Modelling nitrogen, phosphorus, potassium, calcium and magnesium uptake, and uptake concentration of greenhouse tomato with the VegSyst model

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ABSTRACT

The existing version of the VegSyst model (V2) simulates daily dry matter production (DMP), crop evapotranspiration (ETc) and crop N uptake of tomato and other vegetable crops grown in greenhouse in SE Spain. In this study with greenhouse tomato, (i) the VegSyst model was adapted to simulate daily values of seasonal (i.e. throughout the crop) uptake of K, P, Ca and

Mg, (ii) the simulation of seasonal N, K, P, Ca and Mg uptake was validated, and (iii) the simulation of seasonal uptake concentration (UC) of N, K, P, Ca and Mg was validated. For K, P, Ca and Mg, dilution curves (i.e. relationship of crop content of the nutrient (%) to DMP) were obtained from pooled data of six treatments from two greenhouse tomato crops. These relationships were all described by power equations with R^2 values of 0.72–0.92 for all nutrients, except Mg that had a R^2 of 0.40. For the simulation of tomato crop N uptake, the dilution curve previously used in V2 was replaced by the critical N curve for tomato of Padilla et al., (2015). The simulation of uptake of N, K, P, Ca and Mg was validated with a spring, soil-grown, long-life type, tomato crop (Tomato-11) and two long season soilless cherry tomato crops (Cherry-16 and Cherry-17). Seasonal uptake of N, K, P and Ca was adequately simulated in the three validation crops, with best performance (Relative Error (RE) ≤0.2) in the Cherry-17 crop. In the three validation crops, modelling of Mg uptake had a poor performance. For simulation of UC in the two cherry tomato crops, there was good performance for N, K, P and Ca in Cherry-17, and reasonable to good performance in Cherry-16. The simulation of the UC for Mg was poor. The revised VegSyst model, identified as V3, will be incorporated into a decision support system (DSS) to provide recommendations for nutrient solution composition for soil-grown and soilless tomato crops grown in greenhouses.

Keywords: *Solanum lycopersicum*, uptake concentration, fertigation, modeling, macronutrients, Decision Support System

1. Introduction

Intensive vegetable production in plastic greenhouse is an economically important industry in southeast (SE) Spain. This greenhouse system is mostly concentrated in the province of Almeria, where there are 32,000 hectares of greenhouses. The system also extends along the neighbouring coastal provinces of Granada, Malaga and Murcia. Fresh tomato is one of the most important crops in this system (Valera et al., 2016). The two major regions for fresh tomato production in Spain are the provinces of Almeria and Granada with 10,100 and 3,300 ha, respectively (MAPAMA, 2020). Various types of tomato, for fresh consumption, are produced in greenhouse production in these provinces. Cherry tomato is one of the most important types, representing 20% of production and 36% of economic value (Junta de Andalucía, 2018).

Approximately 90% of the greenhouse surface area in SE Spain is cropped in soil, the rest in soilless systems (García et al., 2016). For both cropping media, irrigation and nutrients are frequently applied to drip irrigated vegetable crops using advanced fertigation systems (García et al., 2016; Thompson et al., 2007; 2017a). These fertigation systems have the technical capacity to frequently apply nutrients and irrigation as required by the crop (Thompson et al., 2017a). However, this technical capacity is not effectively used because most growers apply nutrients and irrigation based on local experience of what ensures high levels of production (Thompson et al., 2007; 2017a). There is little use of scientific tools to ensure that applications match crop requirements.

The customary practice of applying standard complete nutrient solutions using experiential management (Thompson et al., 2007) is associated with excessive nutrient application. This is apparent in the considerable nitrate (NO_3^-) contamination of underlying aquifers (Pulido-Bosch et al., 2018; BOJA, 2015), and the accumulation of available phosphorus (P) and exchangeable potassium (K) in greenhouse soils (Gil de Carrasco, 2000). Additionally, excessive nutrient application represents an unnecessary regular cost for growers. Given that growers have the technical capacity for precise, frequent nutrient and irrigation application, they require tools that enable them to take advantage of this technical capacity.

Optimal nutrient management of soil-grown vegetable crops, using advanced fertigation systems, requires detailed knowledge of nutrient requirements. Given that calculations of crop nutrient requirements are based on crop nutrient uptake, accurate information on the uptake of nutrients throughout individual crops is necessary. Nutrient uptake of macronutrients, defined here as nitrogen (N), phosphorous (P), potassium (K), calcium (Ca) and magnesium (Mg), during the crop, has been determined experimentally for greenhouse tomato in SE Spain (Alarcón et al., 2001; Rincón Sánchez et al., 1991; Segura et al., 2007) and elsewhere (Adams and Massey, 1984; Signore et al., 2016; Voogt, 1993). However, it is very difficult to extrapolate nutrient uptake from individual experimental crops, to an individual commercial crop. There is considerable variation amongst commercial crops in cropping dates, weather conditions, greenhouse and soil characteristics, and crop management practices.

Given the variability of nutrient uptake with time, amongst commercial crops, the most effective way to anticipate the dynamics of nutrient absorption, of a particular crop, is the use of simulation models. Simulation models can calculate the daily uptake of a nutrient considering the specific conditions of an individual crop.

For soil-grown fertigated vegetable crops that frequently receive nutrient solution, nutrient uptake rates can provide a basis for the amounts of nutrients to be applied. In soilless crops, the concentration of nutrients applied in the nutrient solution can be effectively managed using the uptake concentration (UC) of a given nutrient (Sonneveld and Voogt, 2009). The UC is the ratio between the uptake of a nutrient and the transpiration of water, in the same period of time (Sonneveld and Voogt, 2009). This ratio, which is expressed as concentration (e.g. mmol L^{-1}) has no physiological basis, but is very useful for the optimization of the composition of nutrient solutions (Sonneveld and Voogt, 2009). The potential for management based on uptake concentrations was demonstrated for N management of soilless tomato by Thompson et al., (2013), who reported recoveries of applied N as high as 82% in a free-draining system when the UC N concentration was generally slightly less than or very similar to the applied N concentration.

The VegSyst simulation model (Gallardo et al., 2011; 2014; 2016; Giménez et al., 2013) calculates daily dry matter production (DMP), crop N uptake, and crop evapotranspiration

(ETc) of the main greenhouse crops in SE Spain. This model has been integrated into a decision support system (DSS), the VegSyst-DSS, that provides recommendations for daily irrigation rates, daily nitrogen (N) fertiliser rate and the daily N concentration in the nutrient solution for seven vegetable species grown in greenhouses in Almeria (Gallardo et al., 2014; 2017). A MS Windows® compatible version in English and Spanish is available at https://w3.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml.

In order to optimise the management of all macro nutrients using VegSyst-DSS, it is necessary to make recommendations for K, P, Ca, and Mg in addition to N. For soil-grown crops, to provide recommendations for these nutrients, it is firstly necessary to simulate their daily uptake. For soilless crops, simulation of daily uptake concentration of each nutrient will provide an intermediate step in the development of recommendations of nutrient concentrations in applied nutrient solution.

Various models and DSSs simulate N uptake of greenhouse vegetable crops (Le Bot et al., 1998; Gallardo et al., 2020), and of open field vegetable crops (e.g. Machet et al., 2007; Rahn et al., 2010; Elia and Conversa, 2015). Other models simulate uptake of other nutrients for soilless greenhouse vegetable crops, using empirical (Pardossi et al., 2004) or mechanistic photosynthesis-driven approaches (e.g. Bar-Yosef et al., 2004; Marcelis et al., 2005; Ramírez-Pérez et al., 2018). We are unaware of (i) applications of models for practical nutrient management of greenhouse crop, or (ii) models that simulate uptake of K, P, Ca and Mg in soil-grown, greenhouse vegetable crops. No models provide these functions for greenhouse tomato crops in SE Spain.

The adaptation of VegSyst-DSS to provide recommendations of the concentrations of macronutrients, according to crop demand, will reliably enable optimization of crop growth by matching the supply of N, K, P, Ca and Mg to crop demand. This will result in an appreciable reduction of fertiliser costs. These concentration recommendations will be science-based guidelines for farmers and technical advisors for the formulation of nutrient solutions. The initial step to achieve this, is to model daily crop uptake of K, P, Ca and Mg, in addition to daily N uptake.

The present work consisted of three components. Firstly, the VegSyst model was calibrated and validated to simulate seasonal DMP and ETc of cherry tomato. Secondly, the VegSyst V2 simulation model (Gallardo et al., 2016) was modified to simulate the daily uptake and uptake concentration of N, K, P, Ca and Mg for tomato. Thirdly, simulations of daily uptake and uptake concentrations of N, K, P, Ca and Mg by the VegSyst model were validated using data from a soil-grown, spring, long-life, tomato crop and two soilless, autumn to summer, cherry tomato crops.

2. Materials and Methods

2.1. Calibration and validation of the VegSyst model for cherry tomato

Site and cropping details

The VegSyst V2 model, described by Gallardo et al. (2016), was calibrated for cherry tomato (*Solanum lycopersicum* L.). Two cherry tomato crops, grown in seasons 2016-17 and 2017-18, were used for calibration and validation. The crops were grown in a commercial plastic greenhouse located in Motril, Granada (36°73´N, 3°48´W and 80 m elevation). The greenhouse was a "Parral-type" greenhouse (Castilla and Hernández, 2005) of 6.5 ha with no heating and a roof of low density polyethylene cladding. A representative area of 500 m^2 was used for the experimental work, in both seasons. The 2016-17 cherry tomato (cv. Angelle), hereafter referred to as Cherry-16, was grown from 14 September 2016 to 20 June 2017 (279 days). The 2017-18 cherry tomato (cv. Bambelo), hereafter referred to as Cherry-17, was grown from 14 September 2017 to 14 May 2018 (242 days). Both crops were grown in 30 L perlite slabs placed in PVC trays with a 1% longitudinal slope; each tray held three perlite slabs. They were free-draining crops. Crop density was 0.95 plants m^{-2} (3 plants per slab, 2.25 m between rows of slabs and 0.4 m between slabs in the same row). Six-week old seedlings, were transplanted into the perlite slabs. Plants were vertically supported by nylon cord guides; they were pruned and managed following local practices.

In both crops, complete nutrient solutions were applied in all irrigations through a drip irrigation system (3 emitters per slab, discharge rate of 3 L h^{-1}, with one dripper per plant). The nutrient solutions used (Table 1) were prepared in accordance with established local practice to ensure adequate crop nutrition. The composition of the nutrient solution for each crop was maintained throughout the crop. The applied volumes of nutrient solution maintained a drainage fraction of 15–20%. Irrigation frequency was controlled with a demand tray system (Gallardo et al., 2013); fixed volumes were applied.

Table 1. Composition of the nutrient solutions, with the exception of micronutrients, for the 2011 tomato crop (Tomato-11) and the two cherry tomato crops (Cherry-16 and Cherry-17).

	EC	pH	NO_3^-	H_2PO_{4-}	SO_4^{-2}	HCO_3^-	NH_4^+	K^+	Ca^{+2}	Mg^{+2}
Tomato-11	2.5	6.9	12.0	2.5	4.9	4.4	0.5	6.5	4.0	3.6
Cherry-16	1.9	6.5	10.2	1.2	2.7	1.5	0.3	6.8	3.6	1.7
Cherry-17	1.8	5.9	9.9	1.3	2.4	0.8	0.4	5.8	3.4	1.6

The concentration of nutrients is expressed in mmol L^{-1}; EC in dS m^{-1}

In both crops, all measured parameters were the mean of four replicates. Climatic conditions (solar radiation, air temperature, relative humidity) were continuously monitored using a climate station (Model WatchDog 1650, Spectrum Technologies Inc., Aurora, IL, USA)

Measurements

In each crop, daily transpiration was determined using a water balance approach, as the difference between the measured daily volumes of irrigation and drainage. Given that no evaporation occurred from the perlite slabs, which were completely enclosed with plastic, transpiration was considered to be equal to crop evapotranspiration (ETc). Daily irrigation and drainage were measured in four replicate PVC drainage trays; each tray contained three perlite slabs with 9 plants and 10 drippers; irrigation volume was measured in the 10th dripper without a plant. Each drainage tray was positioned mid-way along the length of a crop row; the crop rows were selected to ensure representative sampling of the greenhouse. The daily volume of irrigation was collected in 5 L containers, in each of the four replicate drainage trays. Analysis of the composition of the nutrient solution (Table 1) was conducted every month in samples collected separately from two drippers. The analyses of the nutrient solution were conducted in a commercial laboratory. Drainage from each drainage tray was collected in underground enclosed 25 L containers.

Measurements of aboveground dry matter production (DMP) throughout the growing season, of each of the two cherry tomato crops, were made by harvesting two plants, once per month, in each of the four replicate plots. At each biomass sampling, the amounts of dry matter in leaves, stems and fruits were determined. Dry matter determinations were made by weighing all fresh material of each component, and by oven-drying representative samples at 65°C until constant weight. Additionally, the amounts of all pruned shoot material and fruit production were determined throughout each crop, in the nine plants in each of the four replicate drainage trays. At each pruning, the amount of dry matter removed was determined, as described previously. For the Cherry-16 and Cherry-17, respectively there were a total of 9 and 10 biomass samplings, and 20 and 25 prunings with dry matter determinations in each pruning. During the cropping cycle there were 37 and 49 fruit harvests, in the Cherry-16 and Cherry-17 crops, respectively. The dry matter content of harvested fruits was determined three times in Cherry-16, and six times in Cherry-17 and applied to the closest harvests in time. For each biomass sampling, total shoot DMP was determined from the sum of dry matter of leaves, stems and immature fruits for that sampling date, plus the combined dry matter of all pruned material and harvested fruit until that sampling date.

Crop macronutrient (N, K, P, Ca, Mg) content was determined in the following way. Representative samples of dry matter samples of (i) leaves, stems, and fruit from various biomass samplings, (ii) pruned material from various prunings and (iii) fruit from various harvests were separately finely-ground. For the Cherry-16 crop, samples for macronutrients analysis were obtained from four biomass samplings (every two months) and from two fruit harvests. For other harvest during the crop, it was assumed that the nutrient content was the same as that of the closest analysed sample in time. For pruned material of the Cherry-16, it was assumed that it had a ratio of leaves to stems of 75:25, and that the nutrient content of each component was the same as that in the biomass sampling that was closest in time.

For the Cherry-17 crop, samples for analysis of nutrients were obtained from eight biomass samplings (every month), ten prunings, and six fruit harvests. For other prunings and harvests during the crop, it was assumed that the nutrient content was the same as that of the closest analysed sample in time.

The nutrient contents of plants samples were determined as follows. Total N content was determined with an elemental analyser (Model TRUSPEC CN628, LECO Corporation, MI, USA). The contents of K, P, Ca and Mg were determined by Inductively Coupled Plasma (ICP) sprectrometry (Model ICAP 6500DUO, ThermoFisher Scientific, MA, USA) after sample digestion. Above-ground crop uptake of each analysed element was calculated for each biomass sampling, in each crop, as the sum of uptake in leaves, stems and immature fruit, plus the uptake in pruned and harvested material until the biomass sampling. For each component, on each date, uptake was calculated as the product of dry matter production and element content.

2.2. Development of dilution curves for macronutrients in tomato

Dilution curves, i.e. the relationships between uptake of a given nutrient and dry matter production (DMP) in a well-fertilised crop, were developed for long-life tomato for K, P, Ca and Mg. Data from two earlier studies were used. Data from one study were obtained from Segura and Contreras, (2014) and from M.L. Segura (IFAPA La Mojonera, Almeria, Spain, unpublished data). Data for the other study was from Castilla, (1986). The tomato crops from these two studies were grown in plastic greenhouses in Almeria in “enarenado” soils, that are typically used in Almeria greenhouses (Castilla, 2013; Thompson et al., 2007). They were grown with drip irrigation and fertigation, and crop management followed local practices.

In the study of Segura and Contreras (2014), the long-life tomato crop (cv. Pitenza) was grown from 9 October 2004 to 17 May 2005 (220 days) with a planting density of 1.6 plants m^{-2}. In that study, a factorial experimental design was used with electrical conductivity (EC) of irrigation water (two levels) and fertiliser applications of N, P and K (three levels) being the main factors. For the current study, data from treatments of the two EC treatments (0.6 and 2.2 dS m^{-1}) and the fertiliser treatments providing 100% and 200% of expected crop uptake (Segura and Contreras, 2014) were used. Hereafter, these four treatments will be referred to as Segura-100-EC0.6, Segura-100-EC2.2, Segura-200-EC0.6, and Segura-200-EC2.2. Data from three samplings during the crop of DMP and crop uptake of K, P, Ca and Mg, in each of the four treatments were used. Full details of the experiments and methodology are presented in Segura and Contreras (2014) and Segura et al. (2009).

In the study of Castilla (1986), a long-life tomato crop (cv. Vemone) was grown from 26 October 1982 to 28 May 1983 with a planting density of 2 plants m^{-2}. In this study, three N treatments of 200, 400 and 600 kg N ha^{-1} were applied; the other nutrients were supplied to ensure that they were not deficient. Data from the 400 and 600 kg N ha^{-1} treatments were used in the current study. Data from six samplings of DMP and crop uptake of K, P, Ca and Mg were used in the present study. Full details of the experiment and methodology are given in Castilla (1986).

2.3. Adaptation to VegSyst to simulate uptake of macronutrients and uptake concentrations

In the VegSyst version V2 model, described by Gallardo et al., (2016), the outputs of the model were daily values of DMP, ETc and crop N uptake. In the present work, simulations of daily uptake of major macronutrients apart from N (i.e. of K, P, Ca and Mg) were added to the model, using the same general methodology described for N (Gallardo et al., 2016). As for N, uptake of K, P, Ca and Mg, for a given day (i) was the product of DMP_i, i.e. the DMP of that day, and the simulated crop nutrient content (%) for that day, calculated as follow:

$$\%Nutrient_i = a \times DMP^{b}_{i} \qquad (1)$$

were a and b are calibration factors determined from fitting power equations to the series of experimental data of nutrient content versus DMP; the data were from the studies described in section 2.2. For each nutrient, daily uptake was calculated as the product of simulated dry matter production and nutrient content. For N uptake, the critical N curve determined, for greenhouse tomato in SE Spain, by Padilla et al., (2015) was used, replacing the N dilution curve for tomato that was previously used in the VegSyst V2 model (Gallardo et al., 2014).

Uptake concentration (UC) of macronutrients was simulated for N, K, P, Ca and Mg, on a daily basis, as the ratio of simulated daily nutrient uptake and simulated daily evapotranspiration (ETc). To simulate ETc, the Almeria radiation equation calibrated for SE Spain (Fernández et al., 2010) was used because of its accuracy and simplicity (Gallardo et al., 2016). VegSyst also has a Penman-Monteith equation, modified for local conditions (Gallardo et al., 2013), as an alternative. The simulation of UC was conducted in the two cherry tomato crops described in section 2.1.

2.4. Evaluation of model performance to simulate the uptake of macronutrients and the uptake concentration

The performance of the simulation of uptake of N, K, P, Ca and Mg in tomato by VegSyst, developed in section 2.3, was validated using experimental data from three tomato experiments. One crop was a long-life spring tomato crop (cv. Ramyle) grown from 14 March 2011 to 14 July 2011, hereafter referred to as Tomato-11. The nutrient solution used in this crop to ensure adequate nutrition of all nutrients, is presented in Table 1. Full details of this experimental crop are given in Gallardo et al. (2014) including seasonal evolution of DMP, ETc and crop N uptake. To determine the periodic crop uptake of K, P, Ca and Mg of the Tomato-11 crop, K, P, Ca and Mg contents were determined in five samplings of biomass, two of pruning material and in four fruit harvests. For other prunings and harvests during the crop, it was assumed that the nutrient content was the same as that of the closest analysed sample in time. Representative samples of leaves, stems, and fruit were finely ground. The contents of K, P, Ca and Mg were determined by ICP (Model ICAP 6500DUO, ThermoFisher Scientific, MA, USA) after digestion. Above-ground crop uptake of each element, was calculated for each date of biomass sampling from the corresponding data of DMP and the element content of all constituent components, as described in Section 2.1. The Cherry-16 and Cherry-17 crops, described in section 2.1, were used for validation of the nutrient uptake model developed in section 2.2.

The simulated uptake concentration (UC) of N, K, P, Ca and Mg was validated using data of the Cherry-16 and Cherry-17 crops; measured values of ETc were available for both crops. For the validation of UC of each nutrient, firstly, second degree polynomial curves were fitted to the measured values of cumulative curves of both seasonal ETc (as crop water consumption) and nutrient uptake. For all nutrients in both crops, these relationships had coefficient of determination (R^2) values of >0.98. Daily values of nutrient uptake and of ETc were determined as the derivatives of the polynomial functions.

2.5. Statistical indices to evaluate model performance

To evaluate the agreement between simulated and measured values, the following statistical indices were used: (i) the root mean square error (RMSE), (ii) the relative error (RE) (Stöckle et al., 2004) and (iii) the Willmott index of agreement (Willmott, 1982). Values of RE ≤ 0.25 and d ≥0.75 were considered to indicate good model performance, following Yang et al., (2014). The values of these three statistical parameters were presented in tables in the Results section. However, only the relative or dimensionless indices, i.e. RE and d, were referred to in the text. RMSE has the same units as the variable; therefore, it is not appropriate to compare variables with different units (Yang et al., 2014).

3. Results

3.1. Calibration and validation of VegSyst for cherry tomato

The VegSyst version V2 model described by Gallardo et al. (2016) was calibrated for cherry tomato to simulate daily values of dry matter production (DMP) and ETc. The Cherry-16 crop (described in section 2.1) was used for calibration, and the Cherry-17 crop for validation. For the calibration of cherry tomato, the calibration parameters for long-life tomato presented in Table 2 of Gallardo et al. (2014) were mostly used. The exceptions were (i) a radiation use efficiency (RUE) value of 3.0 instead of 4.0, and (ii) maximum and final crop coefficient (Kc) values of 1.4 and 1.0, respectively, instead of the value of 1.0 previously used for both Kc parameters in long-life tomato (Gallardo et al., 2014).

Measured and simulated values of cumulative seasonal DMP, and of daily ETc averaged for weekly periods, of the Cherry-16 and Cherry-17 crops are presented in Fig. 1. There was generally very good agreement between the simulated and measured values of cumulative DMP throughout the calibration and validation crops (Fig. 1a). The exceptions were the last three samplings dates of the validation Cherry-17 crop when DMP was overestimated by the model. The combination of two severe late season prunings at 174 and 186 DAT, and the occurrence of a bacterial infection (*Pseudomonas syringae*) in the latter part of the crop explain the discrepancy in the last three DMP samplings of the Cherry-17 crop. The statistical indices showed very good model performance for DMP simulation in the Cherry-2016 crop (RE=0.08, d=1.0; Table 2). The results were slightly inferior for simulation of cumulative DMP in

Cherry-17 (RE=0.30, d=0.95; Table 2), largely because of the last three sampling points included in the analysis. The performance of the model was also evaluated from planting until DAT 180, prior to the Pseudomonas infection; for this period, the statistical indicators indicated a very good model performance (RE=0.10, d=0.99; Table 2).

The model performed very well for simulation of daily ETc (averaged for one week), with a good agreement between measured and simulated values in the Cherry-16 calibration crop, and until 180 DAT, in the Cherry-17 validation crop (Fig.1b, c). After 180 DAT in the validation crop, there was a notably larger difference between measured and simulated values. Considering the complete cropping season, the statistical indices indicated that model performance for simulation of ETc throughout the Cherry-17 validation crop was moderately good (RE=0.34, d=0.81) (Table 2), and that model performance was good when the evaluation was conducted until DAT 180 (RE=0.18, d=0.90; Table 2). The lower values of measured ETc in relation to the model from DAT 180 on, were consistent with the underestimation of DMP in the same period (Fig. 1a).

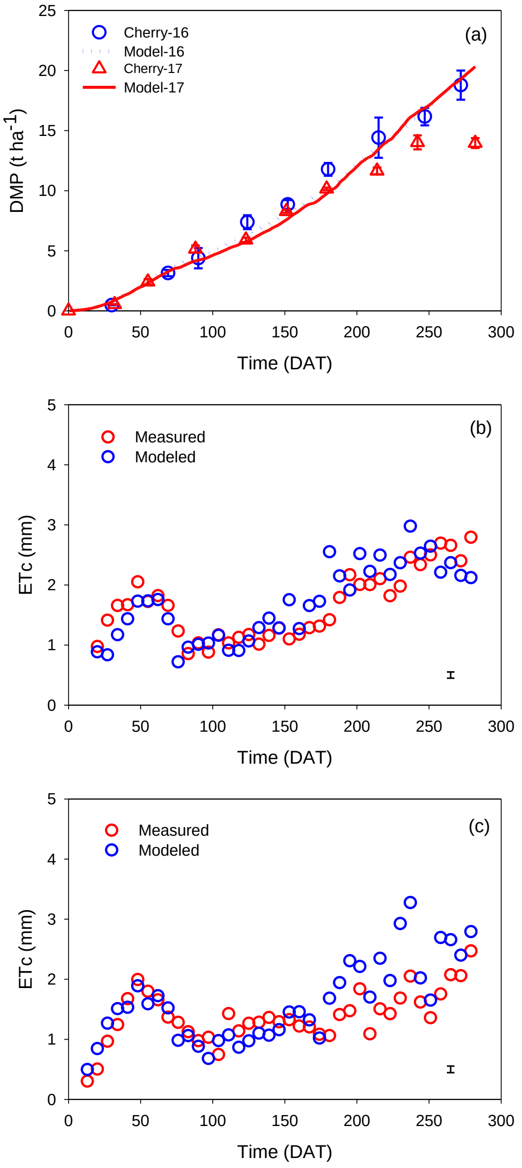

Fig.1. Time course of the simulated and measured values of (a) dry matter production for the two cherry tomato crops (b) daily ETc for the Cherry-16 crop and (c) daily ETc for the Cherry-17 crop. The daily ETc values presented are averages of daily rates for one-week periods. Vertical bars represent ± the standard error.

Table 2. Summary of results of the statistical indices used to evaluate the performance of the model for simulation of dry matter production (DMP), and cumulative ETc for the Cherry-16 and Cherry-17 crops. For the Cherry-17 crop, statistical indices for the period from planting to DAT 180 were included to evaluate the performance of the model prior to the incidence of the

bacterial infection. RMSE: root mean square error; RE: relative error; d: Wilmott index of agreement . n is the number of data.

Parameter	Crop	n	RMSE	RE	d
DMP	Cherry-16	9	0.73	0.08	1.00
	Cherry-17	9	2.38	0.30	0.95
	Cherry-17 (180 DAT)	6	0.52	0.10	0.99
ETc	Cherry-16	38	0.38	0.23	0.89
	Cherry-17	39	0.48	0.34	0.81
	Cherry-17 (180 DAT)	24	0.22	0.18	0.90

3.2. Dilution curves for macronutrients

The relationships between the contents of K, P, Ca and Mg in total plant biomass and DMP were determined using pooled data from six treatments of tomato from two studies, as described in section 2.2. The relationships between the contents of K, P, Ca and Mg with DMP of the pooled data were described by power equations with R^2 values of 0.77, 0.92, 0.72 and 0.40, respectively (Fig. 2). The data of Castilla-600 (see section 2.2) were not included for fitting of the power equation for K-DMP because of the unusual large fluctuations in the data (Fig. 2a). For the relationships, K-DMP and Mg-DMP, the elemental content values from Castilla-400 and Castilla-600 were generally well above the values for corresponding DMP values in the four Segura treatments, probably because of luxury consumption (Fig. 2a, d). The relationship Mg-DMP had the lowest R^2 value since data were more scattered (Fig. 2d).

3.3. Validation of the model for uptake of macronutrients

The use of the VegSyst model modified in this study (hereafter, referred to as VegSyst model V3) to simulate crop uptake of N, K, P, Ca and Mg was validated using three different crops, the soil-grown Tomato-11, and the soilless Cherry-16 and Cherry-2017 crops, described in sections 2.1 and 2.4, respectively. The simulation of crop N uptake was also evaluated because as described in section 2.3, the VegSyst V3 model, used in the present work, uses the critical N curve of Padilla et al. (2015) rather than the N dilution curve described by Gallardo et al. (2014) that was used in previous versions of the model.

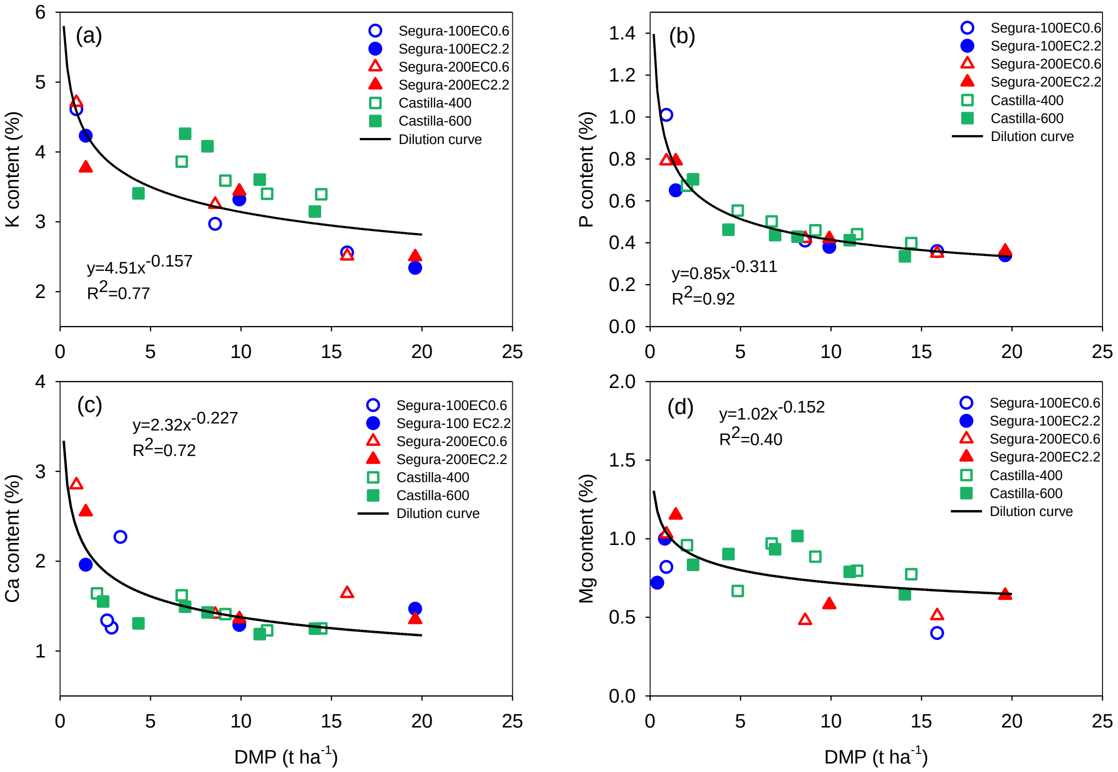

Fig.2. Relationships between dry matter production and (a) K content, (b) P content, (c) Ca content and (d) Mg content. In all panels data from four treatments of Segura and Contreras (2009) and two treatments of Castilla (1986) are included. In each panel, a power equation fitted to the pooled data is included with the exception of panel 2a where data of Castilla-600 were not included in the fitted equation.

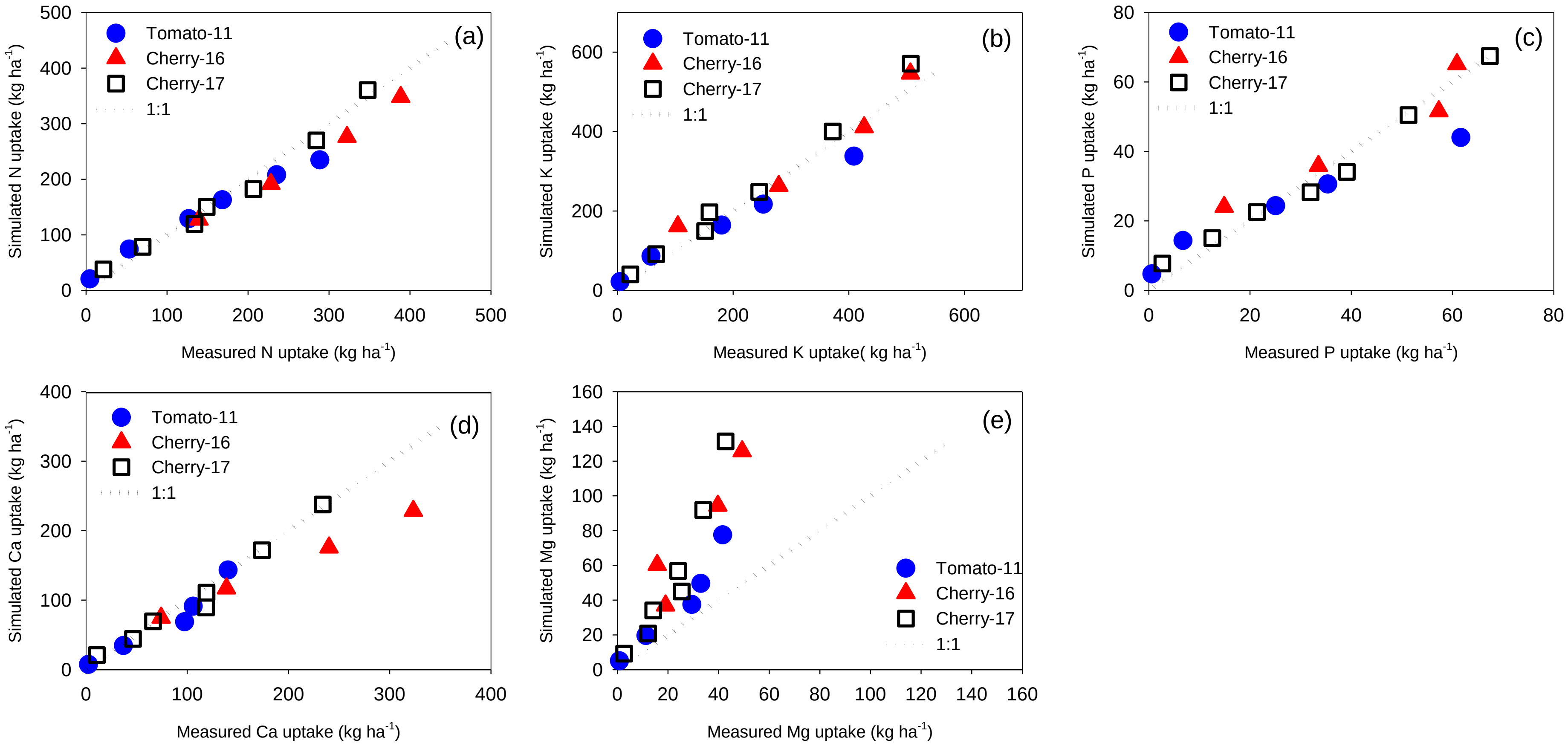

Fig.3. Simulated versus measured values of crop uptake of (a) N, (b) K, (c) P, (d) Ca and (e) Mg for the Tomato-11, Cherry-16 and Cherry-17 crops. The 1:1 line is shown in all figures.

Simulated values of N, K, P, Ca and Mg uptake were plotted against measured values, for the three validation crops in Fig. 3. For N, K, P and Ca uptake, most values were close to the 1:1 line (Fig. 3a-d; Table 3), indicating that the model adequately simulated uptake in the three validation crops. The simulation of Mg uptake was the exception (Fig. 3e). The statistical indices (Table 3) showed in general a good model performance for the simulation of N, K, P, and Ca uptake (Table 3). For these nutrients, the least accurate simulations were for P uptake in Tomato-11 (RE=0.35, d=0.93), and for Ca uptake in Cherry-16 (RE=0.30, d=0.87). Apart from these two cases, RE values were ≤0.22 and d≥0.96, for N, K, P, and Ca uptake (Table 3). The Cherry-17 crop, which had the largest data set and was the validation crop for DMP, had excellent performance for the simulation of uptake of all macronutrients, except Mg, as indicated by the statistical indices (RE≤0.15, d≥0.99; Table 3), and the very close proximity of values to the 1:1 line (Fig. 3). The model overestimated Mg uptake in the Tomato-11 crop and substantially overestimated it in the Cherry-16 and Cherry-17 crops (Fig. 3e); the statistical indices showed a poor performance of the model to simulate Mg uptake in the three validation crops (Table 3).

Table 3. Summary of results of the statistical indices used to evaluate the performance of the model for simulation of N, K, P, Ca and Mg uptake (kg ha^{-1}) for the Tomato-11, Cherry-16 and Cherry-17 crops. RMSE: root mean square error; RE: relative error; d: Wilmott index of agreement. n is the number of data.

Parameter	Crop	n	RMSE	RE	d
N uptake	Tomato-11	6	26.9	0.18	0.98
	Cherry-16	4	36.6	0.14	0.96
	Cherry-17	7	14.7	0.09	1.00
K uptake	Tomato-11	5	39.0	0.22	0.98
	Cherry-16	4	36.5	0.11	0.98
	Cherry-17	7	31.9	0.15	0.99
P uptake	Tomato-11	5	9.1	0.35	0.93
	Cherry-16	4	5.9	0.14	0.97
	Cherry-17	7	3.2	0.10	0.99
Ca uptake	Tomato-11	5	11.8	0.15	0.98
	Cherry-16	4	58.4	0.30	0.87
	Cherry-17	7	12.3	0.11	0.99
Mg uptake	Tomato-11	5	18.6	0.80	0.81
	Cherry-16	4	52.7	1.71	0.45
	Cherry-17	7	43.4	1.96	0.51

3.4. Simulation and validation of uptake concentrations

Measured and simulated daily values of uptake concentration (UC) of macronutrients, for the dates of biomass sampling are presented in Figs. 4a-e for Cherry-16, and in Figs. 4f-j for Cherry-17. Daily simulated values (averaged weekly) for the entire cropping season are included in Fig. 4 for both cherry tomato crops.

Simulated UC values for each macronutrient varied during the cropping season as a function of crop growth stage and climatic conditions (Fig. 4). In both crops, simulated UC values, generally had a pattern of rapid initial decline to approximately 50 DAT followed by relatively constant values, during the winter months (from early November to end of February) until approximately DAT 160, after which modelled values declined slowly (Fig. 4). The decline in Spring (from end of February to early summer) (Fig. 4) is attributed to a larger relative increase in transpiration compared to nutrient uptake.

In general, excluding Mg, the simulation of UC for the different macronutrients was acceptable. Model performance of simulation of UC was consistently better for all nutrients for Cherry-17 than for Cherry-16 (Table 4), which was consistent with simulation of uptake (Table 3). In Cherry-16, the model had acceptable performance for the simulation of UC of N, K and P ($RE \leq 0.29$, $d \geq 0.84$), and poorer performance for Ca ($RE=0.27$, $d=0.62$; Table 4). In Cherry-17, the model had excellent performance for simulation of UC of N, P and Ca ($RE \leq 0.15$, $d \geq 0.85$; Table 4) and poor performance for simulation of UC of K ($RE=0.19$, $d=0.21$). In both Cherry-16 and Cherry-17, the model appreciably overestimated UC of Mg (Fig. 4e, 4j), with large errors (Table 4) in both crops.

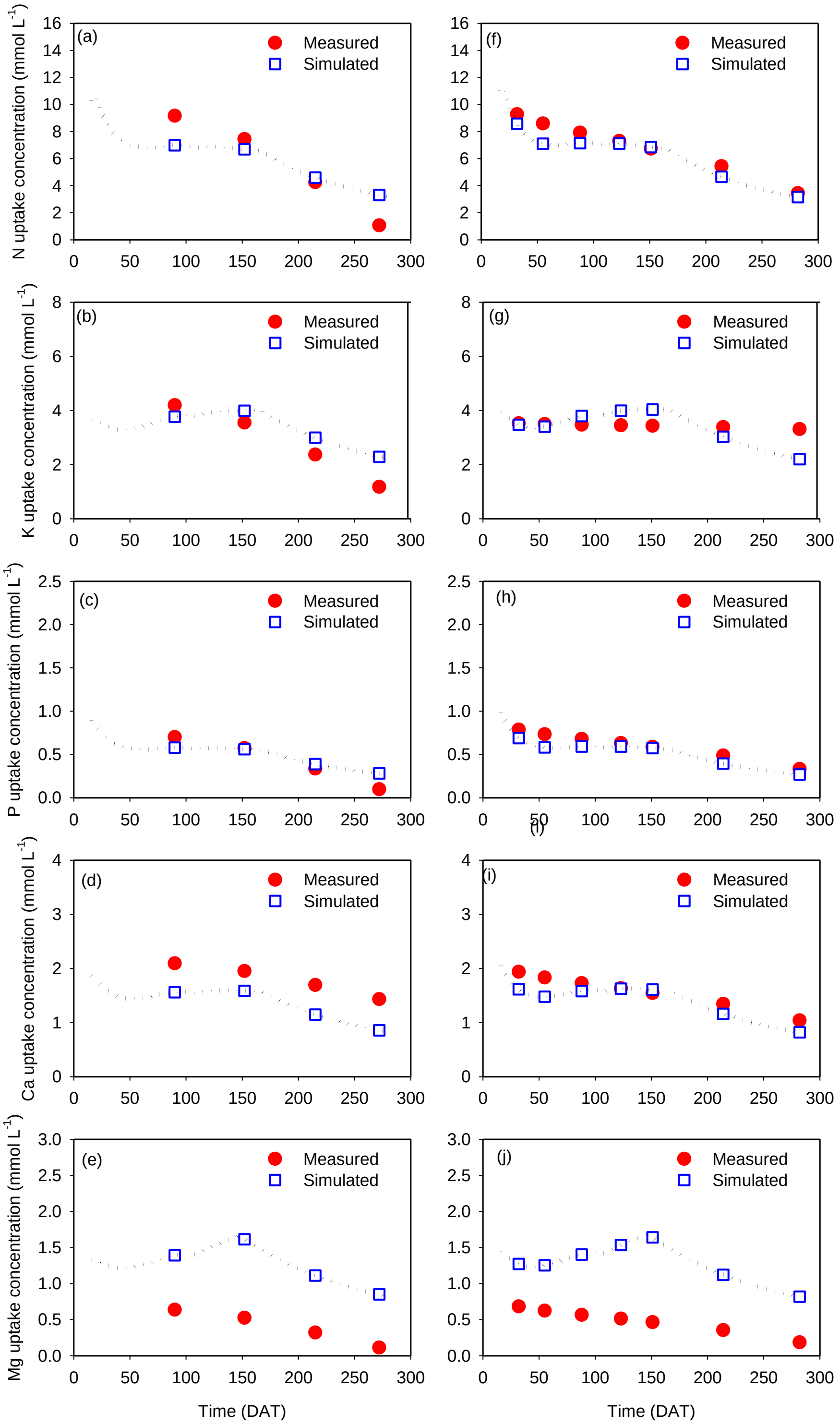

Fig.4. For the Cherry-2006 (4a to 4e) and Cherry-17 crops (4f to 4j), seasonal evolution of measured and simulated values of the uptake concentration of N (4a, 4f), K (4b, 4g), P (4c, 4h), Ca (4d, 4i) and Mg (4e, 4j). The uptake concentration values presented with symbols correspond to daily values for the sampling dates; the continuous broken line is the simulated uptake concentration for the complete growing season.

Table 4. Summary of results of the statistical indices used to evaluate the performance of the model for simulation of uptake concentration (UC) (mmol L^{-1}) of N, K, P, Ca and Mg for the Cherry-16 and Cherry-17 crops. RMSE: root mean square error; RE: relative error; d: Wilmott index of agreement. n is the number of data.

Parameter	Crop	n	RMSE	RE	d
N UC	Cherry-16	4	1.57	0.29	0.89
	Cherry-17	7	0.82	0.12	0.95
K UC	Cherry-16	4	0.78	0.28	0.84
	Cherry-17	7	0.65	0.19	0.21
P UC	Cherry-16	4	0.11	0.27	0.90
	Cherry-17	7	0.09	0.15	0.91
Ca UC	Cherry-16	4	0.49	0.27	0.62
	Cherry-17	7	0.23	0.15	0.85
Mg UC	Cherry-16	4	0.86	1.73	0.18
	Cherry-17	7	0.83	1.72	0.23

4. Discussion

This work presents a revised version of the VegSyst simulation model, VegSyst model V3, in which additional outputs have been incorporated. Earlier versions of the VegSyst model simulated, for several greenhouse vegetable crops, daily values of DMP, crop N uptake, ETc and the recommended nutrient solution N concentration to apply (Gallardo et al., 2011; 2014; 2016; Giménez et al., 2013). The additions in the new version of the model simulate daily crop uptake of K, P, Ca and Mg, and daily values of the uptake concentrations of these four macronutrients, for tomato. The present study also adapted the VegSyst model to cherry tomato. Previously, it had been calibrated and validated for long-life type tomato (Gallardo et al., 2014).

4.1 Simulation of macronutrient uptake

The VegSyst model was adapted and calibrated to simulate uptake of K, P, Ca and Mg, and validated for the simulation of uptake of N, K, P, Ca and Mg. Nitrogen uptake was included in the validation, because the N dilution curve used for tomato in previous versions of VegSyst (Gallardo et al., 2014) was replaced by a critical N curve (Padilla et al., 2015).

To simulate uptake of macronutrients, dilution curves (i.e. relationships between the content of a nutrient (%) and total DMP) were developed with data from two earlier studies with tomato. Using these data, the contents of K, P, Ca and Mg declined as DMP increased. This decline has been well characterized for N (Greenwood et al., 1990; Lemaire and Gastal, 1997). However, there are few data available for other nutrients, particularly for vegetable crops. The dilution curves developed in the present work for K, P, Ca and Mg were similar to those of Marcelis et al. (2005) for greenhouse-grown pepper, with the exception of Ca that remained constant in the work of Marcelis et al. (2005). Marschner (2012) reported that declines in mineral nutrient content were common as plants age, with the exception of Ca and sometimes of iron and boron. This decline is the result of a relatively larger increase in structural material and storage compounds, than of nutrient accumulation as plants grow

In the present work, the relationships between the contents of K, P, Ca and Mg, with DMP were described by power equations. The best fitting curve was for P with a R^2 of 0.92, and the worst was for Mg with a R^2 of 0.40. The higher nutrient contents for the K-DMP and Mg-DMP curves, from the Castilla-400 and Castilla-600 treatments compared to the four treatments from Segura and Contreras, (2014), were attributed to luxury consumption on account of larger K and Mg applications, and that K and Mg were applied at pre-planting and by fertigation in Castilla (1986). The relatively low R^2 value for the Mg-DMP relationship was related to the notable scatter of these data (Fig. 2d). The Mg contents of the Castilla-400 and Castilla-600 treatments (Castilla, 1986) were unusually high in relation to other published values for tomato grown in greenhouses (e.g. Rincón Sánchez et al., 1991; Gertsson, 1995; Alarcón et al., 1977; Signore et al., 2016).

In the three validation crops for nutrient uptake (soil-grown tomato, two soilless cherry tomato crops), the model adequately simulated N, K, P and Ca uptake. The accuracy of simulation of these four macronutrients in Cherry-2017 was particularly notable. For the validation of Mg uptake, the model slightly overestimated the soil-grown crop and appreciably overestimated the two soilless cherry tomato crops. Future work will be required to establish the relationship between DMP and Mg content in tomato.

There are few models that simulate the dynamics of uptake of macronutrients, other than N, particularly for use in practical fertiliser management of vegetable crops grown in greenhouses. For soilless greenhouse sweet pepper, Marcelis et al. (2005) developed a mechanistic photosynthesis-driven model to simulate DMP, and to calculate macronutrient uptake in plant organs as a function of organ age. Similarly, Juárez-Maldonado et al. (2014) developed a mechanistic photosynthesis-driven model to simulate growth and macronutrient uptake of different organs in greenhouse soilless tomato. Their model was subsequently calibrated for cucumber by Ramírez-Pérez et al. (2018) to simulate growth and uptake of N, P and K. Several models of macronutrient uptake have been specifically developed for closed soilless crops. Examples are the empirical model of Pardossi et al. (2004) for melon, the mechanistic substrate-climate model of Bar-Yosef et al. (2004), and the simulation model of crop water and mineral relations of Massa et al. (2011). These models are examples of models as aggregation of science; we are unaware of practical application of these models for crop nutrient management.

4.2 Simulation of uptake concentration of macronutrients

In general, the adapted VegSyst model provided good simulation of the uptake concentration (UC) of N, K, P, and Ca. The exception was Mg where the model consistently and appreciably overestimated measured UC values. The results for the UC simulation were similar to those of simulation of nutrient uptake, with similarly better general performance in the Cherry-2017 crop. In the Cherry-2016 crop, there were some notable discrepancies between measured and simulated values for Ca. The simulation of the Mg uptake concentration was poor in both crops, which was a consequence of the poor simulation of Mg uptake.

There are few published studies that model UC of greenhouse grown vegetable crops. Two examples are Gallardo et al. (2009) and Voogt et al. (2006). Gallardo et al. (2009) developed an aggregated model for open soilless greenhouse tomato combining TOMGRO (Jones et al., 1999) to simulate crop N uptake, and PrHo (Fernández et al., 2009; Gallardo et al., 2020) to simulate ETc. Combining these models allowed calculation of daily N uptake concentration. However, while this study demonstrated that accurate modelling of UC was possible, the TOMGRO model is too complex for practical application. The Fertigation Model of Voogt et al. (2006) was developed as a DSS for water and nutrient management of soil-grown greenhouse crops. It calculates daily uptake and the UC of macronutrients. However, this model has only been validated for N uptake of chrysanthemum, and has not been validated for vegetable crops.

Modelling UC of nutrients is challenging since the output of two modelled processes, nutrient uptake and water uptake (or ETc), are combined in a ratio. This magnifies errors due to (i) the combination of the errors associated from the two sub-models, and (ii) error amplification when the divisor is small. The use of the derivative of cumulative values, as in the present work, to obtain daily values of the component parameters, reduces the error of UC calculation.

4.3. Recommendations for nutrients solutions

The intended end use of the simulation of nutrient uptake and of uptake concentration, by the VegSyst model, is to provide recommendation of nutrient concentrations for nutrient solutions applied to vegetable crops grown in greenhouses. It is envisaged that simulated nutrient uptake values be used for soil-grown crops, and simulated uptake concentration for soilless crops. These recommendations would form a nutrient management plan to be used as the prescriptive part of a prescriptive-corrective management approach (Granados et al., 2013; Thompson et al., 2017a, 2017b). The subsequent corrective part would involve the use of crop/soil monitoring to make adjustments to ensure optimal crop nutrient status.

For soil-grown crops, the simulated applied N concentration use the daily N balance approach and the nitrogen use efficiency factors, as described in detail by Gallardo et al. (2014). For K, P, Ca and Mg of soil-grown crops, the proposed approach is that available/exchangeable nutrients, in soil, be measured before planting. The recommended applied concentrations will consider (i) modelled nutrient uptake, and (ii) the available/exchangeable nutrients in the soil.

For soilless crops, it is proposed that simulated UC be used by applying the approach described by Sonneveld and Voogt (2009). For both soil-grown and soilless crops, the recommended applied nutrient concentrations will also take into account the recommended ratios between nutrients applied by fertigation (Sonneveld and Voogt, 2009).

5. Conclusions

For greenhouse tomato, the VegSyst model was adapted to simulate crop uptake, and uptake concentrations of K, P, Ca and Mg using dilution curves developed for each nutrient using data from earlier studies. The revised model is VegSyst model V3. For N, a critical N dilution curve replaced the N dilution curve in previous versions of VegSyst. Simulated nutrient uptake was validated with three tomato crops, a short cycle, soil-grown long-life tomato crop, and two long cycle soilless cherry tomato crops. The model adequately simulated the uptake of N, K, P and Ca. For uptake of Mg, simulation was poor; further work is required with the Mg dilution curve. The simulation of uptake concentration was validated with data of the two cherry tomato crops. Simulation was good for the uptake concentration for N, K, P and Ca. The exception of Mg where the model consistently overestimated uptake concentration.

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