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Evaluation of the Modified VegSyst Model to Simulate Growth, Nitrogen Uptake and Evapotranspiration of Pumpkin (*Cucurbita pepo* L.) Under Different Management Practices

Mohammad Reza Naderi, Mohammad Bannayan*, Morteza Goldani and Amin Alizadeh
Department of Agronomy, Faculty of Agriculture, Ferdowsi university of Mashhad, Mashhad, Iran.

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Abstract

Simulation models can be used for predicting crop behavior under various environmental conditions and management practices. By prediction of crop behavior, it may be possible to adopt management practices which can maximize crop growth and yield. In this study, the VegSyst model which was introduced for simulation of daily crop dry weight (DW), fraction of intercepted PAR ($f_{i\text{-}PAR}$), crop N uptake and crop evapotranspiration (ET_c) of vegetables grown under intensively managed greenhouse conditions, was modified by attaching a component for simulation of the daily radiation use efficiency (RUE) and by introducing corrective factors for non-optimum growth conditions in order to apply it under field conditions and various management practices. The modified VegSyst model was calibrated and validated for pumpkin using growth data obtained from four years field experiments (2010, 2012, 2013 and 2014). This model very accurately simulated dry weight, fraction of intercepted PAR, radiation use efficiency, crop N uptake and crop evapotranspiration under optimum conditions for pumpkin growth (i.e. nitrogen rate of 250 kg ha^{-1}, plant density of 2.5 plant m^{-2} and sowing date between 1-11 May). Under non-optimum growth conditions, model performance for simulating growth parameters of pumpkin was mostly very good or good. Suitable performance of the modified VegSyst model in simulation of *DW*, $f_{i\text{-}PAR}$, *RUE*, *N* uptake and ET_c of pumpkin under optimum and non-optimum growth conditions indicated that this model can be effectively used for studying growth of this important medicinal and forgotten crop under different management practices including nitrogen regimes, plant densities and sowing dates.

Keywords: Forgotten crops, Field conditions, Radiation use efficiency, Crop modeling, Model performance

Introduction

One of the main topics in agronomic research is to find management strategies that maximize crop production and minimize environmental degradation (Gayler et al., 2002). In this regard, agricultural production can benefit from changes at the tactical level such as optimizing of sowing date, fertilization intensity (Lehmann et al., 2013) and plant density. Hence, evaluation of the crop response to the various levels of these management practices will play a meaningful role to increase food

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* Corresponding Author, Email: mobannayan@yahoo.com

production and to abate the negative impacts of environment on crop growth.

Nitrogen plays an important role in plant growth (Naderi et al., 2016). Optimum nitrogen level enhances crop growth by increasing leaf area index (*LAI*), intercepted photosynthetically active radiation (Razzaghi et al., 2012) and radiation use efficiency (*RUE*). Whereas, yield and growth reduction is often observed under excessive N input due to greater pest incidence, disease damage (Peng et al. 2010) and too much accumulation of metabolites such as nitrates, amides, and free amino acids which can be toxic for crop growth in excessive levels (Aulakh and Malhi, 2005). Thus, by optimizing the N fertilizer inputs, not only crop requirements can be met, but also the environmental problems such as nitrate leaching to ground water and greenhouse gas emissions can be decreased too.

Sowing date is one of the most important management factors affecting crop production and quality (Bannayan et al., 2013). In a given region, the optimum sowing date depends mainly upon the timing of rainfall (Ferrise et al., 2010, Bannayan et al., 2011). In most cases, delaying sowing beyond the optimum period reduces crop growth and yield (Bassu et al., 2009) due to increasing temperatures and diminishing moisture conditions (Subedi et al., 2007). Therefore, selecting the optimum planting date can be considered as an adaptation response to climate change (Lashkari et al., 2012).

Other important management factor that influences crop growth and yield is plant density (Amiri et al., 2011). Maximum crop growth and yield is achieved at optimum plant density which depends upon cropping system, environmental condition and cultivar (Dong et al., 2010).

Crop models simulate the growth and production of crops under various environments and management factors and are adopted for analyzing regional production, to explore impact of climate change on regional food productivities and options for adaptations (Bannayan et al., 2003). However, the various available models that simulate crop growth such as EPIC, STICS, CropSyst and the DSSAT group of models are large and complex models which commonly require numerous inputs (Gallardo et al., 2011).

VegSyst, which was initially introduced by Gallardo et al. (2011), is relatively simple crop simulation model driven by thermal time and calculates daily crop biomass production, *N* uptake and ET_c. Gallardo et al. (2011) evaluated the VegSyst model for muskmelon to simulate its growth, nitrogen uptake and evapotranspiration. They concluded that VegSyst very accurately simulated crop biomass production and accurately simulated crop *N* uptake over time. However, this model assumes that crops have no water, nutrient or temperature limitation, which is realistic for intensively managed crops grown in greenhouses (Gallardo et al., 2011). Under such conditions, the crop growth rate (*CGR*) and intercepted photosyntheticaly active radiation (PAR_i) for intensively managed greenhouse crops is approximately constant and thus, fixed value of *RUE* was considered for the entire growth cycle of crop in the VegSyst model.

Under field conditions, when moisture, nutrients, temperature, and biotic stresses are not growth-limiting, increase of crop biomass depends upon the amount of solar energy absorbed by the crop leaf canopy and the efficiency with which the radiant energy is utilized by the plant (i.e. *RUE*) (Loy, 2004). Therefore, determining *RUE* is an important approach for estimating crop growth (Sinclair and Muchow, 1999) as *RUE* is stable across environments under optimal growing conditions (Sinclair and Muchow, 1999) and this parameter can be effectively used for simulation of crop growth in different environments. Accordingly, in numerous amounts of crop simulation models such as APES, CropSyst, DSSAT, FASSET and STICS, biomass production of crop is calculated as the product of intercepted *PAR* and radiation use efficiency. However, there are reports suggesting that under field conditions, *RUE* may be influenced by developmental stage and aging of plant organs such as roots, shoots and leaves (Jahan et al., 2013). Therefore, assuming a fixed value for *RUE* in whole growth cycle of plant can led to high error in simulations. Therefore by incorporating a component to simulate daily radiation use efficiency (*RUE*) of crop, the VegSyst model can be adapted for use with open field vegetables grown under no water and nitrogen limitations.

Furthermore, for crops grown under field conditions, stresses such as nutrient deficiency or excess, moisture deficits or excess (Setiyonoa et al., 2012) and non-optimum weather conditions will decrease growth and yield of crops compared to non-growth limiting conditions. These stresses reduce the leaf photosynthetic rate and could result in lower biomass production of crop (Amiri et al., 2013). Therefore, with introducing the corrective components, VegSyst model can also be adapted for use under growth limiting conditions.

Cucurbita pepo L. commonly known as pumpkin, is an important horticultural crop worldwide, but there has been relatively a few studies to describe its growth and improve its productivity (Loy, 2004). However, in current years, the popularity of pumpkin fruits (seeds, biomass) in various systems of traditional medicine for several ailments (as antidiabetic, antihypertensive, immunomodulation, and antimicrobial) has attracted lots of attention to this plant (Nosalova et al., 2011). Therefore, as a forgotten plant, development and validation of a relatively simple model for pumpkin can be useful in studying its growth response to changes in cultivar, soil, weather, climate and management practices. Hence, the aims of current study were to modify and evaluate VegSyst model by incorporation of the *RUE* component to simulate growth, nitrogen uptake and evapotranspiration of pumpkin under field conditions.

Material and methods

Description of the VegSyst Model

VegSyst simulates the fraction of intercepted photosynthetically active radiation ($f_{i\text{-}PAR}$) based on plant age which is calculated by thermal time (Gallardo et al., 2011). Thermal time (^{o}Cd) was estimated from daily maximum and minimum air temperature as:

$$TT = \sum_{1}^{n}\left(\frac{T_{\max}+T_{\min}}{2}\right) - T_b \qquad (1)$$

where TT is thermal time (^{o}Cd) T_{max} and T_{min} are daily maximum and minimum air temperatures (^{o}C), respectively, and T_b is the base temperature (^{o}C). If $[(T_{max}+T_{min})/2] < T_b$, then $[(T_{max}+T_{min})/2] = T_b$ (McMaster and Wilhelm, 1997).

The fraction of intercepted PAR ($f_{i\text{-}PAR}$) was calculated as a function of the relative thermal time (RTT) (Eqs. (2a) and (2b)) (Gallardo et al., 2011).

$$RTT_1 = \frac{CTT_i}{CTT_f} \qquad (2a)$$

$$RTT_2 = \frac{CTT_i - CTT_f}{CTT_{mat} - CTT_f} \qquad (2b)$$

where RTT_1 and RTT_2 are relative thermal times for period 1 (from crop emergence until maximum *PAR* interception; for pumpkin: $CTT \leq 840$ ^{o}Cd) and period 2 (from maximum *PAR* interception until crop maturity; for pumpkin: $CTT > 840$ ^{o}Cd), respectively, and CTT_i, CCT_f and CTT_{mat} are the cumulative thermal time (CTT) at day i, at maximum *PAR* interception, and at crop maturity, respectively (Gallardo et al., 2011).

Two exponential relationships between $f_{i\text{-}PAR}$ and RTT, one for each period, were developed (Gallardo et al., 2011):

Period 1:

$$f_{i-PAR} = f_0 + \left[\frac{f_f - f_0}{1 + B_1 \exp(-a_1 RTT_1)}\right] \qquad (3a)$$

Period 2:

$$f_{i-PAR} = f_f + \left[\frac{f_f - f_{mat}}{1 + B_2 \exp(-a_2 RTT_2)}\right] \tag{3b}$$

where f_f is the maximum fraction of intercepted PAR, and f_0 and f_{mat} are the fractions of PAR intercepted at crop emergence and at maturity, respectively (Gallardo et al., 2011). The coefficients a_1, and a_2, are the equation fitting coefficients (called from here as "shape coefficients") for periods 1 and 2, respectively (Gallardo et al., 2011). B_1 and B_2 are coefficients derived from $RTT_{0.5}$ for periods 1 and 2, respectively. $RTT_{0.5}$ represents the relative thermal time at which $f_{i-PAR} = 0.5\times(f_0+f_f)$ (for period 1) or $f_{i-PAR} = 0.5\times(f_f+f_{mat})$ (for period 2). In Eqs. (3a) and (3b), the B_1 and B_2 coefficients were calculated as (Gallardo et al., 2011):

$$B_1 = \frac{1}{\exp(-a_1 RTT_{0.5})} \tag{4a}$$

$$B_2 = \frac{1}{\exp(-a_2 RTT_{0.5})} \tag{4b}$$

In which $RTT_{0.5}$ in Eq. (4a) was for period 1, and $RTT_{0.5}$ in Eq. (4b) was for period 2.

Daily PAR interception (PAR_i) was calculated from daily values of f_{i-PAR} and the daily global PAR that was obtained by multiplying daily global solar radiation (R_s) to the PAR/R_s ratio of 0.45 (Maddonni and Otegui, 1996).

Dry weight for a given day (DW_i) was calculated as:

$$DW_i = \sum PAR_i \times RUE_i \tag{5}$$

where RUE_i is radiation use efficiency in a given day.

Crop N uptake for a given day was determined as the product of the simulated dry weight (DW_i) and crop nitrogen content ($\%N_i$) for that day. The crop nitrogen content ($\%N_i$) for a given day was simulated as (Gallardo et al., 2011):

$$\%N_i = a \times DW_i^{-b} \tag{6}$$

where a and b are calibration factors obtained from experimental data (Gallardo et al., 2011). For estimation of these factors, a power function was fitted between experimental data of shoot nitrogen content (N_i) (%) and shoot dry weight (DW_i) (g m^{-2}) using non-linear (NLIN) Procedure of SAS software through the Gauss-Newton method (Elia and Conversa, 2012). Quality of the function obtained was assessed by the determination coefficient (R^2) of linear regression between observed and simulated values.

Crop evapotranspiration (ET_c) was simulated following the FAO approach as the product of reference evapotranspiration (ET_o) and a crop coefficient (kc) (Gallardo et al., 2011). ET_o was calculated using the Penman-Monteith equation of CROPWAT 8.0 software. The crop coefficient for a given day (kc_i) was calculated as (Gallardo et al., 2011):

$$kc_i = kc_{ini} + (kc_{\max} - kc_{ini}) \times \left(\frac{f_{i-SR}}{f_{f-SR}}\right) \tag{7a}$$

$$kc_i = kc_{end} + (kc_{\max} - kc_{end}) \times \left[\frac{f_{i-SR} - f_{mat-SR}}{f_{f-SR} - f_{mat-SR}}\right] \tag{7b}$$

where, kc_{ini}, kc_{max} and kc_{end} are the initial, maximum and end of crop life kc values, and f_{i-SR}, f_{f-SR} and f_{mat-SR} are the fraction of solar radiation intercepted by the crop on a given day, at maximum solar radiation interception, and at crop maturity, respectively (Gallardo et al., 2011). Eq. (7a) applies to period 1 from crop emergence until maximum PAR interception and Eq. (7b) to period 2 from maximum PAR interception until crop maturity (end of the crop). The fraction of solar radiation intercepted by the crop (f_{i-SR}) was obtained from the simulated fraction of PAR intercepted (f_{i-PAR}) using Eq. (8) (Gallardo et al., 2011):

$$f_{i-SR} = 1 - \exp\left[\frac{\ln(1 - f_{i-PAR})}{1.4}\right] \tag{8}$$

Modifications of the VegSyst model

The VegSyst model is used for simulation of crop growth under optimum conditions (i.e. conditions without nutrient and water limitation). However, under field conditions, the crop growth may be suppressed by different limiting factors such as nutrient deficiency, water shortage, biotic and abiotic stresses and etc. Therefore, the VegSyst model which calibrated and validated for optimum growth conditions was modified using a series of corrective factors in order to applying it under non-optimum growth conditions.

In the modified VegSyst model, the f_{i-PAR} for conditions with nitrogen limitation was simulated through multiplying the VegSyst functions of f_{i-PAR}(Eqs. (3a) and (3b)) into the nitrogen corrective factor (NCF_f), which was calculated as follow:

$$NCF_f = (A_f \times CTT_i^2) + (B_f \times CTT_i) + C_f \qquad (9)$$

where CTT_i is the cumulative thermal time (°Cd) at a given day and coefficients of A_f, B_f and C_f were obtained from experimental data.

In the modified VegSyst model, radiation use efficiency (*RUE*) was separately calculated for periods 1 and 2 using Eqs. (10a) and (10b), respectively.

Period 1:

$$RUE_i = RUE_0 + \left[\frac{RUE_f - RUE_0}{1 + B_1 \exp(-a_1 RTT_1)}\right] \qquad (10a)$$

Period 2:

$$RUE_i = RUE_f - \left[\frac{RUE_f - RUE_{mat}}{1 + B_2 \exp(-a_2 RTT_2)}\right] \qquad (10b)$$

where RUE_f is the maximum radiation use efficiency during crop growth cycle, and RUE_0 and RUE_{mat} are the radiation use efficiency at crop emergence and at maturity, respectively. Furthermore, these equations (i.e. Eqs. (10a) and (10b)) were multiplied by the nitrogen corrective factor of *RUE* (NCF_{RUE}) to obtain the radiation use efficiency (*RUE*) of pumpkin under conditions with nitrogen deficiency. The NCF_{RUE} was developed based on the nitrogen nutrition index (*NNI*) and is calculated as follows:

$$NCF_{RUE} = A_{RUE} \exp(B_{RUE} \times NNI) \qquad (11)$$

where A_{RUE} and B_{RUE} are the calibration coefficients which were obtained from experimental data.

NNI is the nitrogen nutrition index which was calculated as the ratio between the actual crop *N* content ($\%N_a$) and the critical *N* content ($\%N_c$), corresponding to the actual crop mass (Lemaire et al., 2008) (Eq. (12)).

$$NNI = \frac{\%N_a}{\%N_c} \qquad (12)$$

In 2010 and 2012 experiments, the fraction of intercepted *PAR* (f_{i-PAR}) and radiation use efficiency (*RUE*) were not measured. Therefore, in these experiments, for simulation of the dry weight produced under nitrogen deficiency or excess, the dry weight equation of VegSyst model (Eq. (5)) was directly multiplied by a cubic function (NCF_{DW}), which was developed based on the nitrogen nutrition index (*NNI*) as follows:

$$\begin{aligned} \mathrm{NCF_{DW}} = {} & \left(\mathrm{A_{DW}} \times \mathrm{NNI}^3\right) + \left(\mathrm{B_{DW}} \times \mathrm{NNI}^2\right) + \\ & \left(\mathrm{C_{DW}} \times \mathrm{NNI}\right) + \mathrm{D_{DW}} \end{aligned} \qquad (13)$$

where A_{DW}, B_{DW}, C_{DW} and D_{DW} are the calibration coefficients which were obtained from experimental data of pumpkin.

Furthermore, under conditions which plant density was lower or higher than optimum level, the dry weight obtained from optimum growth conditions was multiplied by the following corrective component which named as the density effect factor (*DEF*):

$$DEF = \frac{A_p}{1 + \exp\left(-\frac{d - B_p}{C_p}\right)} \qquad (14)$$

In which, *d* is the plant density (plant m^{-2}) and A_p, B_p and C_p are the calibration coefficients which were obtained from experimental data of pumpkin.

The dry weight produced under optimum sowing date (DW_i) was also converted to the dry weight obtained from non-optimal sowing dates with multiplying DW_i into the following corrective factor which shows the effect of temperature stress on crop growth and thus named as the temperature stress factor (TSF).

$$TSF = \frac{A_T}{1 + \exp\left(-\frac{T_{ave} - B_T}{C_T}\right)} \quad (15)$$

where, T_{ave} is average of air temperature (^{o}C) during the growing season and A_T, B_T and C_T are the calibration parameters which were achieved from experimental data.

In nitrogen deficient conditions, crop N content ($\%N_i$) was simulated by multiplying the crop N content obtained from conditions without nitrogen deficiency into the nitrogen nutrition index (NNI).

Field experiments

The field data of pumpkin were collected from four years experiments which have been conducted in 2010, 2012, 2013 and 2014 at research farm of Ferdowsi university of Mashhad, Iran (with latitude 36^{o} 16′ N, longitude 59^{o} 38′ E, elevation 999 m, annual average of minimum temperature 8.3 ^{o}C, annual average of maximum temperature 21.6 ^{o}C and total precipitation of 256.5 mm) (Bannayan and Sanjani, 2011). The treatments of these experiments are presented in Table 1. Furthermore, monthly average of weather data for 2010, 2012, 2013 and 2014 growing seasons are presented in Table 2.

Table 1. Employed treatments in four years experiments

Experiment	Sowing date	Treatments	Identification Code
2010	May 1	150 kg N ha^{-1} and 0.625 plant m^{-2}	T1-2010
		150 kg N ha^{-1} and 1.25 plant m^{-2}	T2-2010
		150 kg N ha^{-1} and 2.5 plant m^{-2}	T3-2010
		250 kg N ha^{-1} and 0.625 plant m^{-2}	T4-2010
		250 kg N ha^{-1} and 1.25 plant m^{-2}	T5-2010
		250 kg N ha^{-1} and 2.5 plant m^{-2}	T6-2010
		350 kg N ha^{-1} and 0.625 plant m^{-2}	T7-2010
		350 kg N ha^{-1} and 1.25 plant m^{-2}	T8-2010
		350 kg N ha^{-1} and 2.5 plant m^{-2}	T9-2010
2012	May 1, May 11 and May 21	Sowing date May 1 and 2.5 plant m^{-2}	T1-2012
		Sowing date May 1 and 4 plant m^{-2}	T2-2012
		Sowing date May 11 and 2.5 plant m^{-2}	T3-2012
		Sowing date May 11 and 4 plant m^{-2}	T4-2012
		Sowing date May 21 and 2.5 plant m^{-2}	T5-2012
		Sowing date May 21 and 4 plant m^{-2}	T6-2012
2013	May 6	50 kg N ha^{-1} with plant density of 2.5 plant m^{-2}	T1-2013
		150 kg N ha^{-1} with plant density of 2.5 plant m^{-2}	T2-2013
		250 kg N ha^{-1} with plant density of 2.5 plant m^{-2}	T3-2013
2014	May 6	50 kg N ha^{-1} with plant density of 2.5 plant m^{-2}	T1-2014
		150 kg N ha^{-1} with plant density of 2.5 plant m^{-2}	T2-2014
		250 kg N ha^{-1} with plant density of 2.5 plant m^{-2}	T3-2014

Table 2. Monthly weather data for 2010, 2012, 2013 and 2014 growing seasons

Year	Month	T_{avg} (^oC)[a]	T_{max} (^oC)	T_{min} (^oC)	P (mm)	RH_{avg} (%)	R_s (MJ m^{-2} d^{-1})
2010	May	21.9	28.8	14.9	39.2	48.0	22.3
	June	27.4	35.5	19.3	4.5	22.0	26.8
	July	28.6	36.3	20.9	0.0	19.0	27.3
	August	26.4	34.5	18.2	0.0	20.0	25.5
2012	May	20.9	28.0	13.9	18.4	41.4	23.1
	June	26.0	33.3	18.7	9.5	24.8	26.4
	July	28.8	36.2	21.5	0.0	19.1	26.7
	August	27.3	35.4	19.2	0.0	18.1	25.4
2013	May	20.9	28.0	13.6	26.8	31.5	24.3
	June	26.7	33.9	19.5	0.4	22.1	25.9
	July	28.7	36.1	21.3	0.0	22.0	26.8
	August	25.9	33.0	18.8	2.4	25.4	24.0
2014	May	22.9	30.2	15.5	27.1	27.4	23.5
	June	27.1	34.8	19.3	4.0	20.3	26.5
	July	28.0	35.6	20.3	0.0	15.0	27.2
	August	27.4	35.5	19.3	0.0	15.3	25.1

[a] T_{avg}, T_{max}, and T_{min} are average, maximum, and minimum temperatures, respectively, P is monthly total precipitation, RH_{avg} is monthly average of relative humidity and R_s is monthly average of solar radiation.

In all experiments, the seedbed preparation was carried out using common practices (including plow, disk and leveler) and sowing was performed as mound planting. When establishment of plants was ensured, the extra seedlings were thinned and only one plant per mound was kept. The furrow irrigation was employed in order to supply the water requirement of plants and first irrigation was carried out immediately after sowing and other irrigations were performed on a weekly basis. For nitrogen application, the N fertilizer was band-dressed on the planted side of furrow. During the season, weeds were manually controlled. Destructive samplings were carried out at different dates during the growth season in order to cover the various developmental stages of pumpkin. In each sampling, three plants were randomly harvested from each plot and after measuring the green leaf area using a leaf area meter, the shoot of each plant was separately dried at 75 ^oC for 72 h. The mean dry weight of the three sampled plants was considered for each plot and the mean dry weight of all replications of each treatment was considered for that treatment.

In the first experiment (2010), treatments (including nitrogen rate and plant density) were arranged using a split plot design in the form of completely randomized blocks with three replications. Nitrogen application as the main plot was applied in three levels including 150, 250 and 350 kg ha^{-1} (using urea containing 46% nitrogen) and plant density as the sub-plot was employed in three levels including 2.5, 1.25 and 0.625 plant m^{-2}. For the plant densities of 2.5, 1.25 and 0.625 plant m^{-2}, the space between plants on the row was 20, 32 and 64 cm, respectively. The size of each plot was 10 m × 6 m and distance between rows was considered 2 m with a 50 cm furrow for each row. Sowing was performed on first day of May. The first portion of urea fertilizer (one-third of the amount required for each treatment) was applied two weeks after sowing and the second partition (two-third of the amount required for each treatment) was accomplished 6 weeks after sowing. Destructive samplings were carried out six times at different dates during the growth season. The first sampling was performed 27 days after planting and other samplings were accomplished with an interval of 15 days.

In the second experiment (2012), treatments (including sowing date and plant density) were arranged using a split plot design in the form of completely randomized blocks with three replications. Sowing date as the main plot was employed in three levels including May 1, May 11 and May 21 and plant density as the sub-plot was performed in two levels including 2.5 and 4 plant m^{-2}. The size of each plot was 10 m × 5 m and distance between rows was considered 2 m with a 0.5 m furrow for each row. For the plant densities of 2.5 and 4 plant m^{-2}, the space between plants on the row was 20 cm and 10 cm, respectively. During the growing season no fertilizer was applied. Six destructive samplings were carried out during the growth of pumpkin. First sampling for May 1, May 11 and May 21 sowing dates was performed 20, 25 and 29 days after sowing, respectively. The rest of samplings were carried out with an interval of 14 days.

In 2013 and 2014 experiments, pumpkin plants were seeded at 6-May with plant density of 2.5 plant m^{-2}. The plot size was 15 m × 5 m and in each plot, 6 planting lines with a 2 m row spacing and 0.5 m furrow between each line were considered. Treatments were included three levels of nitrogen application (including 50, 150 and 250 kg ha^{-1} using urea fertilizer containing 46% Nitrogen), which were arranged according to the design of completely randomized blocks with four replications. In both years, the first portion of urea fertilizer (half of the total) was applied four weeks after sowing (coinciding with 4-6 leaf stage) and the second fertilization (the second half) was used 6 weeks after sowing (coinciding with flowering stage). Five destructive samplings were carried out during the crop growth cycle, starting from 30 days after planting and others were taken 42, 56, 70 and 77 days after planting.

Radiation use efficiency (RUE)

In 2013 and 2014 experiments, from 30 to 77 days after sowing (DAS) and coinciding with destructive samplings, photosynthetically active radiation (*PAR*) above and below the canopy were measured at the rows devoted for final harvest yield using a ceptometer with 90-cm line probe (AccuaPAR LP-80; Pullman, Washington, USA). The measurements were taken on clear days between 10:30 a.m. and 13:30 p.m. with three replications per plot. The fraction of photosynthetically active radiation intercepted by the canopy ($f_{i\text{-}PAR}$) for a particular day was calculated with the following equation:

$$f_{i-PAR} = 1 - \left(\frac{PAR_t}{PAR_0}\right) \qquad (16)$$

where PAR_t is the *PAR* measured at ground level (μmol m^{-2} s^{-1}) and PAR_0 is the *PAR* at the top of the canopy (μmol m^{-2} s^{-1}) (Hamzei and Soltani, 2012). On days where $f_{i\text{-}PAR}$ was not directly measured, it was estimated by linear interpolation between measured values (Fletcher et al., 2013). The Angstrom model (Eq. (17)) was employed in order to calculate the global solar radiation (R_s) (Pohlert, 2004) for a particular day using daily sunshine hours.

$$R_s = R_a\left(A + B\left(\frac{n}{N}\right)\right) \qquad (17)$$

where R_s is daily global solar radiation (MJ m^{-2} d^{-1}), R_a is daily extra-terrestrial radiation (MJ m^{-2} d^{-1}), A and B are empirical coefficients (for Mashhad, A=0.3 and B=0.37; Ameri and Nassiri-Mahallati, 2009), n is sunshine duration (h) and N is the daylength (h) (Pohlert, 2004). Global solar radiation was multiplied by 0.45 to obtain global *PAR*. Then, daily global *PAR* values were multiplied by corresponding daily $f_{i\text{-}PAR}$ values to compute daily intercepted *PAR* (PAR_i) (Pradhan et al., 2014). Finally, radiation use efficiency (*RUE*) for each sampling was calculated as the ratio between shoot dry weight and cumulative intercepted *PAR* (Eq. (18)) (Sadras et al., 2012).

$$\text{RUE (g MJ}^{-1}) = \frac{\text{Shoot dry matter (g m}^{-2})}{\text{Cumulative intercepted PAR (MJ m}^{-2})} \qquad (18)$$

Nitrogen concentration and uptake

In 2013 and 2014 experiments, for determining the nitrogen content of plant shoots, the dried samples were finely ground to less than 1 mm and digested in a mixture of concentrated H_2SO_4 and H_2O_2 (Zhou et al., 2011). The nitrogen content of digests was measured based on the Kjeldahl method in four samples per treatment. The nitrogen content of shoots was expressed on the basis of dry weight (%). The nitrogen uptake of plant samples (g m^{-2}) was determined by multiplying shoot dry weight (g m^{-2}) in nitrogen content (%).

Crop evapotranspiration (ET_c)

Crop evapotranspiration was measured weekly using the water balance approach, based on the following equation (Gallardo et al., 2011):

$$ET_c = (SWC_{t0} - SWC_{t1}) + I + P \qquad (19)$$

where (SWC_{t0}-SWC_{t1}) is the change in volumetric soil water content between two measurement dates (*t0* and *t1*), *I* and *P* are the total volume of applied irrigation and precipitation for the weekly period. Water losses due to runoff and leaching were assumed to be negligible (Cantero-Martinez et al., 2003). For measuring the volumetric soil water content (*SWC*), the soil samples were taken using a 4-cm diameter soil auger, before and after of each irrigation. At each sampling, two samples per plot were taken from 0-20 cm depth. Soil samples were dried in an oven at 105 ^{o}C for 48 h and gravimetric water content (*GWC*) in a % basis was calculated by the following equation:

$$GWS = \left(\frac{MWS - MDS}{MDS} \right) \times 100 \qquad (20)$$

where, *MWS* and *MDS* are the mass of wet (g) and dry soil (g), respectively. Then, *SWC* was computed from *GWC* and bulk density (*BD*) of soil, assuming a 200 mm (20 cm) sampling depth (Eq. (21)) (Morell et al., 2011).

$$SWC = GWC \times BD \times 200 \qquad (21)$$

The potential evapotranspiration (ET_o) was calculated using the Penman-Monteith equation of CROPWAT 8.0 software. The crop coefficient (*Kc*) for a particular day was estimated using FAO approach (Eq. (22)). The weather data required (including daily maximum and minimum temperature, daily average of relative humidity, daily average of wind speed, daily sunshine hours and daily precipitation) were obtained from meteorological station of Mashhad.

$$k_c = \left(\frac{ET_c\,(\text{mm})}{ET_o\,(\text{mm})} \right) \qquad (22)$$

Model calibration

The model was calibrated using data obtained from treatment of 250 kg N ha^{-1} in 2014 experiment (T3-2014), which had a higher pumpkin growth compared to other treatments because of more suitable weather conditions.

Evaluation of model performance

To evaluate the agreement between simulated and observed values, the following statistical indices were used: (i) the root mean square error (RMSE), (ii) the relative error (RE), (iii) the Willmott index of agreement (d) (Willmott, 1982) and (iv) the slope (m) and coefficient of determination (R^2) of the linear regression between simulated and observed values. The slope and intercept of the linear regression equations were compared with the 1:1 line by determining simultaneous confidence intervals at $P < 0.05$.

The performance of these indices was interpreted using the following criteria developed by Stöckle et al. (2004).

$d \geq 0.95$ and $RE \leq 0.10$	Very good
$d \geq 0.95$ and $0.15 \geq RE > 0.10$	Good
$d \geq 0.95$ and $0.20 \geq RE > 0.15$	Acceptable
$d \geq 0.95$ and $0.25 \geq RE > 0.20$	Marginal

Other combinations of d and RE values indicated poor performance (Stöckle et al., 2004).

Results and discussion

Model calibration

Assessment of the pumpkin growth data showed that in 2010 experiment which three levels of nitrogen application (including 150, 250 and 350 kg ha^{-1}) and three levels of plant densities (including 0.625, 1.25 and 2.5 plant m^{-2}) were evaluated, nitrogen rate, plant density and their interactions had very significant effect on maximum dry weight (DW_{max}) of pumpkin (Table 3). Among three levels of nitrogen application, the highest DW_{max} was obtained from nitrogen rate of 250 kg ha^{-1} and increasing nitrogen amount from 250 to 350 kg ha^{-1}, caused significant decrease in maximum dry weight of pumpkin (Table 4). By increasing plant density, the pumpkin maximum dry weight was also increased, as the highest DW_{max} was obtained from density of 2.5 plants per square meter (Table 5). Interaction between different levels of nitrogen rate and plant density demonstrated that pumpkin DW_{max} in treatment with nitrogen rate of 250 kg ha^{-1} and plant density of 2.5 plant m^{-2} (i.e. T6-2010 treatment) was higher than other treatments (from 32 to 351%) (Table 6). In conclusion, this study showed that T6-2010 treatment (i.e. treatment with 250 kg N ha^{-1} and 2.5 plant m^{-2}) was the optimum treatment for achieving highest pumpkin growth.

Table 3. Analysis of variance for effect of nitrogen rate, plant density and their interaction on maximum dry weight of pumpkin in 2010 experiment

Source of variation	Degree of freedom	Mean square
Nitrogen rate	2	22746.07**
Plant density	2	263784.03**
Nitrogen rate × Plant density	4	2986.37**
Error	12	52.6
CV (%)		4.7

*, ** and NS are significant at probability level of 0.05, 0.01 and non-significant, respectively.

Table 4. Effect of nitrogen rate on maximum dry weight of pumpkin in 2010 experiment

Nitrogen rate (kg ha^{-1})	Maximum dry weight (g m^{-2})
150	300.00b
250	386.00a
350	297.89b

Means with same letter do not have significant difference at probability level of 0.05 according to the least significant difference (LSD) test.

Table 5. Effect of plant density on maximum dry weight of pumpkin in 2010 experiment

Density (plant m^{-2})	Maximum dry weight (g m^{-2})
0.625	142.89c
1.25	360.33b
2.5	480.67a

Means with same letter do not have significant difference at probability level of 0.05 according to the least significant difference (LSD) test.

Table 6. Effect of interaction between nitrogen rate and plant density on maximum dry weight of pumpkin in 2010 experiment

Nitrogen rate (kg ha^{-1})	Density (plant m^{-2})	Maximum dry weight (g m^{-2})
150	0.625	135.33e
	1.25	328.67c
	2.5	436.00b
250	0.625	165.67d
	1.25	416.67b
	2.5	575.67a
350	0.625	127.66e
	1.25	335.66c
	2.5	430.33b

Means with same letter do not have significant difference at probability level of 0.05 according to the least significant difference (LSD) test.

Table 7. Analysis of variance for the effect of sowing date, plant density and their interaction on pumpkin's maximum dry weight (DW_{max}) in 2012 experiment.

Source of variation	Degree of freedom	Mean square	F
Sowing date	2	11012.50	209.51**
Plant density	1	129.60	2.47NS
Sowing date × Plant density	2	31.20	0.59NS
Error	6	52.56	
CV (%)	3.75		

*, ** and NS are significant at probability level of 0.05, 0.01 and non-significant, respectively.

Table 8. Effect of sowing date on pumpkin's maximum dry weight (DW_{max}) in 2012 experiment.

Sowing date	DW_{max} (g m^{-2})
May 1	221a
May 11	215a
May 21	144b

Means with same letter do not have significant difference at probability level of 0.05 according to the least significant difference (LSD) test.

For 2012 experiment which three levels of sowing date (including May 1, May 11 and May 21) and two levels of plant density (including 2.5 and 4 plant m^{-2}) were studied, analysis of variance showed that there was no significant difference between maximum dry weight (DW_{max}) of pumpkin obtained from two plant densities (Table 7). Therefore, the results of this study, in agreement with 2010 experiment, demonstrated that plant density of 2.5 plant m^{-2} was the optimum plant density for pumpkin growth. Furthermore, there was no significant difference between sowing dates of May 1 and May 11 regarding pumpkin DW_{max} (Table 8), but DW_{max} obtained from these two sowing dates was significantly ($P \leq 0.05$) different from that achieved in sowing date of May 21 (Table 8). Therefore, maximum growth of pumpkin was achieved by planting this crop from 1 to 11 May and when sowing date delayed to late May, the pumpkin growth was significantly decreased (Table 8). Hence, it can be concluded that the optimum plant density and sowing date for pumpkin growth is 2.5 plant m^{-2} and 1-11 May, respectively.

From 2010 and 2012 experiments, it was concluded that sowing date of 1-11 May, plant density of 2.5 plant m^{-2} and nitrogen rate of 250 kg ha^{-1} were the optimum conditions for pumpkin growth. Hence, for confirming that nitrogen rate of 250 kg ha^{-1} is the optimum amount for pumpkin growth, a two years experiment with different levels of N application (including 50, 150 and 250 kg ha^{-1}) was performed in 2013 and 2014. The other management practices (including sowing date and plant density) of all treatments were similar to the optimum conditions obtained from 2010 and 2012 experiments (i.e. sowing date between 1-11 May and plant density of 2.5 plant m^{-2}).

In both 2013 and 2014 experiments, maximum dry weight (DW_{max}) of pumpkin was linearly increased as the nitrogen rate increased and highest amount of pumpkin DW_{max} was obtained from application of 250 kg N ha^{-1} (i.e. treatments of T3-2013 and T3-2014) (Fig. 1). Thus, application of 250 kg N ha^{-1}as optimum nitrogen rate for pumpkin growth was also confirmed in 2013 and 2014 experiments, was in consistent with results of 2010.

The treatment T3-2014 was used for model calibration. Calibration parameters of the model under optimum growth conditions (i.e. no nitrogen and water stress) are presented in Table 9. All of these parameters were obtained from treatment of 250 kg N ha^{-1} in 2014 experiment (i.e. T3-2014 treatment).

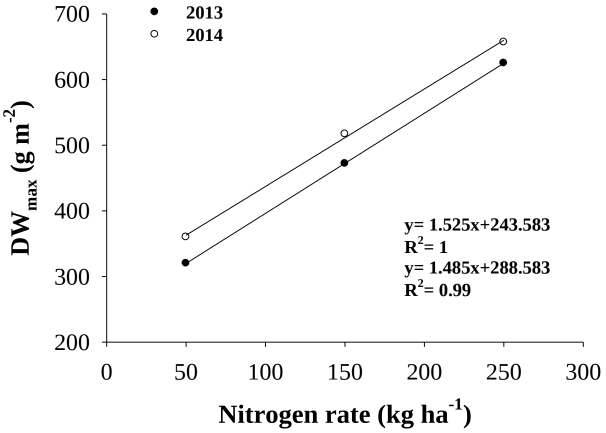

Fig. 1. Effect of nitrogen rate on maximum dry weight (DW_{max}) of pumpkin in 2013 and 2014 experiments.

Table 9. Calibration parameters of the VegSyst model for pumpkin. All the parameters were experimentally obtained apart from the base temperature that was taken from the literature.

Parameter	Value
Base temperature (T_b) (°C)	10.00
Initial fraction of intercepted *PAR* (f_0)	0.03
Maximum fraction of intercepted *PAR* (f_f)	0.84
Fraction of intercepted *PAR* at crop maturity (f_{mat})	0.00
Maximum fraction of intercepted solar radiation ($f_{f\text{-}SR}$)	0.72
Relative thermal time ($RTT_{0.5}$)	0.60
Cumulative thermal time at the end of canopy growth (CTT_f) (°Cd)	845.00
Shape coefficients	
a_1	14.00
a_2	9.00
Initial radiation use efficiency (RUE_0)	0.80
Maximum radiation use efficiency (RUE_f)	2.02
Radiation use efficiency at crop maturity (RUE_{mat})	1.20
$\%N=a\times DW^{-b}$	
a	4.97
b	-0.19
Initial crop coefficient (kc_{ini})	0.60
Maximum crop coefficient (kc_{max})	1.04
Crop coefficient at the end of crop (kc_{end})	0.50

Gallardo et al. (2011) found that under greenhouse conditions, there was no decrease in muskmelon biomass at the end of crop attributable to senescence, and the maximum *PAR* interception was maintained until the crop maturity, thus the maximum fraction of intercepted *PAR* (f_f) was equal to the fraction of intercepted *PAR* at maturity (f_{mat}). Therefore the equations of VegSyst for period 1 only were used with muskmelon, and the calibration parameters associated with the exponential growth curve such as $RTT_{0.5}$ and shape coefficient were only obtained for this period (Gallardo et al., 2011). However, evaluation of the relationship between cumulative thermal time (*CTT*) and fraction of intercepted *PAR* ($f_{i\text{-}PAR}$) (Fig. 2a) showed that under field conditions, the $f_{i\text{-}PAR}$ of pumpkin decreased after gaining the maximum fraction of intercepted *PAR* (f_f) due to leaf abscission (Fig. 2a). Thus, for pumpkin under field conditions, the fraction of intercepted *PAR* at crop maturity (f_{mat}) was not equal to the maximum fraction of intercepted *PAR* (f_f). Hence, compared to Gallardo et al. (2011), equations of the VegSyst model for both periods 1 and 2 were used with pumpkin under field conditions. Furthermore, due to completely abscission of pumpkin leaves at maturity, the fraction of intercepted *PAR* at crop maturity (f_{mat}) was 0.0 (Table 9). Therefore, the $RTT_{0.5}$ for period 2 was approximately equal to $RTT_{0.5}$ for period 1, thus only one value of $RTT_{0.5}$ was considered for both periods (Table 5). Similar to Gallardo et al. (2011), the calibration parameters obtained from Fig. 2a were maximum fraction of intercepted *PAR* (f_f), the relative thermal time for a *PAR* interception of 50% of the maximum ($RTT_{0.5}$), and the cumulative thermal time at the end of the canopy growth (CTT_f) (Table 9).

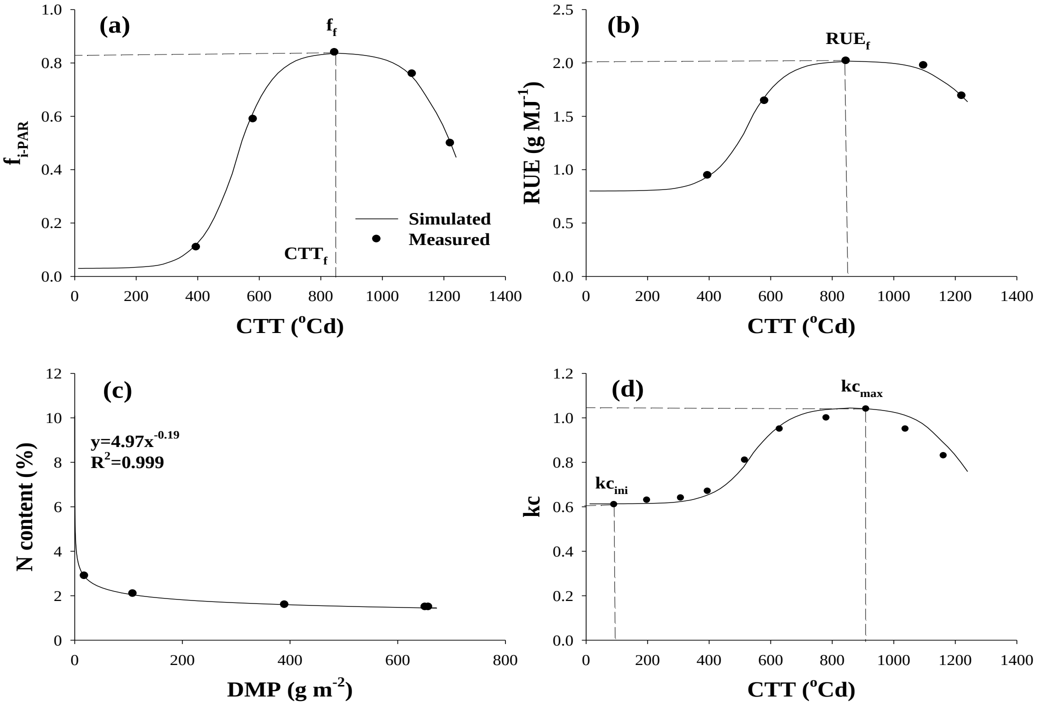

Fig. 2. Relationship between (a) fraction of intercepted *PAR* (f_{i-PAR}) and cumulative thermal time (*CTT*) for the calibration treatment, (b) radiation use efficiency (*RUE*) and *CTT* for the calibration treatment, (c) crop N concentration and dry weight (*DW*) for the calibration treatment, and (d) the crop coefficient (*kc*) and *CTT* for the calibration treatment.

In nitrogen deficient treatments of 2013 and 2014 experiments (i.e. treatments with 50 and 150 kg N ha^{-1}, including T1-2013, T2-2013, T1-2014 and T2-2014), the f_{i-PAR} measured at different growth stages of pumpkin was lower than that obtained from optimum nitrogen rate (i.e. 250 kg ha^{-1}). Thus, in these treatments, the nitrogen corrective factor for f_{i-PAR} (NCF_f) (Eq. (9)) was used for simulation of their f_{i-PAR} from f_{i-PAR} obtained under optimum nitrogen rate. The NCF_f was developed by evaluation of the association between relative f_{i-PAR} and cumulative thermal time (CTT_i) for 2014 treatments (Fig. 3). The relative $f_{i-PAR}$for nitrogen deficient treatments (i.e. treatments with 50 or 150 kg *N* ha^{-1}) was calculated at different growth stages of pumpkin as the ratio of their f_{i-PAR} to the f_{i-PAR} of treatment with optimum nitrogen rate (i.e. 250 kg *N* ha^{-1}).This ratio was not constant at various growth stages of pumpkin (Fig. 3) and thus, a quadratic association (as: $A_f \times CTT_i^2 + B_f \times CTT_i + C_f$) was obtained for NCF_f in both treatments of 50 and 150 kg *N* ha^{-1} (Fig. 3). Parameters of this association (including A_f, B_f and C_f) were -0.0000011808, 0.0018403 and -0.0213 for nitrogen rate of 50 kg ha^{-1} and -0.000001401, 0.0023012 and 0.00068965 for nitrogen rate of 150 kg ha^{-1}, respectively. This quadratic association showed that difference between $f_{i\text{-}PAR}$ of nitrogen deficient treatments and nitrogen sufficient treatment in initial and terminal stages of pumpkin growth cycle was higher than that obtained at stage of maximum leaf area index (*LAI*). This may be due to when *LAI* was maximum, $f_{i\text{-}PAR}$ was not linearly increased with *LAI* because of leaf shading, but at initial and terminal stages of pumpkin growth cycle, $f_{i\text{-}PAR}$ was linearly increased as the *LAI* increased.

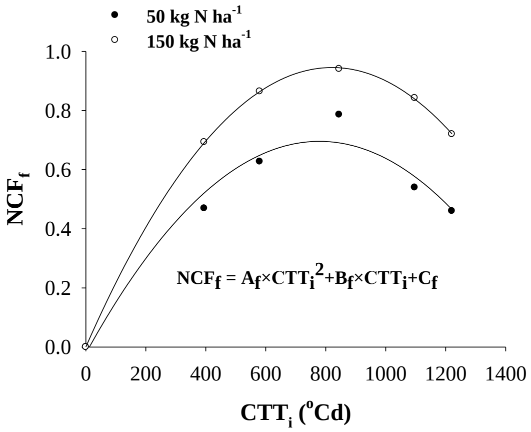

Fig. 3. Relationship between NCF_f (or relative $f_{i\text{-}PAR}$) and cumulative thermal time (CTT_i) for treatments of 50 and 150 kg N ha^{-1} in 2014 experiment.

The radiation use efficiency (*RUE*) of pumpkin measured at different stages of crop growth cycle was not constant (Fig 2b) and pumpkin *RUE* varied according to its developmental stage. The radiation use efficiency of this crop increased up to the maximum intercepted *PAR* (maximum *LAI*) and thereafter, the pumpkin *RUE* exponentially decreased due to leaf senescence (Fig. 3b). Thus, it is not appropriate to consider a constant value of *RUE* for the entire growth cycle of pumpkin. Similarly, Rouphael and Colla (2005) reported that value of *RUE* for greenhouse-grown pumpkin changed depending on crop development. Although Gallardo et al. (2011) considered double and single *RUE* values for whole growth cycle of muskmelon under greenhouse conditions, here daily *RUE* of pumpkin was used by a two segmented exponential function, one segment for period 1 and other segment for period 2 (Eqs. (10a) and (10b)). The pattern of changes in pumpkin *RUE* was completely similar to that obtained for pumpkin $f_{i\text{-}PAR}$ and coefficient of determination (R^2) for the correlation between them (*RUE* vs. $f_{i\text{-}PAR}$) was 0.98. Therefore, the function which was applied for simulation of the daily *RUE* in modified VegSyst model was similar to that used for simulation of the $f_{i\text{-}PAR}$ in original version of the VegSyst model.

A comparison between pumpkin dry weight simulated using single *RUE*, double *RUE* and daily *RUE* for calibration treatment (T3-2014) is presented in Table 10. For single and double *RUE* approaches, the values were used for *RUE* which minimize differences between simulated and observed dry weight of pumpkin in the calibration treatment. Accordingly, value of 1.8 was used for single *RUE* approach and values of 1.4 and 1.8 were applied for periods 1 and 2 in double *RUE* approach, respectively. Approximately in all developmental stages of pumpkin, the relative difference between simulated and observed values of pumpkin dry weight for daily *RUE* approach was lower than those obtained for single and double *RUE* approaches (Table 10). Furthermore, the RMSE and relative error (RE) of model for daily *RUE* approach was significantly less than two other approaches. These results clearly demonstrated that by using the daily *RUE* approach, the model performance for simulation of the pumpkin dry weight (especially in initial and terminal stages of crop cycle) was improved. Hence, the daily *RUE* approach for simulation of pumpkin dry weight under field conditions was used.

The calibration parameter obtained from Fig. 2b was the maximum *RUE* (RUE_f). Furthermore, the initial radiation use efficiency (RUE_{ini}) and radiation use efficiency at crop maturity (RUE_{mat}) were estimated using the values which minimize differences between simulated and observed *RUE* in the calibration treatment (T3-2014). Under nitrogen limitation, crop ability in converting intercepted *PAR* into shoot biomass which can be represent by *RUE* decreased compared to conditions of the optimum nitrogen application. Results of the current study and previous studies (e.g. Sinclair and Muchow, 1999; Casanova et al., 2002) showed that *RUE* is affected by the nitrogen status of crop. This effect can be described by nitrogen nutrition index (*NNI*). In 2014 experiment, the relative radiation use efficiency of pumpkin which was calculated as the ratio of *RUE* in treatments with nitrogen deficiency (i.e. treatments with 50 and 150 kg N ha^{-1}) to the *RUE* under optimum nitrogen application (i.e. treatment with 250 kg N ha^{-1}) was approximately constant during the crop growing season and thus, the growing season average values of 0.77, 0.87 and 1.00 were considered for relative *RUE* in treatments with nitrogen rate of 50, 150 and 250 kg N ha^{-1}, respectively (Fig. 4). Evaluation of the association between these relative *RUE*s and their corresponding *NNI* (Fig. 4) showed that relative *RUE* of pumpkin was exponentially increased by increasing the nitrogen nutrition index (*NNI*) (Fig. 4). Therefore, for 2013 and 2014 experiments, the daily radiation use efficiency of pumpkin for treatments with nitrogen application lower than optimum level (i.e. treatments with nitrogen rate of 50 and 150 kg ha^{-1}) was simulated through multiplying the *RUE* obtained from optimum nitrogen rate (i.e. 250 kg N ha^{-1}) into this exponential function which named as nitrogen corrective factor for *RUE*(NCF_{RUE}) (Eq. (11)) and indicates the effect of nitrogen nutrition index (*NNI*) on crop *RUE* (Fig. 4). The calibration coefficients of A_{RUE} and B_{RUE} for this function (NCF_{RUE}) were 0.499 and 0.686, respectively (Fig. 4). Similarly, in LINTUL3 model which was a simulation model for nitrogen-limited situations, Shibu et al. (2010) used an exponential function to implement N stress effect (defined through the *NNI*) on crop *RUE*.

Table 10. Comparison between pumpkin dry weight (*DW*) simulated using single *RUE*, double *RUE* and daily *RUE* for calibration treatment (T3-2014). Relative difference (RD) was calculated as: (simulated value-observed value)/observed value; Gallardo et al. (2011).

		Simulated *DW* (g m^{-2})			Relative difference (%)		
CTT_i (^{o}Cd)	Observed *DW* (g m^{-2})	Single *RUE*	Double *RUE*	Daily *RUE*	Single *RUE*	Double *RUE*	Daily *RUE*
395	18	27.2	21.1	15.5	50.9	17.4	-13.9
580	108	108.9	84.7	111.9	0.9	-21.5	3.6
845	390	358.2	358.2	407.1	-8.1	-8.1	4.4
1097	657	612.1	612.1	653.1	-6.8	-6.8	-0.6
1221	651	707.4	707.4	640.8	8.7	8.7	-1.6
	RMSE	35.5	34.7	9.3			
	RE	0.1	0.09	0.02			

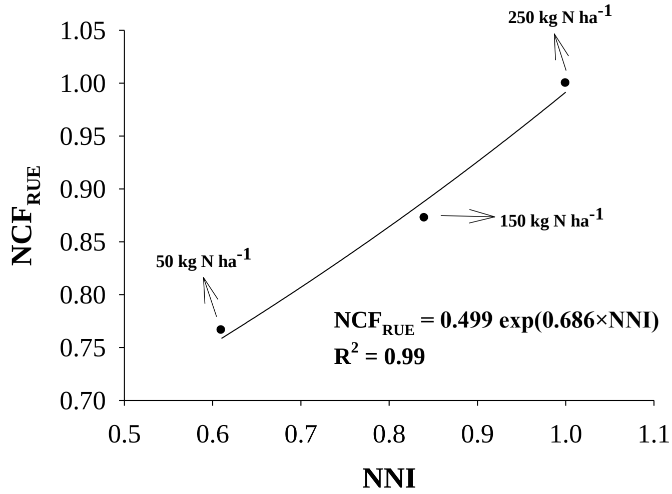

Fig. 4. Relationship between *NCF_{RUE}* (or relative *RUE*) and nitrogen nutrition index (*NNI*) for 2014 experiment.

Nitrogen nutrition index (*NNI*) is recognized as a reference method for detecting *N* deficiency in crop (Ziadi et al. 2010) and can be used as a priori diagnosis of plant N status during crop growth to determine the necessity of applying additional fertilization (Christos 2011) when *NNI* is less than 1.0. It is estimated through comparison of the actual crop *N* concentration (%N_a) with the critical N concentration (%N_c) at a given day. By definition, critical N concentration (%N_c) is the minimal concentration of total N in shoots that produced the maximum aerial dry matter, at a given time and field situation (Justes et al., 1994). It is experimentally estimated as the ordinate of the intersection point between an oblique linear regression representing the joint increase in N concentration and dry weight and a vertical line corresponding to an increase in N concentration without significant variation in shoot dry weight (Justes et al., 1994). Experimental data of 2014 trial showed that in all sampling dates after nitrogen application, shoot dry weight of pumpkin was significantly increased as the nitrogen rate increased to 250 kg ha^{-1} (Table. 11). Therefore, since the shoot nitrogen concentration of pumpkin in treatment with 250 kg N ha^{-1} was the minimal N concentration which produced the maximum dry weight of pumpkin, the shoot N concentration of this treatment was considered as the critical N concentration and *NNI* was calculated based on it (Table. 11). Since there was no considerable variation in *NNI* during pumpkin growth cycle for treatments with nitrogen rates of 50 and 150 kg ha^{-1} (Table. 11), the average values of 0.61 and 0.84 were considered for *NNI* in these treatments, respectively.

Table 11. Mean comparison of pumpkin shoot dry weight together with corresponding N content and nitrogen nutrition index at various days after application of nitrogen treatments in 2014 experiment.

	Shoot dry weight (g m^{-2})				Shoot N content (%)				NNI			
N rate (kg ha^{-1})	42 DAS	56 DAS	70 DAS	77 DAS	42 DAS	56 DAS	70 DAS	77 DAS	42 DAS	56 DAS	70 DAS	77 DAS
50	60c	225c	360c	350c	1.33	0.95	0.93	0.91	0.63	0.59	0.62	0.61
150	86b	310b	517b	509b	1.81	1.35	1.27	1.22	0.86	0.84	0.85	0.81
250	108a	390a	657a	651a	2.10	1.60	1.50	1.50	1.00	1.00	1.00	1.00

* For shoot dry weight, in each column, means with the same letter do not have a significant difference according to the LSD test at probability level of 0.10. DAS: days after sowing.

In 2010 and 2012 experiments, the fraction of intercepted *PAR* ($f_{i\text{-}PAR}$) and subsequently, the radiation use efficiency (*RUE*) of pumpkin did not measure. Thus, for treatments of these experiments which their nitrogen rate was lower or higher than optimum rate, the shoot dry weight of pumpkin was directly simulated as the product of the shoot dry weight produced under optimum nitrogen rate into a nitrogen corrective factor for dry weight (NCF_{DW}) (Eq. (13)), which was developed based on the nitrogen nutrition index (*NNI*) using four years experimental data (Fig. 5). For developing this corrective factor (NCF_{DW}), treatments which their plant density and sowing date were similar to the optimum growth conditions (i.e. plant density of 2.5 plant m^{-2} and sowing date 1-11 May) and only their nitrogen rate was lower or higher than optimum rate (250 kg ha^{-1}), were selected in different years. Accordingly, the treatments of T1-2012, T1-2014, T2-2014, T3-2014 and T9-2010 were selected for nitrogen rates of 0, 50, 150, 250 and 350 kg ha^{-1}, respectively. Then, in each year, the relative dry weight (calculated as the ratio between dry weight of treatments with nitrogen deficiency or excess and dry weight of treatment with optimum growth conditions) for these treatments was estimated at different times of the pumpkin growing season. It is noteworthy that in 2012 experiment, there was no treatment with all optimum growth conditions and thus, for estimation of the relative dry weight in T1-2012 treatment, the VegSyst model was ran under optimum growth conditions (using calibration parameters of Table 9 and weather data of the 2012 year) and then, dry weight of the T1-2012 treatment was compared to the dry weight obtained from VegSyst model. Results showed that for all these treatments, the relative dry weight during the pumpkin growing season was approximately constant and as a result, the growing season average of 0.35, 0.53, 0.78, 1.00 and 0.77 were considered as the values of the relative dry weight for nitrogen rates of 0, 50, 150, 250 and 350 kg ha^{-1}, respectively (Fig. 5).

A cubic function was obtained for association between these relative dry weights and their corresponding *NNI* (Fig. 5). This function which named as the nitrogen corrective factor for dry weight (NCF_{DW}) shows that relative dry weight of pumpkin was increased as nitrogen rate increased to 250 kg ha^{-1} (*NNI*=1) and thereafter, this ratio decreased (Fig. 5). In nitrogen rates higher than optimum level, the N absorbed in excess of protein synthesis requirement accumulates as nitrates, amides, and free amino acids in crop and excessive levels of these metabolites are considered to be toxic for crop growth (Aulakh and Malhi, 2005). The nitrogen nutrition index (*NNI*) for nitrogen rates of 0, 50, 150, 250 and 350 kg ha^{-1} was considered to be 0.45, 0.61, 0.84, 1.0 and 1.3, respectively. The *NNI* values for nitrogen rates of 50, 150 and 250 kg ha^{-1} were obtained from experimental data of 2014 experiment (Table. 11), while the *NNI* values for nitrogen rates of 0 and 350 kg ha^{-1} were estimated using the value which minimizes differences between simulated and observed shoot dry weight in corresponding treatments. Furthermore, values of -3.84, 8.44, -4.77 and 1.15 were obtained for calibration parameters of A_{DW}, B_{DW}, C_{DW} and D_{DW} in NCF_{DW} function, respectively (Fig. 5).

In 2010 and 2012 experiments, the plant density of some treatments was lower or higher than the optimum plant density (i.e. 2.5 plant m^{-2}) (Table. 1). For these treatments, a density effect factor (*DEF*) was used in order to convert dry weight obtained from optimum plant density to the dry weight produced under non optimum plant density. For this purpose, the treatments which their sowing date and nitrogen rate were similar to the optimum conditions (i.e. sowing date 1-11 May and nitrogen rate of 250 kg ha^{-1}) and only their plant density was lower or higher than the

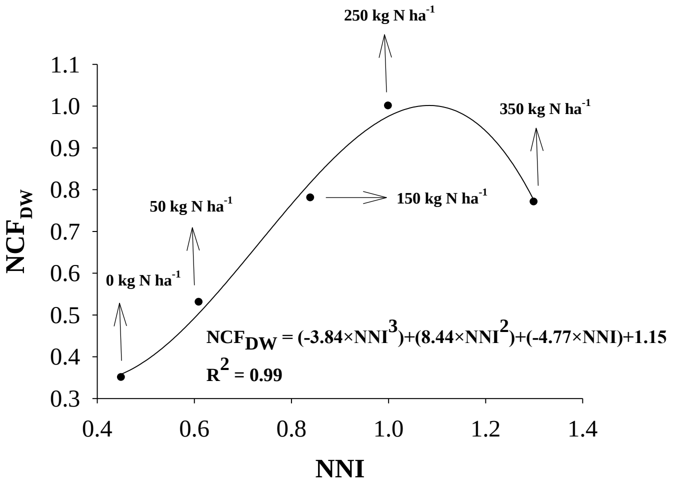

Fig. 5. Relationship between NCF_{DW} (or relative dry weight) and nitrogen nutrition index (*NNI*).

optimum, were selected in 2010 and 2012 experiments. Thus, the T4-2010, T5-2010 and T2-2012 treatments were chosen for plant densities of 0.625, 1.25 and 4 plant m^{-2}, respectively. For T4-2010 and T5-2010 treatments, the relative dry weight was calculated as the ratio of their dry weight to the dry weight in treatment with optimum growth conditions (i.e. T6-2010 treatment). Whereas, in 2012 experiment, due to lacking a treatment with nitrogen rate of 250 kg ha^{-1} (Table 1), the dry weight of T2-2012 treatment was compared to the T1-2012 treatment, which all growth conditions of it were similar to the T2-2012 treatment, except for the plant density (Table 1). The relative dry weight for these treatments (T4-2010, T5-2010 and T2-2012) was calculated during the growing season of pumpkin and the average values of 0.30, 0.74, 1.00 and 1.07 were considered for plant densities of 0.625, 1.25, 2.5 and 4 plant m^{-2}, respectively (Fig. 6).

There was a sigmoidal relationship between these relative dry weights and their corresponding plant density (Fig. 6) and thus, the density effect factor (*DEF*) was implemented using this sigmoidal function (Eq. (14)). This function was used for converting dry weight obtained from optimum plant density (2.5 plant m^{-2}) to the dry weight of pumpkin produced from non-optimum plant densities (lower or higher than 2.5 plant m^{-2}). The density effect factor (*DEF*) indicates that in plant densities below optimum level, shoot dry weight of pumpkin was decreased (Fig. 7) due to decline in both PAR_i and *RUE*. Whereas, at plant densities higher than optimum level, overlapping of leaves makes that photosynthesis no longer linearly proportional to the plant population (Cao et al., 2009). Thus, dry weight obtained from plant densities higher than optimum level is approximately equal to that obtained from optimum plant density (Fig. 6) or even is lower than dry weight produced under optimum plant density because of increase in intra-specific competition. Values obtained for calibration coefficients of A_p, B_p and C_p were 1.043, 0.941 and 0.355, respectively (Fig. 6).

Compared to the greenhouse conditions which providing optimum temperature for crop growth is possible in all year round, deviation from optimum sowing date (optimum temperature) for field crops can decrease crop growth due to unfavorable temperature. Therefore, applying a temperature stress factor (*TSF*) is essential for estimation of crop growth under non optimum sowing. For developing the temperature stress factor (*TSF*) based on 2012 experiment, the dry weights obtained from two plant densities of sowing dates May 11 and May 21 were compared with

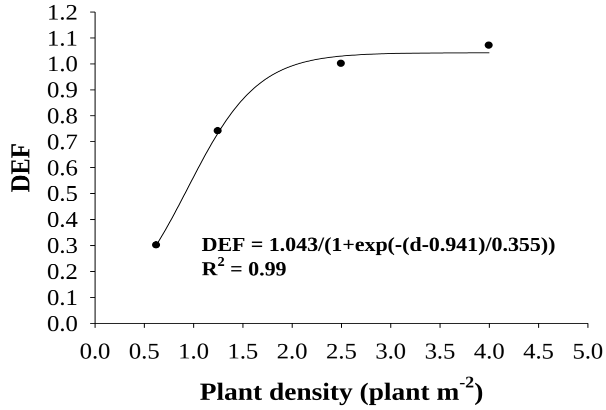

Fig. 6. Effect of plant density (*d*) on relative dry weight (or *DEF*) of pumpkin

corresponding plant densities of sowing date May 1, which had the maximum shoot dry weight of pumpkin among three sowing dates evaluated in 2012 experiment. Accordingly, growing season average of the relative dry weight for plant density of 2.5 plant m^{-2} in sowing dates May 1, May 11 and May 21was 1.00, 0.99 and 0.64, respectively, versus 1.00, 0.96 and 0.66 for plant density of 4 plant m^{-2}, respectively (Fig. 7). As previously showed in Table. 8, there was no significant difference between sowing dates of May 1 and May 11 regarding shoot dry weight of pumpkin (Table 8).Therefore, sowing date 1-11 May considered as the optimum sowing date and thus applying the temperature stress factor (*TSF*) for sowing dates from 1 to 11 May was not necessary. When the relative dry weights were regressed against the growing season average of air temperature (T_{ave}) in different sowing dates (Fig. 7), it was showed that with delaying sowing date to May 21 (i.e. T_{ave} = 27.1 ^{o}C) the relative dry weight for both plant densities significantly decreased (Fig. 7) and thus, applying the temperature stress factor (*TSF*) for this sowing date was essential. Accordingly, the temperature stress factor (*TSF*) (Eq. (15)) which obtained through evaluation of the relationship between relative dry weights and growing season average of air temperature (Fig. 7), only was used for treatments with non-optimum sowing date for pumpkin (i.e. T5-2012 and T6-2012 treatments).The values of 1.0, 27.248 and -0.236 were obtained for calibration coefficients of A_T, B_T and C_T, respectively (Fig. 7).

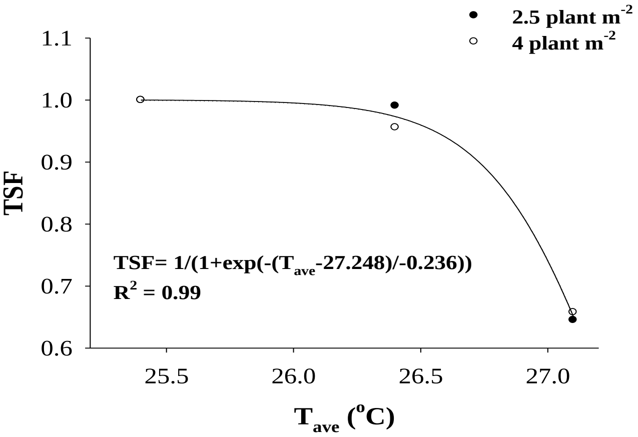

Fig. 7. Effect of growing season average of air temperature (T_{ave}) on relative dry weight (or *TSF*) of pumpkin for 2012 experiment.

The actual plant N concentration in a crop stand declines even under favorable N supply as the crop mass increases (Greenwood et al., 1986). This decline can be described empirically by a negative power function ($\%N= a\times DW^{-b}$) (Lemaire et al., 2008) relating plant N concentration ($\%N$) to crop mass (DW). By fitting the power N dilution curve ($\%N=a\times DW^{-b}$) to the data of calibration treatment (T3-2014), the values of 4.97 and 0.19 were obtained for a and b parameters, respectively (Table 9) and the coefficient of determination (R^2) for this curve fitting was 99.9% (Fig. 2c). Furthermore, for nitrogen deficient treatments of 2013 and 2014 experiments (i.e. treatments with 50 and 150 kg N ha^{-1}), the N concentration was simulated by multiplying the N concentration obtained from conditions with optimum nitrogen rate into the nitrogen nutrition index (NNI).

The initial crop coefficient (kc_{ini}) and maximum crop coefficient (kc_{max}) were obtained from Fig. 2d, while the crop coefficient at the end of crop (kc_{end}) were estimated by using the value which minimize differences between simulated and observed ET_c in the calibration treatment (T3-2014). Accordingly, the values of 0.60, 1.04 and 0.50 were obtained for kc_{ini}, kc_{max} and kc_{end}, respectively (Table 9).

Model validation

The data relevant to treatments of 2010, 2012, 2013 and 2014 field experiments were used for model validation. Details of these treatments previously showed in Table 1. Among these treatments, conditions of two treatments (i.e. T6-2010 and T3-2013) regarding the amount of nitrogen application (250 kg ha^{-1}), plant density (2.5 plant m^{-2}) and sowing date (1-11 May) were similar to the calibration treatment (i.e. T3-2014). However, due to lack of measurement of intercepted PAR, nitrogen content and crop evapotranspiration in 2010 and 2012 experiments, the data of these experiments were only used for validation of pumpkin dry weight (DW). Evaluation of the association between simulated and observed values of pumpkin growth parameters (including shoot dry weight (DW), fraction of intercepted PAR ($f_{i\text{-}PAR}$), radiation use efficiency (RUE), nitrogen uptake and crop evapotranspiration (ET_c)) for T6-2010 and T3-2013 treatments (Fig. 8) which had the optimum conditions similar to the calibration treatment (T3-2014) showed that there was a close linkage between simulated and observed values for all growth parameters (Fig. 8). Most simulated data were closely distributed around the 1:1 line (Fig. 8). Furthermore, the intercept and slope of the linear regression between simulated and observed values of dry weight in T6-2010 and T3-2013 treatments and $f_{i\text{-}PAR}$, RUE, N uptake and ET_c in T3-2013 treatment did not have a statistically significant difference ($P \leq 0.05$) with 0 and 1, which are the intercept and slope of the 1:1 line, respectively (Table 12).

The relative difference (RD) (calculated as: ((simulated value-observed value)/observed value)(Gallardo et al. 2011) between growing season average of simulated and observed dry weight in T6-2010 and T3-2013 treatments was only -0.31 and +2.1%, respectively. Similarly, the simulated values of $f_{i\text{-}PAR}$, RUE, N uptake and ET_c in T3-2013 treatment only had +5.2, +5.4, +5.2 and -0.6% difference relative to the observed values. Therefore, close association between simulated and observed values (Fig. 8), non-significant difference between intercept and slope of the linear regression and 1:1 line (Table 12) and low values of relative difference between simulated and observed data indicated that modified VegSyst model very accurately simulated shoot dry weight, fraction of intercepted PAR, radiation use efficiency, nitrogen uptake and evapotranspiration of pumpkin in treatments which similar to calibration treatment, had the optimum growth conditions. Similarly, Gallardo et al. (2011) reported that the VegSyst model very accurately simulated shoot dry weight, fraction of intercepted PAR, crop N uptake and evapotranspiration of muskmelon under greenhouse condition with no water and nitrogen limitation.

The model performance for simulation of dry weight for T6-2010, T3-2013 and T3-2014 treatments which had the optimum growth conditions, was very good and a high value of the Willmott index of agreement (d ≥ 0.95) and low value of relative error (RE ≤ 0.10) were obtained (Table 13). Gallardo et al. (2011) also reported that performance of the VegSyst model in simulation of the muskmelon dry weight under no water and nitrogen limitations was very good. Furthermore, the VegSyst model had a very good performance for simulation of the fraction of intercepted *PAR* ($f_{i\text{-}PAR}$), *RUE*, nitrogen uptake and crop evapotranspiration (ET_c) in T3-2013 and T3-2014 treatments due to high value of the Willmott index of agreement (d ≥ 0.95) and low value of the relative error (RE ≤ 0.10) between simulated and observed data (Table 14).

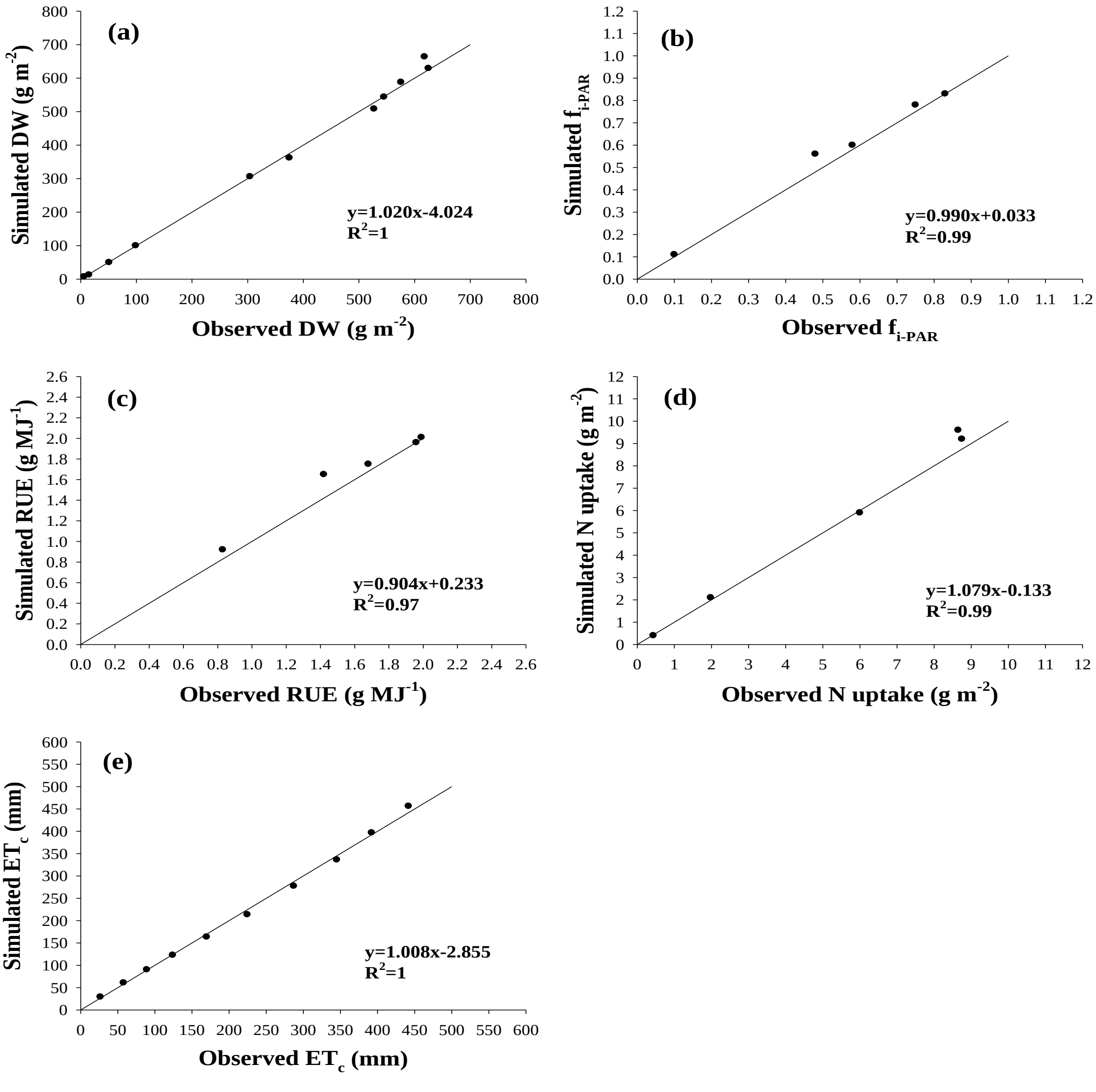

Fig. 8. Relationship between simulated and observed values of (a) dry weight (*DW*) for T6-2010 and T3-2013 treatments, (b) the fraction of intercepted *PAR* ($f_{i\text{-}PAR}$) for T3-2013 treatment, (c) the radiation use efficiency (*RUE*) for T3-2013 treatment, (d) the nitrogen uptake for T3-2013 treatment and (e) the crop evapotranspiration (ET_c) for T3-2013 treatment. The linear regression equations and the coefficients of determination (R^2) are given in the figures.

Table 12. Statistical comparison of the slope and intercept of linear regression between simulated and observed growth data with the slope and intercept of 1:1 line (*DW*: dry weight (g m^{-2}) for T6-2010 and T3-2013 treatments, f_{i-PAR}: fraction of intercepted *PAR* for T3-2013 treatment, *RUE*: radiation use efficiency (g MJ^{-1}) for T3-2013 treatment, *NU*: nitrogen uptake (g m^{-2}) for T3-2013 treatment and ET_c: crop evapotranspiration (mm) for T3-2013 treatment).

		Linear regression		**Standard Error**		**t value**		**P value**	
Growth parameter	n	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope
DW	11	-4.024	1.020	8.589	0.021	0.468	0.952	0.649	0.363
f_{i-PAR}	5	0.033	0.990	0.038	0.063	0.868	0.159	0.434	0.882
RUE	5	0.233	0.904	0.154	0.094	1.513	1.021	0.205	0.365
NU	5	-0.133	1.079	0.288	0.046	0.462	1.717	0.668	0.161
ET_c	10	-2.855	1.008	4.912	0.019	0.581	0.421	0.575	0.684

Table 13. Summary of statistical indices used to evaluate model performance regarding dry weight (*DW*) for T6-2010, T3-2013 and T3-2014 treatments. (RMSE: root mean square error; RE: relative error; d: Willmott index of agreement; m: slope of the linear relationship between observed and estimated values; R^2: determination coefficient of that relationship. Performance: VG (very good), G (good), ACC (acceptable), P (poor). n is the number of data).

Treatment	**n**	**RMSE**	**RE**	**d**	**m**	**R^2**	**Performance**
T6-2010	6	9.30	0.03	1.00	1.00	1.00	VG
T3-2013	5	21.42	0.06	1.00	1.04	1.00	VG
T3-2014	5	9.31	0.02	1.00	0.99	1.00	VG

Table 14. Summary of statistical indices used to evaluate model performance regarding fraction of intercepted *PAR* (f_{i-PAR}), radiation use efficiency (*RUE*), crop nitrogen uptake and crop evapotranspiration for T3-2013 and T3-2014 treatments. (RMSE: root mean square error; RE: relative error; d: Willmott index of agreement; m: slope of the linear relationship between observed and estimated values; R^2: determination coefficient of that relationship. Performance: VG (very good), G (good), ACC (acceptable), P (poor). n is the number of data).

Growth parameter	**Treatment**	**n**	**RMSE**	**RE**	**d**	**m**	**R^2**	**Performance**
Fraction of intercepted *PAR*	T3-2013	5	0.04	0.07	0.99	0.99	0.99	VG
	T3-2014	5	0.04	0.08	0.99	0.95	0.97	VG
Radiation use efficiency (g MJ^{-1})	T3-2013	5	0.11	0.07	0.98	0.90	0.97	VG
	T3-2014	5	0.06	0.03	0.99	0.95	0.98	VG
Crop N uptake (g m^{-2})	T3-2013	5	0.47	0.09	0.99	1.08	0.99	VG
	T3-2014	5	0.28	0.05	1.00	0.96	1.00	VG
Crop evapotranspiration (mm)	T3-2013	10	7.66	0.03	1.00	1.00	1.00	VG
	T3-2014	10	4.85	0.02	1.00	0.99	1.00	VG

Other treatments of 2013 and 2014 experiments (including T1-2013, T2-2013, T1-2014 and T2-2014) did not have the optimum rate of nitrogen application, thus for simulation of the fraction of intercepted PAR ($f_{i\text{-}PAR}$) and radiation use efficiency (RUE) in these treatments, the nitrogen corrective factors for $f_{i\text{-}PAR}$ (NCF_f) (Eq. (9)) and for RUE (NCF_{RUE}) (Eq. (11)) were used. In these treatments, the $f_{i\text{-}PAR}$ and RUE were simulated by multiplying the $f_{i\text{-}PAR}$ and RUE obtained from conditions without nitrogen limitation into the corresponding nitrogen corrective factors (i.e. NCF_f for $f_{i\text{-}PAR}$ and NCF_{RUE} for RUE). Then, the shoot dry weight (DW_i) was simulated through Eq. (5) using daily $f_{i\text{-}PAR}$ and RUE obtained for nitrogen deficient conditions. Model performance in simulation of dry weight was very good for T1-2013, T2-2013 and T2-2014 treatments and was good for T1-2014 treatment (Table 15). The relative difference between simulated and observed growing season average of dry weight for T1-2013, T2-2013, T1-2014 and T2-2014 treatments was -5.5, +1.3, -13.5 and -3.4%, respectively.

Table 15. Comparison between simulated (Sim.) and observed (Obs.) data and Summary of statistical indices used to evaluate model performance regarding of dry weight, fraction of intercepted *PAR* ($f_{i\text{-}PAR}$), radiation use efficiency (*RUE*) and crop nitrogen uptake for treatments with no optimum nitrogen application in 2013 and 2014 experiments. RE: relative error and d: Willmott index of agreement. Performance: VG (very good), G (good), ACC (acceptable), P (poor).

Growth parameter	Treatment							RE	d	Performance
Dry weight (g m^{-2})	T1-2013	Sim.	12.8	37.7	169.9	307	320.5	0.10	1.00	VG
		Obs.	15	50	205	320	307			
	T2-2013	Sim.	12.8	58.7	266.4	488.9	510.6	0.10	1.00	VG
		Obs.	15	77	293	472	463			
	T1-2014	Sim.	15.5	42.3	194.2	317.8	306.7	0.15	0.99	G
		Obs.	18	60	225	360	350			
	T2-2014	Sim.	15.5	66	305.2	508.3	495.4	0.04	1	VG
		Obs.	18	86	310	517	509			
Fraction of intercepted *PAR*	T1-2013	Sim.	0.11	0.37	0.58	0.48	0.29	0.20	0.98	ACC
		Obs.	0.1	0.34	0.64	0.38	0.2			
	T2-2013	Sim.	0.11	0.49	0.78	0.69	0.44	0.12	0.99	G
		Obs.	0.1	0.49	0.78	0.62	0.34			
	T1-2014	Sim.	0.14	0.41	0.58	0.42	0.21	0.12	0.99	G
		Obs.	0.11	0.37	0.66	0.41	0.23			
	T2-2014	Sim.	0.14	0.54	0.79	0.62	0.32	0.06	1.00	VG
		Obs.	0.11	0.51	0.79	0.64	0.36			
Radiation use efficiency (g MJ^{-1})	T1-2013	Sim.	0.92	1.24	1.52	1.49	1.33	0.10	0.98	VG
		Obs.	0.83	0.98	1.54	1.5	1.3			
	T2-2013	Sim.	0.92	1.44	1.78	1.74	1.56	0.09	0.97	VG
		Obs.	0.83	1.23	1.7	1.66	1.43			
	T1-2014	Sim.	0.97	1.3	1.53	1.45	1.24	0.06	0.99	VG
		Obs.	0.95	1.19	1.57	1.53	1.34			
	T2-2014	Sim.	0.97	1.52	1.79	1.7	1.45	0.03	1.00	VG
		Obs.	0.95	1.43	1.76	1.72	1.49			
Crop N uptake (g m^{-2})	T1-2013	Sim.	0.40	0.50	1.69	2.74	2.82	0.09	1.00	VG
		Obs.	0.43	0.60	1.78	2.72	2.52			
	T2-2013	Sim.	0.4	1.03	3.64	6.00	6.26	0.12	1.00	G
		Obs.	0.43	1.30	3.69	5.66	5.46			
	T1-2014	Sim.	0.46	0.53	1.88	2.81	2.72	0.18	1.00	ACC
		Obs.	0.52	0.80	2.14	3.35	3.18			
	T2-2014	Sim.	0.46	1.14	4.10	6.20	6.10	0.07	1.00	VG
		Obs.	0.52	1.56	4.18	6.57	6.21			

The model performance for simulating fraction of intercepted *PAR* ($f_{i\text{-}PAR}$) and *RUE* in nitrogen deficient treatments of 2013 and 2014 experiments was very good, except for T1-2013, T2-2013 and T1-2014 treatment which model had acceptable, good and good performance in simulation of their $f_{i\text{-}PAR}$, respectively (Table 15). The relative difference between simulated and observed values in T1-2013, T2-2013, T1-2014 and T2-2014 treatments was +10.2, -7.7, -1.1 and 0.0% for $f_{i\text{-}PAR}$, respectively, versus to +5.7, +8.6, -1.4 and +1.1% for *RUE*, respectively.

For simulation of crop nitrogen uptake in nitrogen deficient treatments of 2013 and 2014 experiments (i.e. T1-2013, T2-2013, T1-2014 and T2-2014), the N concentration obtained from conditions without nitrogen deficiency was multiplied by the nitrogen nutrition index (*NNI*) and then, the crop N uptake was simulated through multiplying the crop N concentration into the shoot dry weight. Model performance for N uptake simulation in T1-2013 and T2-2013 treatments was very good and good, respectively, while its performance for T1-2014 and T2-2014 treatments was acceptable and very good, respectively (Table 15). The relative difference between simulated and observed growing season average of crop nitrogen uptake for T1-2013, T2-2013, T1-2014 and T2-2014 treatments was +1.17, +4.63, -15.92 and -5.46%, respectively.

However, for simulation of crop evapotranspiration in nitrogen deficient treatments of 2013 and 2014 experiments, the original model components were used without any change as compared to the optimum nitrogen conditions. Accordingly, model had a good and very good performance in simulation of crop evapotranspiration for T1 and T2 treatments of both years, respectively (Table 16). The relative difference between growing season average of simulated and observed crop evapotranspiration (ET_c) for T1-2013, T2-2013, T1-2014 and T2-2014 treatments was +8.90, +4.64, +9.10 and +4.38%, respectively. The very good and good performance of the model in nitrogen deficient treatments of 2013 and 2014 experiments was due to non-significant difference between these treatments with T3-2014 treatment (calibration treatment) regarding crop evapotranspiration. Therefore, these results suggested that VegSyst model can be used for simulation of crop evapotranspiration in nitrogen deficient conditions without any special modifications as compared to the optimum nitrogen conditions.

Table 16. Comparison between simulated (Sim.) and observed (Obs.) data and Summary of statistical indices used to evaluate model performance regarding crop evapotranspiration for treatments with no optimum nitrogen application in 2013 and 2014 experiments. RE: relative error and d: Willmott index of agreement. Performance: VG (very good), G (good), ACC (acceptable), P (poor).

	T1-2013		**T2-2013**		**T1-2014**		**T2-2014**	
	Sim.	**Obs.**	**Sim.**	**Obs.**	**Sim.**	**Obs.**	**Sim.**	**Obs.**
	29.1	26.6	29.1	26.6	32.6	28.4	32.6	28.4
	60.9	57.9	60.9	57.9	66.6	63.2	66.6	63.2
	90.2	89.2	90.2	89.2	98.9	98.5	98.9	98.5
	122.8	124.2	122.8	124.2	128.5	128.3	128.5	128.3
	163.6	165.3	163.6	167.6	169	170.5	169	172.9
	213.6	211.3	213.6	217.1	219.8	213.9	219.8	220.1
	277.4	262.4	277.4	272.6	291.6	272	291.6	283.9
	330.2	309.7	330.2	324.4	356.4	323.9	356.4	341.2
	396.9	345.2	396.9	364.9	419.1	368.8	419.1	392.9
	456.3	379.7	456.3	407.3	477.1	404	477.1	435.3
RE	0.15		0.09		0.15		0.08	
d	0.99		1.00		0.99		1.00	
Performance	G		VG		G		VG	

All treatments of 2012 experiments did not receive any amount of nitrogen. Furthermore, T2-2012, T4-2012 and T6-2012 treatments did not have the optimum plant density (2.5 plant m^{-2}) and the sowing date of T5-2012 and T6-2012 treatments was out of the optimum sowing date (1-11 May). Thus, the nitrogen corrective factor for dry weight (NCF_{DW}) (Eq. (14)) was used for all treatments of 2012, the density effect factor (*DEF*) (Eq. (14)) was used for T2-2012, T4-2012 and T6-2012 treatments and temperature stress factor (Eq. (15)) was only applied for T5-2012 and T6-2012 treatments. Furthermore, since nitrogen uptake in 2012 experiment was not determined, the nitrogen nutrition index (*NNI*) of 0.45 was considered for treatments of this experiment in order to minimize difference between simulated and observed values of dry weight. Accordingly, the model performance in simulation of shoot dry weight for all treatments of 2012 experiment was very good, except for T2-2012 treatment, which model had a good performance for simulation of dry weight obtained from it (Table 17). The model underestimated the growing season average of shoot dry weigh for T2-2012, T3-2012 and T6-2012 treatments by 4.5, 2.6 and 1.5%, respectively, and overestimated the shoot dry weight for T1-2012, T4-2012 and T5-2012 treatments by 0.5, 0.3 and 4.1%, respectively.

Table 17. Comparison between simulated (Sim.) and observed (Obs.) data and summary of statistical indices used to evaluate model performance regarding dry weight (*DW*) for 2012 treatments. RE: relative error and d: Willmott index of agreement. Performance: VG (very good), G (good), ACC (acceptable), P (poor).

Treatment								RE	d	Performance
T1-2012	Sim.	1.6	4.3	45.2	143.5	235.8	197.7	0.10	1.00	VG
	Obs.	2.2	15	55	148	217	188			
T2-2012	Sim.	2.7	4.5	47.2	149.6	245.9	206.1	0.13	1.00	G
	Obs.	2.2	15	65	170	225	210			
T3-2012	Sim.	3.2	19.1	107.5	209.3	212.4	180.1	0.08	1.00	VG
	Obs.	6.1	25	125	215	200.1	180.2			
T4-2012	Sim.	2.6	19.9	112.4	218.3	221.5	187.8	0.06	1.00	VG
	Obs.	6.1	26.2	120	215.1	208	185			
T5-2012	Sim.	3.3	37.2	106.6	145.5	120.7	115.2	0.10	1.00	VG
	Obs.	7.7	40	90	140	125	105			
T6-2012	Sim.	3.4	38.8	111	155.9	125.8	120.2	0.09	1.00	VG
	Obs.	7.7	55	103.1	148	130	120			

In 2010 experiment, nitrogen rates of 150, 250 and 350 kg ha^{-1} were applied under three plant densities of 0.625, 1.25 and 2.5 plant m^{-2} (Table 1). The results of this experiment showed that pumpkin dry weight increased to 250 kg N ha^{-1} and thereafter, dry weight was decreased. Thus, the nitrogen corrective factor of dry weight (NCF_{DW}) (Eq. (13)) was applied for T1-2010, T2-2010 and T3-2010 treatments which their nitrogen rate (150 kg ha^{-1}) was lower than optimum rate (250 kg ha^{-1}) and also for T7-2010, T8-2010 and T9-2010 which the nitrogen rate of them (350 kg ha^{-1}) was higher than optimum rate. Furthermore, for treatments of T1-2010, T2-2010, T4-2010, T5-2010, T7-2010 and T8-2010 which their plant density was lower than optimum (2.5 plant m^{-2}), the density effect factor (*DEF*) (Eq. (14)) also was used for simulation of their dry weight from dry weight obtained under optimum growth conditions. In this experiment, only T6-2010 treatment had the optimum conditions for pumpkin growth and thus, the original model without any change compared to the calibration treatment (T3-2014) was used for simulation of its dry weight. Model showed very good performance in simulation of shoot dry weight for T1-2010, T2-2010, T5-2010, T7-2010, T8-2010 and T9-2010 treatments and a good performance for T3-2010 and T4-2010 treatments (Table 18). The relative difference between simulated and observed growing season average of dry weight for 2010 treatments was ranged from -0.31% to 15.55%.

Table 18. Comparison between simulated (Sim.) and observed (Obs.) data and summary of statistical indices used to evaluate model performance regarding dry weight (*DW*) for 2010 treatments. RE: relative error and d: Willmott index of agreement. Performance: VG (very good), G (good), ACC (acceptable), P (poor).

Treatment								RE	d	Performance
T1-2010	Sim.	1.8	10.9	72.6	144	137.8	128.3	0.10	1.00	VG
	Obs.	1.9	8.6	64.2	135.3	126.6	118.1			
T2-2010	Sim.	4.2	26	176	348.7	333.9	310.7	0.08	1.00	VG
	Obs.	6.1	16.7	155.4	328.6	314.6	302.8			
T3-2010	Sim.	5.7	36	239.4	474.4	454.1	422.6	0.12	1.00	G
	Obs.	6.1	22.5	208.2	435.8	415.2	385.5			
T4-2010	Sim.	2.1	13.3	88.4	175.1	167.6	156	0.11	1.00	VG
	Obs.	1.9	10.1	76.9	165.7	153.5	140.5			
T5-2010	Sim.	5.1	32.2	214	424	406	377.7	0.06	1.00	VG
	Obs.	9.4	27.4	243.9	416.5	390.3	376.6			
T7-2010	Sim.	1.6	10.3	68.6	135.9	130.1	121.1	0.07	1.00	VG
	Obs.	1.9	7.8	65.6	127.7	121.7	118.8			
T8-2010	Sim.	3.9	25	166.1	329.1	315.1	293.2	0.03	1.00	VG
	Obs.	3.4	16.9	162.9	335.6	316	298.5			
T9-2010	Sim.	5.3	34	225.9	447.7	428.6	398.8	0.03	1.00	VG
	Obs.	6.1	25.2	222.7	430.3	424.5	405.2			

Conclusion

The VegSyst model was initially introduced by Gallardo et al. (2011) to simulate the crop growth, nitrogen uptake and evapotranspiration in crops grown without nutrient, water and temperature limitations, which is realistic for intensively managed greenhouse vegetables. Intensive management of greenhouse crops including high amount of nutrients and water and exact control of climate resulted in almost constant crop growth rate (*CGR*) and intercepted photosyntheticaly active radiation (PAR_i) for greenhouse crops in the whole growth cycle and thus, fixed value of *RUE* can be considered for the entire growth cycle of greenhouse crops. Gallardo et al. (2011) used single or double *RUE* approaches for simulating growth of muskmelon crops grown under intensively managed greenhouse conditions. However, for pumpkin grown under field conditions, *RUE* influenced by developmental stage and as a result, to increase the accuracy of the VegSyst model for simulation of the crop growth under field conditions, a component which simulated daily radiation use efficiency (*RUE*) was attached to it.

In contrast to intensively managed greenhouse plants, the crop growth under field conditions is affected by various limitation factors such as nutrient deficiency, water stress, temperature stress, pests and diseases. These limitation factors can decrease the crop growth compared to optimum conditions. Therefore, the VegSyst model which was developed for simulation of the potential crop growth under optimum growth conditions, was also modified using corrective factors that make possible its application under different nitrogen rates, plant densities and sowing dates.

This model was calibrated and validated for pumpkin crop using field experiments which carried out in 2010, 2012, 2013 and 2014 years. Results showed that the model performance in simulation of pumpkin dry weight (*DW*), fraction of intercepted *PAR* ($f_{i\text{-}PAR}$), radiation use efficiency (*RUE*), nitrogen uptake and crop evapotranspiration (ET_c) under optimum growth condition (i.e. nitrogen rate of 250 kg ha^{-1}, plant density of 2.5 plant m^{-2} and sowing date between 1-11 May) was very good. Under non-optimum growth conditions, the model performance for simulating the growth parameters of pumpkin was also very good or good in almost all cases. Therefore, the simplicity of the model and its accurate performance for crops grown under different nitrogen rates, plant densities and sowing dates, make it suitable for incorporation into a decision support system to provide daily estimates of crop N and water requirements for open field vegetable crops.

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