cherry-tomato crop. However, the initial inputs of the dilution curves used to calibrate the model may be further optimised, as both simulations significantly underestimate the initial K, and Ca uptake. In general, the measured values of K, and Ca uptake during the first 30 days were higher as compared to the simulated ones, while the opposite was observed for the following days.

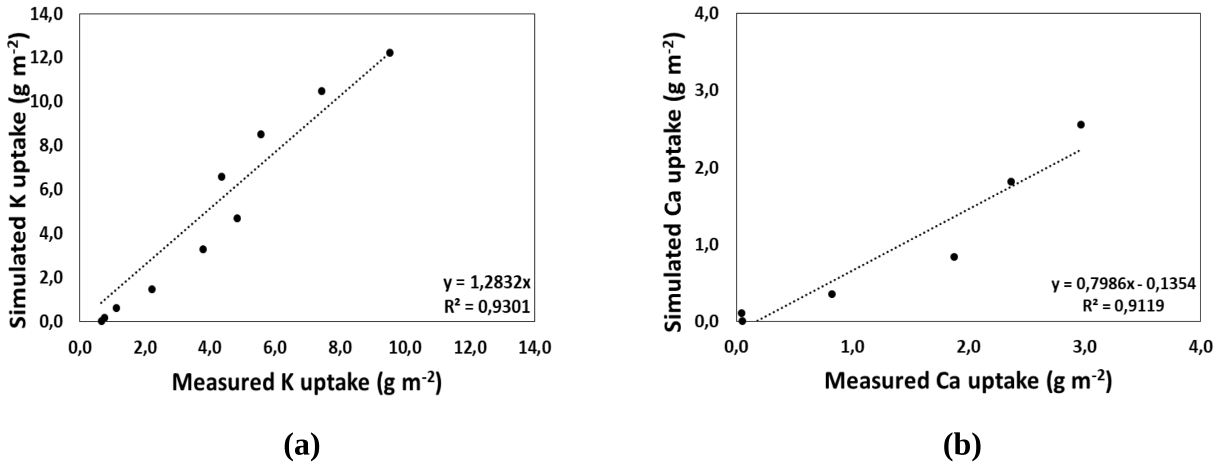

Figure 2. Scatter plot of linear regression analysis for measured and simulated (a) K and (b) Ca concentration values (g m^{-2}).

The evolution of the mean height recorded for the plants of the two different fertigation treatments for several DAT is presented in Fig. 3. As the simulation model depends to a great extent on solar radiation, a nutrient saving of more than 50% was recorded for the plants of the improved treatment. Despite the lesser amount of nutrients imposed to the plants through the nutrient solution of the IT, no significant morphological differences were observed (data not shown). This is also confirmed by the final productivity recorded for the two fertigation treatments, presenting a decrease of only 8% in the case of the improved treatment.

Moreover, taking into consideration fruit yield, i.e. fruits fresh weight (FW), as well as the total amount of nutrients used for both treatments, a significant increase in the nutrient use efficiency (NUE) was observed for the IT. A NUE of 12.86 and 38.22 kg FW kg^{-1} was recorded for the conventional and improved Prcimed treatment, respectively.

4. Conclusion

In general, the Precimed model accurately simulated K and Ca uptake, showcasing the potential for precise fertigation in hydroponics to limit nutrient losses. The productivity of cucumbers fertigated under the model's recommendations reduced only by 8%. However, the integrated fertigation management resulted in a 66% increase in nutrient use efficiency. This model has the potential of predicting more macro-nutrient uptake concentrations (e.g. N, P, and Mg), promoting the development of an integrated decision support system to provide the end-user with an integrated nutrient management program in hydroponics.

Acknowledgements

The work is carried out in the frame of the PRECIMED project that is funded by the General Secretariat for Research and Technology of the Ministry of Development and Investments of Greece under the PRIMA Program. PRIMA is an Art.185 initiative supported and co-funded under Horizon 2020, the European Union's Program for Research and Innovation. Project Acronym/Code: "PRECIMEDPrima2018-09". Project application number: 155331/I4/19.09.18.

References

Gallardo, M., Cuartero, J., Andújar de la Torre, L., Padilla, F.M., Segura, M.L., Thompson, R.B. 2021. Modelling nitrogen, phosphorus, potassium, calcium, and magnesium Uptake, and uptake concentration, of greenhouse tomato with the VegSyst model. *Scientia Horticulturae* 279,109-862

Gallardo, M., Fernandez, M.D., Gimenez, C., Padilla, F.M., Thompson, R.B., 2016. Revised VegSyst model to calculate dry matter production, critical N uptake and ETc of several vegetable species grown in Mediterranean greenhouses. *Agric. Syst.* 146, 30–43.

Gimenez, C., Gallardo, M., Martınez-Gaitan, C., Stockle, C. O., Thompson, R. B., Granados, M. R. 2013. VegSyst, a simulation model of daily crop growth, nitrogen uptake and evapotranspiration for pepper crops for use in an on-farm decision support system. *Irrig. Sci*. 31:465–477

Greenwood, D.J., Lemaire, G., Gosse, G., Cruz, P., Draycott, A., Neeteson, J.J. 1990. Decline in percentage N of C3 and C4 crops with increasing plant mass. *Ann. Bot.* 66:425–436

Katsoulas and Voogt. 2014. Recent trends in salinity control for soilless growing systems management. *Acta Horticulturae* 1034(1034):433-442

Katsoulas, N., Stanghellini, C. 2019. Modelling Crop Transpiration in Greenhouses: Different Models for Different Applications. *Agronomy*, *9*, 392.

Kittas, C., Baille, A., Giaglaras, P. 1999. Influence of cover material and shading on the spectral distribution of light under greenhouse. *J. Agric. Eng. Res.* 73:341–351

Marcelis, L.F.M., Brajeul, E., Elings, A., Garate, A., Heuvelink, E., De Visser, P.H.B. 2005. Modelling nutrient uptake of sweet pepper. *Acta Hortic*. 691, 285–292.

Pardossi, A., Tognoni, F., Incrocci, L. 2004. Mediterranean greenhouse technology. *Chron. Hortic.* 44(2):28–34

Pratt P.F.1984. Nitrogen use and nitrate leaching in irrigated agriculture. In: Hauck RD (ed) Nitrogen in crop production. *American Society of Agronomy*, Madison, pp 319–333