Quantifying the Relationship between Leaf Nitrogen Content and Growth Dynamics and Yield of Muskmelon Grown in Plastic Greenhouse

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Abstract. The aim of this study was to quantitatively investigate the impacts of nitrogen on growth dynamics and yield, so as to facilitate the optimization of nitrogen management for muskmelon crop in plastic greenhouse. For this purpose, four experiments with different levels of nitrogen treatment and planting dates on muskmelon (*Cucumis melo* L. ‘Nanhaimi’ and ‘Xizhoumi 25’) were conducted in plastic greenhouse located at Sanya from Nov. 2012 to Sept. 2014. The quantitative relationship between leaf nitrogen content and growth dynamics and yield of muskmelon was determined and incorporated into a photosynthesis-driven crop growth model (SUCROS). Independent experimental data were used to validate the model. The critical leaf nitrogen content at flowering stage for muskmelon ‘Nanhaimi’ and ‘Xizhoumi 25’ were 19.8 and 21.0 mg·g⁻¹. The coefficient of determination (r^2) and the relative root-mean-squared error (rRMSE) between the predicted and measured value of growth dynamics and yield were, respectively, 0.91 and 10.8% for leaf area index (LAI), 0.90 and 19.6% for dry weight of shoot (DWSH), 0.76 and 30.3%, 0.82 and 21.1%, and 0.92 and 11.9% for dry weight of leaf (DWL), stem (DWST), and fruit (DWF), 0.91 and 17.3%, 0.89 and 13.9%, 0.86 and 27.8%, and 0.88 and 20.6% for soluble sugar content (SU), soluble protein content (PR), vitamin C content (VC), and soluble solids content (SO) of fruit, and 0.90 and 10.1% for fresh weight of fruit (FWF). The model could be used for the optimization of nitrogen management for muskmelon production in plastic greenhouse. Further calibration and test would be needed during the application of the model in wider range of conditions and muskmelon cultivars.

Muskmelon (*Cucumis melo* L.) is one of the most important high-value crops in protective cultivation. In China, the planting area of muskmelon was 42×10^4 ha with the fruit yield exceeded 1400×10^7 kg in 2013.

Nitrogen plays an important role in crop growth and yield formation, which decides on the economic benefits (Dai et al., 2011; He et al., 2009). The excessive application of nitrogen fertilizer causes adverse environmental impacts including the accumulation of soil salt and destruction of crumb structure (Beman et al., 2005; Castellanos et al., 2013). Therefore, the optimization of greenhouse crop nitrogen management is of utmost importance to secure product quality of the muskmelon, which also plays a crucial role in reducing the environmental hazards.

Photosynthesis, LAI, and dry matter partitioning are essential for guaranteeing the

crop growth, yield, and fruit quality (SU, PR, VC, and SO) of horticultural crops. Therefore, for the optimization of crop nitrogen management, it is essential to quantify the impacts of nitrogen on crop growth processes. The existed report on the impacts of nitrogen on crop growth and yield gave the similar conclusions that the increased nitrogen application in a certain range could incline leaf chlorophyll content, the activity of nitrate reductase, the LAI and leaf photosynthetic rate, and then significantly increased dry matter production and nitrogen absorption (Cabello et al., 2009; Kirnak et al., 2005; Padilla et al., 2014; Peri et al., 2003). On the other hand, nitrogen adjusted the dry matter partitioning to leaf and other organs indirectly, which eventually affected fruit yield (Goins et al., 2004; Valdés-Gómez et al., 2014; Zvomuya and Rosen, 2002). These studies provided qualitative description of nitrogen impacts on crop growth and yield, but incapable of quantitative investigation. The simulation studies concentrated on the production system assessment and the methodologies for improving nitrogen resource use and reducing adverse environmental impact (Jamieson and Semenov, 2000; Rinaldi, 2004; Xue et al., 2007). These empirical models use various indicators to account for the crop response to nitrogen fertilizer and lack the reasonable quantitative analysis, thus, cannot well reflect the growth of crops under different nitrogen levels that limits the application and popularization of models (Asseng et al., 2000). Previous simulation studies of muskmelon were reported mainly on the simulation of growth and yield at potential production level (Baker et al., 2001; Yuan et al., 2005; Yuan et al., 2006a, 2006b), hence, cannot be directly applied for crops grown under limited nitrogen supply conditions. For the optimization of nitrogen management, a model is needed for quantitatively assessing the impacts of nitrogen on growth dynamics and yield.

The objective of this study was to develop a dynamics model to quantitatively investigate the impacts of nitrogen on growth dynamics and yield to facilitate the optimization of nitrogen management for muskmelon production in plastic greenhouse. For this purpose, four experiments with different levels of nitrogen treatment and planting dates were carried out in plastic greenhouse to collect data for model development and validation.

Materials and Methods

Plant materials and nitrogen treatment design. Four experiments of different levels of nitrogen treatment and planting dates were conducted in plastic greenhouse of Sanya Science and Technology Academy for Crop Winter Multiplication (18°15' N, 109°30' E) from Nov. 2012 to Sept. 2014.

The orientation of plastic greenhouse is from south to north direction. The length, span, and height were, respectively, 36, 4.6, and 3.2 m. In each experiment, muskmelon

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seedlings with the same size were planted in soilless substrate with silver black compound film cover and irrigated by drip fertigation. The planting density was 2.2 plant/m². The plot of an area of 16.5 m² for each nitrogen treatment with three replicas was arranged in a randomized block design. To keep the same nitrogen treatment level for each experiment, cultivation substrate was made of the new mixture of coconut chaff and river sand with the ratio 2:1. For disinfection, 30 g·m⁻³ carbendazim was used. The pH, available nitrogen (C_n), available phosphorus, available potassium, and bulk density of the substrate were, respectively, 6.63 ± 0.2 , 12.2 ± 0.2 mg·kg⁻¹, 141 ± 16 mg·kg⁻¹, 416 ± 23 mg·kg⁻¹, and $(0.8 \pm 0.1) \times 10^6$ mg·m⁻³. Standard commercial crop management practices (except nitrogen concentration of the nutrient solution during nitrogen treatment period) were used for growing muskmelon crops.

Four levels of nitrogen concentration treatment (N7: 7, N10: 10, N13: 13, and N16: 16 mmol·L⁻¹) were used in each experiment based on the Yamazaki muskmelon nutrient solution concentration. The microelement were NaFe-EDTA 30 mg·L⁻¹, H₃BO₃ 2.85 mg·L⁻¹, MnSO₄·H₂O 2.10 mg·L⁻¹, ZnSO₄·7H₂O 0.22 mg·L⁻¹, CuSO₄·5H₂O 0.08 mg·L⁻¹, and (NH₄)₆Mo₇O₂₄·4H₂O 0.02 mg·L⁻¹.

From planting date to the early stage of fruit development, 0.5 times of nutrient solution with 0.5 L was used once a day (0800–1100 HR) for each plant. From early stage of

fruit development to last stage of fruit development, 1 times of the nutrient solution with 1.0 L was used twice a day (0800–1100 HR and 1500–1800 HR) for each plant. From last stage of fruit development to the harvest date (fruit ripening process), 0.5 times of nutrient solution with 0.5 L was used once a day (0800–1100 HR) for each plant.

Expt. 1: The planting date was 21 Nov. 2012, the flowering date was 24 Dec. 2012, and the harvest date was 4 Feb. 2013. The cultivar was Nanhaimi.

Expt. 2: The planting date was 21 Mar. 2013, the flowering date was 14 Apr. 2013, and the harvest date was 5 May 2013. The cultivar was Nanhaimi.

Expt. 3: The planting date was 13 Jan. 2014, the flowering date was 10 Feb. 2014, and the harvest date was 29 Mar. 2014. The cultivars were Nanhaimi and Xizhoumi 25.

Expt. 4: The planting date was 17 July 2014, the flowering date was 10 Aug. 2014, and the harvest date was 25 Sept. 2014. The cultivars were Nanhaimi and Xizhoumi 25.

Measurements. In each experiment, the light intensity, air temperature at a height of 1.5 m aboveground (ZDR-24; ZEDR Inc., Hangzhou, Zhejiang, China), and substrate temperature (HE-02New; ZEDR Inc.) inside the plastic greenhouse were monitored

automatically every 10 s, and the 30-min averaged data were recorded using a data-logger (Fig. 1; only Expts. 3 and 4 were recorded for substrate temperature). The light intensity (lx) readings were converted to photosynthetic active radiation (PAR , $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) by using the following approximation: $54 \text{ lx} = 1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for sunlight as recommended by Burnell et al. (2014).

To obtain the maximum leaf gross photosynthetic rate ($P_{g,\text{max}}$, $\mu\text{mol CO}_2/\text{m}^2/\text{s}$), a model parameter, the PAR -saturated net photosynthetic rate ($P_{n,\text{max}}$, $\mu\text{mol CO}_2/\text{m}^2/\text{s}$) of new fully expanded leaf (the second leaf from the top downward) at flowering stage, was measured four times (on the same leaf) with 1-h interval during 0900–1200 HR on sunny days using an open gas exchange system (LI-COR 6400; LI-COR Inc., Lincoln, NE) with standard 6-cm² leaf chamber and red-blue LED light source (LI-6400-02B). Saturating PAR was kept at 1500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and three readings (1-min interval for each reading) in $P_{n,\text{max}}$ were recorded to ensure the measurement stability and precision and the average value of the three readings was used for data analysis, and then $P_{g,\text{max}}$ were calculated according to dark respiration rate ($R_d = 0.52 \mu\text{mol CO}_2/\text{m}^2/\text{s}$) obtained by Yuan et al. (2006b).

In each experiment, one plant per plot (three plants in total for each nitrogen treatment) was randomly selected for destructive growth dynamics measurements once every

Fig. 1. Daily maximum temperature, minimum temperature, daily total photosynthetically active radiation (PAR), and daily average substrate temperature since planting date in plastic greenhouse.

15 d since planting date. The measurements of leaf included the length and area of each leaf node (LI-3000A; LI-COR Inc.). The leaf length, measured from leaf tip to the point of petiole intersection along the midrib, was used to estimate leaf area and LAI. The leaf available nitrogen content was determined using the Kjeldahl method. After flowering, fruit quality traits—SU, PR, VC, and SO were determined, respectively, using the anthrone colorimetric method, the Coomassie brilliant blue G250 method, the 2, 6-dichlorindophenol titration method, and the handheld glucose meter. Partitioning of dry matter was modeled in two steps: first, between the root and the shoot, and then among organs within the shoot. Within-shoot organs included leaf, stem, and fruit, which needed measurement of their fresh weight and dry weight (drying 15 min under 105 °C, continuous drying until the weight unchanging under 75 °C).

Model structure. The overall model structure is shown in Fig. 2. The data of Expt. 3 were used for model development, and those of the rest three experiments were used for model validation. The inputs of the model were environmental information (air temperature, PAR at a 1.5-m height aboveground, and substrate temperature inside the plastic greenhouse), available nitrogen during the experimental season (the sum of the available nitrogen in the substrate at the planting stage and the nitrogen applied in the experimental

season), and crop information (planting date and planting density). Using data of Expt. 3, the following six steps were taken to develop the model: 1) the photothermal index (PTI) (defined as the daily average normalized thermal time multiplied by the daily total PAR intercepted by canopy) was calculated according to Xu et al. (2010) using daily total PAR , hourly air temperature at 1.5 m above-ground, and planting density; 2) the nitrogen indicator (N_i , leaf nitrogen content at flowering stage) was calculated according to available nitrogen content during the experimental season and the average temperature of substrate; 3) the leaf gross photosynthetic rate (P_g) was simulated using negative exponential equation and the impacts of N_i on the parameter ($P_{g,max}$, the PAR -saturated leaf gross photosynthetic rate) were determined by curve fitting the experimental data; 4) the LAI was determined as functions of PTI by curve fitting the experimental data and the impacts of N_i on the parameters (LAI_{max} and r_{LAI} , the maximum value of LAI and the increasing rate of LAI) was quantified by curve fitting the experimental data; 5) the seasonal change of partitioning index of dry matter [partitioning index of shoot, leaf, stem, and fruit (PISH, PIL, PIST and PIF, respectively)] and fruit quality traits (SU, PR, VC, and SO) were determined as functions of PTI by curve fitting the experimental data and the impacts of N_i on partitioning index and fruit quality traits were quantified by linking

N_i to the related parameters, 6) the LAI, organ dry weight (DWSH, DWL, DWST, and DWF), FWF and quality (SU, PR, VC, and SO) were estimated by integrated the simulation of leaf photosynthetic rate, LAI, seasonal changes of dry matter partitioning and fruit quality traits into the existing SUCROS (Goudriaan and Van Laar, 1994). Details of this model approach and main equations were outlined below.

Determination of the PTI. Temperature and radiation are the main climate factors affecting the growth dynamics and yield of muskmelon. The accumulated PTI (PTI_{sum}) was used to describe the dynamics of growth and yield. According to Xu et al. (2010), the PTI was calculated as follows (Eqs. [1] and [2]):

$$DPTI(j) = \left(\frac{1}{48} \sum_{i=1}^j TT(i,j) \right) \times PAR_{int}(j) \quad (1)$$

$$PTI_{sum} = \sum DPTI(j) \quad (2)$$

where $DPTI(j)$ ($MJ \cdot m^{-2} \cdot d^{-1}$) is the PTI on day j , $PAR_{int}(j)$ ($MJ \cdot m^{-2} \cdot d^{-1}$) is the daily total PAR intercepted by crop canopy on day j , $TT(i,j)$ is the half-hourly based normalized thermal time on day j , and PTI_{sum} ($MJ \cdot m^{-2}$) is the accumulated PTI. $PAR_{int}(j)$ and $TT(i,j)$ were calculated according to Xu et al. (2010).

Determination of nitrogen indicator. In this study, the available nitrogen during the experimental season (N_s , $kg \cdot ha^{-1}$) was used to explore the impacts of nitrogen on the growth dynamics and yield of muskmelon (Table 1), and calculated as follows (Eqs. [3]–[5]):

$$N_s = N_p + N_a \quad (3)$$

$$N_p = C_p \times H \times B \times 10^{-2} \quad (4)$$

$$N_a = C_f \times M \times L \times \rho \times D \times P \times 10^{-2} \quad (5)$$

where N_s ($kg \cdot ha^{-1}$) is the available nitrogen during the experimental season, N_p ($kg \cdot ha^{-1}$) is the available nitrogen in the substrate at the planting stage, N_a ($kg \cdot ha^{-1}$) is the nitrogen applied in the experimental season, C_p ($mg \cdot kg^{-1}$) is the available nitrogen content in the substrate, H (m) is the depth of root, 0.3, B ($kg \cdot m^{-3}$) is the bulk density, C_f ($mmol \cdot L^{-1}$) is the fertilizer concentration of nutrient solution, M ($g \cdot mol^{-1}$) is the relative molecular mass, L [$L/(plant/d)$] is the daily used nutrient solution per plant, ρ ($plant/m^2$) is the planting density, D (d) is the number of

Fig. 2. Conceptual framework of the model developed in our study.

Table 1. Available nitrogen during the experimental season.

Nitrogen treatment		N7	N10	N13	N16
Available nitrogen in the substrate at the planting stage ($kg \cdot ha^{-1}$)		29.28	29.28	29.28	29.28
Nitrogen applied in the experimental season ($kg \cdot ha^{-1}$)	$Ca(NO_3)_2 \cdot 4H_2O$	87.55	87.55	87.55	87.55
	KNO_3	0	37.55	75.05	75.05
	$NaNO_3$	0	0	0	41.2
Available nitrogen during the experimental season ($kg \cdot ha^{-1}$)		116.83	154.38	191.88	233.08

fertilizations, P is the percentage of nitrogen for the fertilizer, and 10^{-2} is the conversion factor from $\text{mg}\cdot\text{m}^{-2}$ into $\text{kg}\cdot\text{ha}^{-1}$.

Relationship between the leaf nitrogen content at different development stages and available nitrogen during the experimental season (N_s) is shown in Fig. 3. The leaf nitrogen content at flowering stage was the highest and the nitrogen content of this stage played an important role in later growth, yield, and fruit quality. Therefore, this research used the leaf nitrogen content at flowering stage (N_f) to quantify the impacts of nitrogen on growth dynamics and yield of muskmelon.

The relationship between available nitrogen during the experimental season and leaf nitrogen content at flowering stage is shown in Fig. 4A and D and described as Eq. [6] by curve fitting the related data of Expt. 3.

$$N_f = N_{f,\max} \times (1 - \exp(-r_{Nf} \times N_s / N_{f,\max})) \quad (6)$$

where N_f ($\text{mg}\cdot\text{g}^{-1}$) is the leaf nitrogen content at flowering stage, N_s (kg/ha) is the available nitrogen during the experimental season, $N_{f,\max}$ ($\text{mg}\cdot\text{g}^{-1}$) is the maximum value of leaf nitrogen content at flowering stage while available nitrogen during the experimental

season was saturated, and r_{Nf} [$(\text{mg}\cdot\text{g}^{-1})/(\text{kg}\cdot\text{ha}^{-1})$] is the increasing rate of leaf nitrogen content.

The $N_{f,\max}$ and r_{Nf} were affected by substrate temperature. Their relationship is shown in Fig. 4B, C, E, and F and described as Eqs. [7] and [8] by curve fitting the data of experiments.

$$N_{f,\max} = a \times T_s + b \quad (7)$$

$$r_{Nf} = c \times T_s + d \quad (8)$$

where T_s ($^{\circ}\text{C}$) is the average substrate temperature during the experimental season and a , b , c , d are the empirical coefficients (0.2784, 13.3978, 0.0047, 0.2100 for ‘Nanhaimi’ and 0.6805, 3.8028, 0.0098, 0.0567 for ‘Xizhoumi 25’, according to experiments).

Simulation of leaf gross photosynthetic rate. The negative exponential equation (Goudriaan and Van Laar, 1994) was used to calculate leaf gross photosynthetic rate (Eq. [9]):

$$P_g = P_{g,\max} \times (1 - \exp(-\epsilon \times PAR / P_{g,\max})) \quad (9)$$

where P_g ($\mu\text{mol CO}_2/\text{m}^2/\text{s}$) is the leaf gross photosynthetic rate, ϵ ($\mu\text{mol CO}_2/\mu\text{mol PAR}$) is the leaf initial light use efficiency (0.066 according to Yuan et al., 2006b), PAR ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) is photosynthetically active radiation, $P_{g,\max}$ ($\mu\text{mol CO}_2/\text{m}^2/\text{s}$) is the PAR -saturated leaf gross photosynthetic rate

Fig. 3. Relationship between leaf nitrogen content of different development stages and available nitrogen during the experimental season of Expt. 3.

Fig. 4. Relationship between the leaf nitrogen content at flowering stage (N_f) and the available nitrogen during the experimental season (N_s), between the maximum value of leaf nitrogen content at flowering stage ($N_{f,\max}$), the increasing rate of the leaf nitrogen content (r_{Nf}), and the average substrate temperature during the experiment season (T_s).

at the flowering stage and determined as function of the leaf nitrogen content at flowering stage by curve fitting the data of Expt. 3 (Eq. [10], Fig. 5).

$$P_{g,\max} = \begin{cases} P_{g,\max}(0) & (N_l \geq N_c) \\ P_{g,\max}(0) \times (1 + r_1 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (10)$$

where $P_{g,\max}(0)$ ($\mu\text{mol CO}_2/\text{m}^2/\text{s}$) is the PAR -saturated leaf gross photosynthetic rate while the leaf nitrogen content at flowering stage was saturated (i.e., $N_l \geq N_c$), N_l ($\text{mg}\cdot\text{g}^{-1}$) is the leaf nitrogen content at flowering stage,

Fig. 5. Relationship between photosynthetically active radiation (PAR)-saturated leaf gross photosynthetic rate ($P_{g,\max}$) and the leaf nitrogen content at flowering stage (N_l).

N_c ($\text{mg}\cdot\text{g}^{-1}$) is the critical value of leaf nitrogen content at flowering stage ($19.8 \text{ mg}\cdot\text{g}^{-1}$ and $21.0 \text{ mg}\cdot\text{g}^{-1}$ for ‘Nanhai’ and ‘Xizhoumi 25’, according to Expt. 3, and r_1 is the increasing rate of $P_{g,\max}$ along with N_l and the values were shown in Table 2.

Simulation of LAI. According to the relationship between the measured leaf area and leaf length, the LAI is calculated as follows (Eqs. [11] and [12]):

$$LA = k \times LL^2 \quad (11)$$

$$LAI = \sum LA \times \rho \quad (12)$$

where LA (m^2) is the leaf area, LL (m) is the leaf length, k is the empirical coefficient (0.62 and 0.59 for ‘Nanhai’ and ‘Xizhoumi 25’, according to Expt. 3; data not shown), LAI (m^2/m^2) is the LAI, and ρ (plant/m^2) is the planting density.

The relationship between LAI and the accumulated PTI since planting date under different nitrogen supply conditions is shown in Fig. 6A and B and described as Eq. [13] by curve fitting the data of Expt. 3.

$$LAI = LAI_0 + LAI_{\max} \times (1 - \exp(-r_{LAI} \times PTI_{\text{sum}}/LAI_{\max})) \quad (13)$$

where LAI ($\text{m}^2\cdot\text{m}^{-2}$) is the LAI, LAI_0 ($\text{m}^2\cdot\text{m}^{-2}$) is the LAI of planting date (0.09

and 0.08 for ‘Nanhai’ and ‘Xizhoumi 25’ according to Expt. 3), PTI_{sum} ($\text{MJ}\cdot\text{m}^{-2}$) is the accumulated PTI since planting date, $LAI_{\max}$ ($\text{m}^2\cdot\text{m}^{-2}$) is the maximum value of LAI, r_{LAI} [$(\text{m}^2\cdot\text{m}^{-2})/(\text{MJ}\cdot\text{m}^{-2})$] is the increasing rate of LAI.

Parameter $LAI_{\max}$ and r_{LAI} were determined as functions of leaf nitrogen content at flowering stage (Eqs. [14] and [15], Fig. 7A and B).

$$LAI_{\max} = \begin{cases} LAI_{\max}(0) & (N_l \geq N_c) \\ LAI_{\max}(0) \times (1 + r_2 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (14)$$

$$r_{LAI} = \begin{cases} r_{LAI}(0) & (N_l \geq N_c) \\ r_{LAI}(0) \times (1 + r_3 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (15)$$

where $LAI_{\max}(0)$ and $r_{LAI}(0)$ are the value of $LAI_{\max}$ and r_{LAI} while the leaf nitrogen content at flowering stage was saturated (i.e., $N_l \geq N_c$) and r_2 and r_3 are the increasing rate of LAI and r_{LAI} along with N_l and the values are shown in Table 2.

Simulation of dry matter partitioning. The relationship between partitioning index of different organs and the accumulated PTI since planting date under different nitrogen supply conditions is shown in Fig. 6C–J and described as Eqs. [16]–[19] by curve fitting the data of Expt. 3.

Table 2. List of parameter value determined by measured data of Expt. 3.

Parameters	Definition	Units	Nanhai	Xizhoumi 25
$P_{g,\max}(0)$	The maximum leaf gross photosynthetic rate	$\mu\text{mol CO}_2/\text{m}^2/\text{s}$	22.9 ± 1.09	25.1 ± 0.74
$LAI_{\max}(0)$	The maximum LAI	$\text{m}^2\cdot\text{m}^{-2}$	4.2 ± 0.15	3.4 ± 0.27
$r_{LAI}(0)$	Increasing rate of LAI	$(\text{m}^2\cdot\text{m}^{-2})/(\text{MJ}\cdot\text{m}^{-2})$	0.067 ± 0.001	0.059 ± 0.001
$PISH_h(0)$	PISH on the harvest date		0.987 ± 0.010	0.977 ± 0.007
$r_{PISH}(0)$	Increasing rate of PISH		0.004 ± 0.0002	0.004 ± 0.0001
$PIL_h(0)$	PIL on the harvest date		0.148 ± 0.011	0.151 ± 0.015
$r_{PIL}(0)$	Increasing rate of PIL		0.072 ± 0.004	0.068 ± 0.003
$PIF_h(0)$	PIF on the harvest date		0.813 ± 0.008	0.825 ± 0.025
$r_{PIF}(0)$	Increasing rate of PIF		0.061 ± 0.003	0.050 ± 0.006
$PTI_b(0)$	Accumulated PTI from planting date to flowering	$\text{MJ}\cdot\text{m}^{-2}$	77.9 ± 3.75	63.4 ± 6.68
$r_{SU}(0)$	Increasing rate of SU	$(\text{mg}\cdot\text{g}^{-1})/(\text{MJ}\cdot\text{m}^{-2})$	0.0201 ± 0.0002	0.0204 ± 0.0001
$r_{PR}(0)$	Increasing rate of PR	$(\text{mg}/100 \text{ g})/(\text{MJ}\cdot\text{m}^{-2})$	0.0233 ± 0.0006	0.0233 ± 0.0013
$r_{VC}(0)$	Increasing rate of VC	$(\text{mg}/100 \text{ g})/(\text{MJ}\cdot\text{m}^{-2})$	0.0206 ± 0.0010	0.0195 ± 0.0006
$r_{SO}(0)$	Increasing rate of SO	$\%/(\text{MJ}\cdot\text{m}^{-2})$	0.0242 ± 0.0005	0.0251 ± 0.0006
r_1	Increasing rate of $P_{g,\max}$ along with the leaf nitrogen content	$(\mu\text{mol CO}_2/\text{m}^2/\text{s})/(\text{mg}/\text{g})$	0.120 ± 0.010	0.087 ± 0.005
r_2	Increasing rate of $LAI_{\max}$ along with the leaf nitrogen content	$(\text{m}^2\cdot\text{m}^{-2})/(\text{mg}\cdot\text{g}^{-1})$	0.130 ± 0.012	0.062 ± 0.003
r_3	Increasing rate of r_{LAI} along with the leaf nitrogen content	$[(\text{m}^2\cdot\text{m}^{-2})/(\text{MJ}\cdot\text{m}^{-2})]/(\text{mg}\cdot\text{g}^{-1})$	0.052 ± 0.002	0.011 ± 0.003
r_4	Increasing rate of $PISH_h$ along with the leaf nitrogen content		0.016 ± 0.001	0.010 ± 0.001
r_5	Increasing rate of r_{PISH} along with the leaf nitrogen content		0.084 ± 0.001	0.025 ± 0.004
r_6	Increasing rate of PIL_h along with the leaf nitrogen content		0.225 ± 0.021	0.131 ± 0.012
r_7	Increasing rate of r_{PIL} along with the leaf nitrogen content		-0.034 ± 0.003	-0.049 ± 0.009
r_8	Increasing rate of PIF_h along with the leaf nitrogen content		0.066 ± 0.011	0.045 ± 0.005
r_9	Increasing rate of r_{PIF} along with the leaf nitrogen content		0.252 ± 0.020	0.116 ± 0.004
r_{10}	Increasing rate of PTI_b along with the leaf nitrogen content	$(\text{MJ}\cdot\text{m}^{-2})/(\text{mg}\cdot\text{g}^{-1})$	0.078 ± 0.003	0.084 ± 0.010
r_{11}	Increasing rate of r_{SU} along with the leaf nitrogen content	$[(\text{mg}\cdot\text{g}^{-1})/(\text{MJ}\cdot\text{m}^{-2})]/(\text{mg}\cdot\text{g}^{-1})$	-0.047 ± 0.006	-0.028 ± 0.006
r_{12}	Increasing rate of r_{PR} along with the leaf nitrogen content	$[(\text{mg}/100 \text{ g})/(\text{MJ}\cdot\text{m}^{-2})]/(\text{mg}\cdot\text{g}^{-1})$	0.133 ± 0.001	0.068 ± 0.002
r_{13}	Increasing rate of r_{VC} along with the leaf nitrogen content	$[(\text{mg}/100 \text{ g})/(\text{MJ}\cdot\text{m}^{-2})]/(\text{mg}\cdot\text{g}^{-1})$	-0.082 ± 0.005	-0.030 ± 0.007
r_{14}	Increasing rate of r_{SO} along with the leaf nitrogen content	$[\%/(\text{MJ}\cdot\text{m}^{-2})]/(\text{mg}\cdot\text{g}^{-1})$	-0.047 ± 0.003	-0.034 ± 0.005

LAI = leaf area index; SU = soluble sugar content; PR = soluble protein content; VC = vitamin C content; SO = soluble solids content; PISH = partitioning index of shoot; PIL = partitioning index of leaf; PIF = partitioning index of fruit.

Fig. 6. Relationship between leaf area index (LAI), partitioning index of shoot (PISH), partitioning index of leaf (PIL), partitioning index of stem (PIST), partitioning index of fruit (PIF), and the accumulated photo-thermal index since planting date (PTI_{sum}) under different nitrogen supply conditions.

$$PISH = PISH_p + (PISH_h - PISH_p) \times (1 - \exp(-r_{PISH} \times PTI_{sum} / (PISH_h - PISH_p))) \quad (16)$$

$$PIL = PIL_p + (PIL_h - PIL_p) / (1 + \exp(r_{PIL} \times (PTI_{sum} - PTI_b))) \quad (17)$$

$$PIF = PIF_h \times (1 - \exp(-r_{PIF} \times (PTI_{sum} - PTI_b))) \quad (18)$$

$$PIST = 1 - PIL - PIF \quad (19)$$

where PISH_p and PIL_p are the partitioning index of shoot and leaf on the planting date

(0.83 and 0.70 for 'Nanhaimi' and 'Xizhoumi 25', according to Expt. 3); PISH_h, PIL_h, and PIF_h are the partitioning index of shoot, leaf, and fruit on the harvest date; r_{PISH} , r_{PIL} , and r_{PIF} are the increasing rate of partitioning index of shoot, leaf, and fruit; PTI_{sum} (MJ/m²) is the accumulated PTI since planting date; and PTI_b (MJ/m²) is the accumulated PTI from planting date to flowering.

The impacts of leaf nitrogen content at flowering stage on parameters (PISH_h, r_{PISH} , PIL_h, r_{PIL} , PIF_h, r_{PIF} , and PTI_b) are shown in Fig. 7C–I and described as Eqs. [20]–[26] by curve fitting the data of Expt. 3.

$$PISH_h = \begin{cases} PISH_h(0) & (N_l \geq N_c) \\ PISH_h(0) \times (1 + r_4 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (20)$$

$$r_{PISH} = \begin{cases} r_{PISH}(0) & (N_l \geq N_c) \\ r_{PISH}(0) \times (1 + r_5 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (21)$$

$$PIL_h = \begin{cases} PIL_h(0) & (N_l \geq N_c) \\ PIL_h(0) \times (1 + r_6 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (22)$$

$$r_{PIL} = \begin{cases} r_{PIL}(0) & (N_l \geq N_c) \\ r_{PIL}(0) \times (1 + r_7 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (23)$$

$$PIF_h = \begin{cases} PIF_h(0) & (N_l \geq N_c) \\ PIF_h(0) \times (1 + r_8 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (24)$$

$$r_{PIF} = \begin{cases} r_{PIF}(0) & (N_l \geq N_c) \\ r_{PIF}(0) \times (1 + r_9 \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (25)$$

$$PTI_b = \begin{cases} PTI_b(0) & (N_l \geq N_c) \\ PTI_b(0) \times (1 + r_{10} \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (26)$$

where PISH_h(0), r_{PISH} (0), PIL_h(0), r_{PIL} (0), PIF_h(0), r_{PIF} (0), and PTI_b(0) are the values of PISH_h, r_{PISH} , PIL_h, r_{PIL} , PIF_h, r_{PIF} , and PTI_b while the leaf nitrogen content at flowering stage was saturated (i.e., $N_l \geq N_c$) and r_4 – r_{10} are the increasing rate of these parameters along with the leaf nitrogen content at flowering stage and the values are shown in Table 2.

Simulation of fruit quality traits. The relationship between fruit quality traits and the accumulated PTI since planting date under different nitrogen supply conditions is shown in Fig. 8 and described as Eqs. [27]–[30] by curve fitting the data of Expt. 3.

$$SU = SU_0 \times \exp(r_{SU} \times (PTI_{sum} - PTI_b)) \quad (27)$$

$$PR = PR_0 \times \exp(r_{PR} \times (PTI_{sum} - PTI_b)) \quad (28)$$

$$VC = VC_0 \times \exp(r_{VC} \times (PTI_{sum} - PTI_b)) \quad (29)$$

$$SO = SO_0 \times \exp(r_{SO} \times (PTI_{sum} - PTI_b)) \quad (30)$$

where SU₀, PR₀, VC₀, and SO₀ were the initial content of SU, PR, VC, and SO (10 mg·g⁻¹, 8 mg/100 g, 1 mg/100 g, and 1%, the same value for 'Nanhaimi' and 'Xizhoumi 25', according to Expt. 3).

Fig. 7. Relationship between the maximum value of leaf area index (LAI_{max}), the increasing rate of LAI (r_{LAI}), the partitioning index of shoot on the harvest date ($PISH_h$), the increasing rate of partitioning index of shoot (r_{PISH}), the partitioning index of leaf on the harvest date (PIL_h), the increasing rate of partitioning index of leaf (r_{PIL}), the partitioning index of fruit on the harvest date (PIF_h), the increasing rate of partitioning index of fruit (r_{PIF}), accumulated PTI from planting date to flowering (PTI_b), and the leaf nitrogen content at flowering stage (N_l).

PTI_{sum} ($MJ \cdot m^{-2}$) was the accumulated PTI since planting date, and PTI_b ($MJ \cdot m^{-2}$) was the accumulated PTI from planting date to flowering.

The impacts of leaf nitrogen content at flowering stage on parameters (r_{SU} , r_{PR} , r_{VC} , and r_{SO}) are shown in Fig. 9 and described as Eqs. [31]–[34] by curve fitting the data of Expt. 3.

$$r_{SU} = \begin{cases} r_{SU}(0) & (N_l \geq N_c) \\ r_{SU}(0) \times (1 + r_{11} \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (31)$$

$$r_{PR} = \begin{cases} r_{PR}(0) & (N_l \geq N_c) \\ r_{PR}(0) \times (1 + r_{12} \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (32)$$

$$r_{VC} = \begin{cases} r_{VC}(0) & (N_l \geq N_c) \\ r_{VC}(0) \times (1 + r_{13} \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (33)$$

$$r_{SO} = \begin{cases} r_{SO}(0) & (N_l \geq N_c) \\ r_{SO}(0) \times (1 + r_{14} \times (N_l - N_c)) & (N_l < N_c) \end{cases} \quad (34)$$

where $r_{SU}(0)$, $r_{PR}(0)$, $r_{VC}(0)$, and $r_{SO}(0)$ are the values of r_{SU} , r_{PR} , r_{VC} , and r_{SO} while the leaf nitrogen content at flowering stage was saturated (i.e., $N_l \geq N_c$) and r_{11} – r_{14} are the increasing rate of these parameters along with the leaf nitrogen content at

flowering stage and the values are shown in Table 2.

Predicting dry weight of organ and fruit quality. According to Eqs. [1]–[34], a model of plastic greenhouse muskmelon was developed by integrated the simulation of LAI, seasonal changes of dry matter partitioning and fruit quality traits into the existing SUCROS, which could be used to predict the impacts of nitrogen on dry matter production and fruit quality. DWSH, DWL, DWST, and DWF were estimated (Eqs. [35]–[38]).

$$DWSH = BIOMASS \times PISH \quad (35)$$

$$DWL = DWS \times PIL \quad (36)$$

$$DWST = DWS \times PIST \quad (37)$$

$$DWF = DWS - DWL - DWST \quad (38)$$

Predicting the fruit yield. The yield of fruiting vegetables was mainly dependent on fresh weight of individual fruit at harvest. The relationship between dry weight and FWF is shown in Fig. 10 and described as Eq. [39] by curve fitting the data of Expt. 3.

$$FWF = DWF \times g \quad (39)$$

where DWF ($g/plant$) is the dry weight of fruit, and g is the empirical coefficient (11.45

and 12.10 for ‘Nanhaimi’ and ‘Xizhoumi 25’, according to Expt. 3.

Methods for model validation. The coefficient of determination of linear regression (r^2) and the relative root-mean-squared error (rRMSE) between the predicted and measured values were used for model validation. The rRMSE was calculated as the RMSE divided by the means of measured values and was described as follows (Eqs. [40] and [41]):

$$r^2 = \frac{(\sum (x - \bar{x})(y - \bar{y}))^2}{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2} \quad (40)$$

$$rRMSE = \frac{1}{\bar{x}} \sqrt{\frac{\sum_{i=1}^n (x - y)^2}{n}} \quad (41)$$

where x is the measured value, y is the predicted value, $\bar{x}$ is the average of measured value, $\bar{y}$ is the average of predicted value, and n is the numbers of sample.

Results

As shown in Figs. 5 and 7, the relationship between leaf nitrogen content at flowering stage (N_l) and maximum LAI (LAI_{max}), increasing rate of LAI at flowering stage (r_{LAI}), the partitioning index of shoot on the harvest

Fig. 8. Relationship between soluble sugar content (SU), soluble protein content (PR), vitamin C content (VC) and soluble solids content (SO) and the accumulated photothermal index since planting date (PTI_{sum}) under different nitrogen supply conditions.

date ($PISH_h$), the increasing rate of partitioning index of shoot (r_{PISH}), the partitioning index of leaf on the harvest date (PIL_h), the increasing rate of partitioning index of leaf (r_{PIL}), the partitioning index of fruit on the harvest date (PIF_h), and the increasing rate of partitioning index of fruit (r_{PIF}) were increasing linearly along with the leaf nitrogen content at flowering stage. But, these parameters as well as the quality and FWF (Figs. 9 and 10) would not increase when the leaf nitrogen content at the flowering stage increased to 19.8 and 21.0 $mg \cdot g^{-1}$ for 'Nanhaimi' and 'Xizhoumi 25'. Therefore, 19.8 and 21.0 $mg \cdot g^{-1}$ were determined as the critical leaf nitrogen content and could be

used as indicator of nitrogen optimal management for muskmelon production. Corresponding to the critical value of leaf nitrogen content at flowering stage, the available nitrogen in the substrate of Expt. 1–4 for the two cultivars were, respectively, 169, 178, 196, and 145 $kg \cdot ha^{-1}$ for 'Nanhaimi' and 173, 193, 247, and 132 $kg \cdot ha^{-1}$ for 'Xizhoumi 25'.

Independent experimental data (Expts. 1, 2, and 4) were used to validate the model according to the Eq. [1]–[39], and the results are shown in Fig. 11. The r^2 between the predicted and measured value of LAI, DWSH, DWL, DWST, DWF, SU, PR, VC, SO, and FWF are, respectively, 0.91, 0.90,

0.76, 0.82, 0.92, 0.91, 0.89, 0.86, 0.88, and 0.90. The rRMSE between the predicted and measured value are, respectively, 10.8%, 19.6%, 30.3%, 21.1%, 11.9%, 17.2%, 13.9%, 27.8%, 20.6%, and 10.1%. Therefore, our research gave satisfactory predictions of growth dynamics and yield of muskmelon under different levels of nitrogen treatment.

Discussion

Temperature and *PAR* are the main climate factors affecting the growth dynamics and yield of crop (Justus and Kubota, 2010; Ngouajio and Ernest, 2005). It has demonstrated that only using temperature as an input parameter [growing degree days (GDD)-based model] that could not accurately describe crop growth process because temperature did not synchronize with *PAR* (Xu et al., 2010). Although climate of plastic greenhouse were different for the four experiments, the PTI used in our study that integrated effects of *PAR* and temperature were used to quantitatively investigate the impacts of nitrogen on growth dynamics and yield and the results showed that it gave satisfactory predictions. This further verified the reliability of the PTI (Dai et al., 2011; Xu et al., 2010). Impacts of nitrogen on LAI can be estimated by using DWL and specific leaf area (SLA), which need destructive measurements and is strongly influenced by environmental factors and crop developmental stage (Goudriaan and Van Laar, 1994). Small error in predicting SLA values can result in unacceptable error for simulating LAI and crop biomass (Xu et al., 2010; Yin et al., 2000). Impacts of nitrogen on leaf photosynthetic rate are usually quantified using a mechanistic biochemical model (FvCB model; Farquhar, von Caemmerer and Berry, 1980). It can be used to estimate photosynthetic parameters in relation to the nitrogen conditions of plants and therefore, are useful for understanding how nitrogen affects crop growth (Yin et al., 2009). However, the huge set of data and parameters as inputs limits the practical use. In our study, although empirical, variables and parameters have clear biological meanings and are easily obtained for the simulation of LAI and leaf photosynthesis. Like the similar empirical approaches used for dry matter partitioning predictions (Connor and Fereres, 1999; Wubs et al., 2012), the empirical seasonal change of dry matter partitioning index was used to describe the dynamics of dry matter partitioning among organs.

The climate control is limited in a low-investment plastic greenhouse. To obtain the same yield and quality in different planting dates, we can keep the same leaf nitrogen content at flowering stage by changing the available nitrogen during the experimental season. The value was similar to the former studies that showed that the available nitrogen in the substrate was within 116–232 $kg \cdot ha^{-1}$ (Shafeek et al., 2015; Xu et al., 2005). It needed different supply of nitrogen

Fig. 9. Relationship between the increasing rate of soluble sugar (r_{SU}), the increasing rate of soluble protein (r_{PR}), the increasing rate of vitamin C (r_{VC}), the increasing rate of soluble solids (r_{SO}), and the leaf nitrogen content at flowering stage (N_f).

Fig. 10. Relationship between fresh weight and dry weight of muskmelon fruit.

in the substrate at different planting dates. This can be attributed to the fact that the climates of the plastic greenhouse were different for the four experiments that caused

the difference of substrate temperature, and then affected the nitrogen absorption, metabolism, and transport in plant (Chmelíková and Hejčman, 2014; Kim et al., 2002; Liang

et al., 2015; Roohi and Mohammadi, 2002). Therefore, estimating the supply of nitrogen in the substrate based on leaf nitrogen content was feasible for different planting dates and

Fig. 11. Comparison between the predicted and measured leaf area index (LAI), dry weight of shoot (DWSH), dry weight of leaf (DWL), dry weight of stem (DWST), dry weight of fruit (DWF), fresh weight of fruit (FWF), soluble sugar content (SU), soluble protein content (PR), vitamin C (VC), and soluble solids content (SO).

substrate types, and helpful to ensure the yield and quality of muskmelon and improve the use efficiency of nitrogen fertilizer. Further study should focus on the ratio between

different nitrogen forms in the substrate due to its effect on muskmelon growth and yield (Hassanshahian et al., 2014; Liu et al., 2014; Park and Seo, 2012).

Conclusion

In this study, a model that the accumulated PTI as a growth indicator and leaf nitrogen content at flowering stage as nitrogen indicator was developed to quantify the impacts of nitrogen on growth dynamics (leaf photosynthetic rate, LAI, dry matter partitioning and fruit quality) and yield under different levels of nitrogen treatment. Using the planting date, available nitrogen during the experimental season, the light intensity, the air temperature, and the substrate temperature as inputs, the model can give good predictions of LAI, DWSH, dry weight of organs (DWL, DWST, and DWF), FWF and quality (SU, PR, VC, and SO) of muskmelon. It can provide optimization and standardization of nitrogen management for muskmelon. Further model calibration and test would be needed when the model is applied to wider range of conditions and muskmelon cultivars.

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