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MODELLING OF TOMATO STEM DIAMETER GROWTH RATE BASED ON PHYSIOLOGICAL RESPONSES

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Abstract

The stem diameter is an important parameter describing the growth of tomato plant during vegetative growth stage. A stem diameter growth model was developed to predict the response of plant growth under different conditions. By analyzing the diurnal variations of stem diameter in tomato (*Solanum lycopersicum* L.), it was found that the stem diameter measured at 3:00 am was the representative value as the daily basis of tomato stem diameter. Based on the responses of growth rate in stem diameter to light and temperature, a linear regression relationship was applied to establish the stem diameter growth rate prediction model for the vegetative growth stage in tomato and which was further validated by experiment. The root mean square error (RMSE) and relative error (RE) were used to test the correlation between measured and modeled stem diameter variations. Results showed that the model can be used in prediction for stem diameter growth rate at vegetative growth stage in tomato.

Key words: Tomato (*Solanum lycopersicum* L.), Stem diameter, Growth rate, Prediction model.

Introduction

During active vegetative growth and development, crop plants rely on the carbohydrate gained from photosynthesis and the translocation of photo-assimilates from the site of synthesis to sink organs (Yu *et al.*, 2015). The stem plays key role in the transportation of water and the translocation of carbohydrates (Kanai *et al.*, 2008). The fundamentals of stem diameter variations (SDV) has been well documented in a substantial amount of literature (Moon *et al.*, 2009; Fernández & Cuevas, 2010; Matimati *et al.*, 2012; Vandegehuchte *et al.*, 2014). When transpiration starts early in the morning, a tension between leaf surface and other organs is created. The water stored in the plant tissues during the night is partly lost, allowing the plant to respond rapidly to the changes in atmospheric demand, without water uptake of root (Fernández & Cuevas, 2010). This affects all water-storing organs, including the stem and root, so the change of diurnal diameter occurs in stem. It has been documented that SDV is sensitive to water and nutrient conditions and is closely related to the responses of crop plants to the changes of environmental conditions (Klepper & Taylor, 1972; So, 1979; Gallardo *et al.*, 2006; Kanai *et al.*, 2008). The stem diameter is an important parameter describing the growth of crop plants under abiotic stress during vegetative growth stage. Therefore, it is important to improve the stem diameter growth model to predict the response of SDV to the environmental changes and plant growth under different conditions.

Many reports emphasize the need to review critically and improve SDV models for assessments of environmental impacts on crop growth (Xiong *et al.*, 2007; Downes *et al.*, 2009; Moon *et al.*, 2009; Fernández & Cuevas, 2010; Hinckley & Bruckerhoff, 2011). The strong correlation between maximum daily shrinkage of stem and maximum daily radiation was reported in tomato under fully irrigation (Wang *et al.*, 2012). In addition, a daily model of SDV has been developed to accurately predict inter-annual variation in annual growth in balsam fir (*Abies balsamea* L.) (Duchesne & Houle, 2011). It suggests that the inclusion of daily data in growth-climate models may improve predictions of the potential growth response to climate by identifying particular climatic events that may escape to a classical dendroclimatic approach (Duchesne & Houle, 2011). However, models for simulating SDV and plant growth in response to radiation and temperature fluctuations have so far remained limited.

Tomato (*Solanum lycopersicum* L.) is an important vegetable crop widely grown all over the world. Tomato is the number nine crop on the lists of food commodities and widely used as a model crop for plant growth. Numerous studies have demonstrated that the growth is significantly depressed by high temperatures and low light intensity, due to lower photosynthetic carbon assimilation and carbon translocation process (Li *et al.*, 2012; Gerganova *et al.*, 2016). The present study presents the extension of the SDV model based on data obtained from climate controlled experiment with tomato subjected to different radiation and temperature regimes. The objective was to develop new models which are capable of simulating SDV depending on physiological developmental effect. The simulated results were compared with the observed values from the experiments with varied radiation and temperature levels.

Materials and Methods

Experimental design: The experiment was conducted from April 2015 to January 2016 in the climate-controlled glasshouse at School of Agricultural Equipment and Engineering, Jiangsu University, Zhenjiang, China. Single seeds of tomato (*Solanum lycopersicum* L., cv. Hezuo903) were sown in pots (18 cm in height and 20cm in diameter) filled with 0.56 kg of perlite. The Yamazaki nutrient solution was used for culture. A radiation response experiment and a temperature response experiment were included.

Radiation response experiment: In the radiation response experiment, the 30-day-old seedling with three to four fully expanded mature leaves were transferred to a climate chamber (Qiushi, Hangzhou, China) with a set temperature of 25/18ºC for day/night, a 12-h photoperiod, 60% RH, 400 ppm CO_2 concentration and 300 μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) measured at the level of the first fully expanded leaves of the seedlings with an LI-250A quantum sensor (LI-COR, Lincoln, NE, USA). The tomato plants were covered with different layers of white polyethylene nets during the experimental period to provide two shading treatments, i.e. shading with one and two layers of net, which blocked about 10% (S1) and 19% (S2) of the radiation. No shading treatment was set as control (S0). The experiment was a randomized block design, with four replicates for each treatment.

Temperature response experiment: After acclimating for 3 days in the climate chamber, the 30-day-old seedling were transferred to three similar chamber to be grown at 23ºC, 26ºC and 29ºC, respectively. The experiment was a randomized block design, with four replicates for each treatment.

Climate data: The diurnal temperature and light intensity in the tomato canopy were recorded 30 minutes on the top of tomato plants using thermos and light sensors attached to a data-logging and environmental control system (Qishuo Agricultural Environment Investigation System, Beijing, China). The hourly averaged temperature (T_i, i =1, 2, ..., 24) and light intensity *(*LQ_i, i=1, 2, ..., 24) was calculated by the following equation:

$$T_i = \frac{T'_{2i-2} + 2T'_{2i-1} + T'_{2i}}{4}, \qquad (1)$$

$$LQ_i = \frac{LQ'_{2i-2} + 2LQ'_{2i-1} + LQ'_{2i}}{4} \qquad (2)$$

where T'_j is the recorded temperature every 0.5 hour and LQ'_j is the recorded light intensity every 0.5 hour.

Measurement of stem diameter: The stem diameter was recorded hourly on the position 10 cm above the ground using stem diameter sensor (DD-S, Ecomatik, Germany) attached to a data-logger (DL15, Ecomatik, Germany) (Fig. 1).

The diurnal variation rate of stem diameter (mm d^{-1}) was calculated by the difference between the current stem diameter and the stem diameter recorded one day early for a given time point. The hourly variation rate of stem diameter (mm d^{-1}) was calculated by the difference between the current stem diameter and the stem diameter recorded one hour early for a given time point. The SDV rate (mm d^{-1}) was calculated by the difference between the current averaged stem diameter and the averaged stem diameter one day early.

Fig. 1. The sensor used in diurnal measurement of the stem diameter in tomato.

Modelling:

Relative thermal effectiveness: The relative thermal effectiveness (RTE) is the ratio of growth rate under actual temperature to the growth rate under the optimum temperature in crop plants during a given period (Wang *et al.*, 2008). The growth rate of tomato plant is positively correlated to the RTE value (Wang *et al.*, 2008; Wang *et al.*, 2014). The RET (T_i) was calculated by the following equation (Hou *et al.*, 2006; Wang *et al.*, 2014):

$$RTE(T_i) = \begin{cases} 0, & (T_i \le T_b); \\ \sin\left(\frac{T_i - T_b}{T_{ob} - T_b} \times \frac{\pi}{2}\right), & (T_b < T_i \le T_{ob}); \\ 1, & (T_{ob} < T_i \le T_{ou}); \\ \sin\left(\frac{T_m - T_i}{T_m - T_{ou}} \times \frac{\pi}{2}\right)^{\frac{T_m - T_{ou}}{T_{ou} - T_b}}, & (T_{ou} < T_i < T_m); \\ 0, & (T_i \ge T_m). \end{cases} \qquad (3)$$

where RTE (T_i) (0 ≤ RTE ≤ 1) is the relative thermal effectiveness at the given temperature (T_i, ºC). T_b and T_m are the minimum and maximum growth temperature (ºC), while T_{ob} and T_{ou} are the lowest and highest value of optimum growth temperature range (ºC). When $T_i \le T_b$ or $T_i \ge T_m$, RTE is 0, while when $T_{ob} \le T_i \le T_{ou}$, RTE is 1. Here, the tomato plants under the vegetative growth stage were used; therefore the T_b, T_m, T_{ob} and T_{ou} were 15, 25, 30 and 35ºC, respectively.

Relative light effectiveness: The relative light effectiveness (RLE) is the ratio of growth rate under actual light intensity to the growth rate under the optimum light intensity in crop plants during a given period. The RET (T_i) was calculated by the following equation (Gao *et al.*, 2006):

$$RLE(LQ_i)=\begin{cases}0, & (LQ_a < LQ_i, LQ_i > LQ_c);\\ \dfrac{LQ_i - LQ_a}{LQ_b - LQ_a} & (LQ_a \le LQ_i < LQ_b);\\ 1, & (LQ_b \le LQ_i \le LQ_c).\end{cases} \qquad (4)$$

where RTE (LQ_i) is the relative light effectiveness at the given light intensity (LQ_i, °C). LQ_a, LQ_b and LQ_c is light compensation point (µmol m^{-2} s^{-1}), optimum light intensity (µmol m^{-2} s^{-1}) and light saturation point (µmol m^{-2} s^{-1}), respectively. In this study, for the tomato plants under the vegetative growth stage, LQ_a, LQ_b and LQ_c is 300, 800 and 1400 µmol m^{-2} s^{-1}.

Calculation of physiological responsiveness (PR) The PR (°C µmol m^{-2} s^{-1}) is the growth of tomato plant under optimum temperature and light intensity during 1 day (d). During the vegetative growth stage in tomato, the effects of temperature and light intensity on PR is calculated by the following equation (Gao *et al.*, 2006; Lu *et al.*, 2011):

$$PR=\sum_{i=1}^{24}(RTE(T_i)\times RLE_i(LQ_i)) \qquad (5)$$

Results and Discussion

Variation of stem diameter in tomato: At the vegetative growth stage, the stem diameter was increasing during the experimental period (Fig. 2). A similar trend was found in each day: the diurnal increase rate of stem diameter was stable from 0:00 to 6:00, especially in day 2 (Fig. 3). During the period of 6:00-12:00, the variation in the increase rate of stem diameter was enhanced, due to the carbon assimilation and accumulation in tomato stem (Saveyn *et al.*, 2008). The transpiration induced reduction of stem diameter was the main reason of variation in the increase rate of stem diameter (Kanai *et al.*, 2008). From 12:00 to 14:00, the stem diameter was reduced; due to the transpiration induced reduction was higher than the increase resulted by carbon accumulation. The lowest value of hourly variation rate of stem diameter was observed in the period of 13:00-14:00, afterwards the stem diameter started to increase. In addition, the highest increase rate of stem diameter was found at 16:00 (Fig. 4).

In Figs. 2, 3 and 4, it was found that the variation of stem diameter was lowest during 0:00-6:00. This was due to the translocation of photosynthetic carbon assimilates was finished, and the physiological development was stable during this period. Therefore, the stem diameter measured at 3:00 am was the representative value as the daily basis of tomato stem diameter.

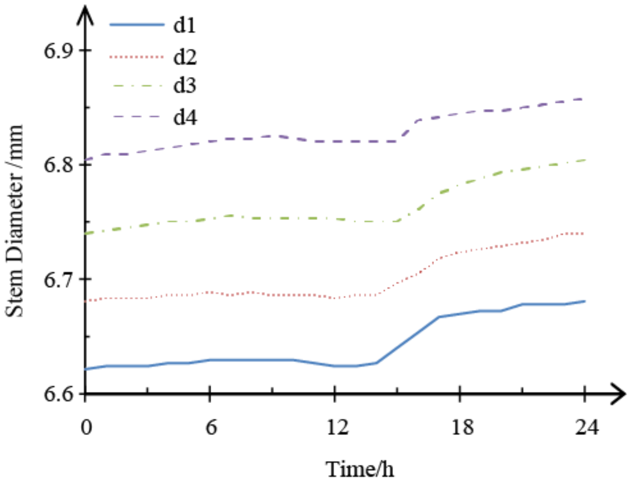

Fig. 2. Diurnal variation of stem diameter in tomato grown under normal conditions for four individual day. The d1, d2, d3 and d4 is the first, second, third and fourth day of the period from 31st of December 2015 to 3rd of January 2016. d, day.

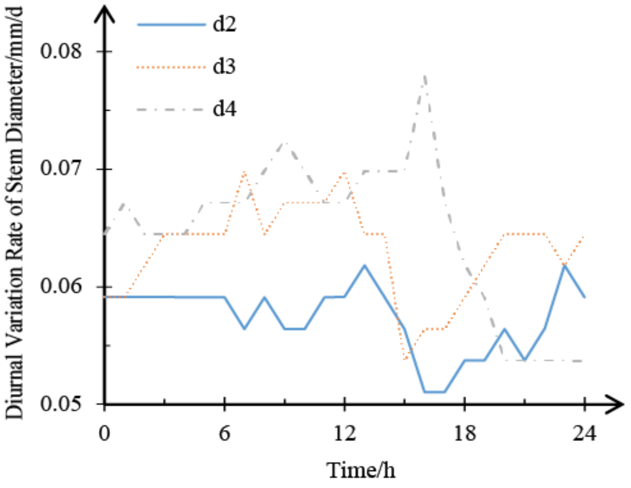

Fig. 3. Diurnal variation rate of stem diameter in tomato grown under normal conditions for four individual day. The d1, d2, d3 and d4 is the first, second, third and fourth day of the period from 31st of December 2015 to 3rd of January 2016. d, day.

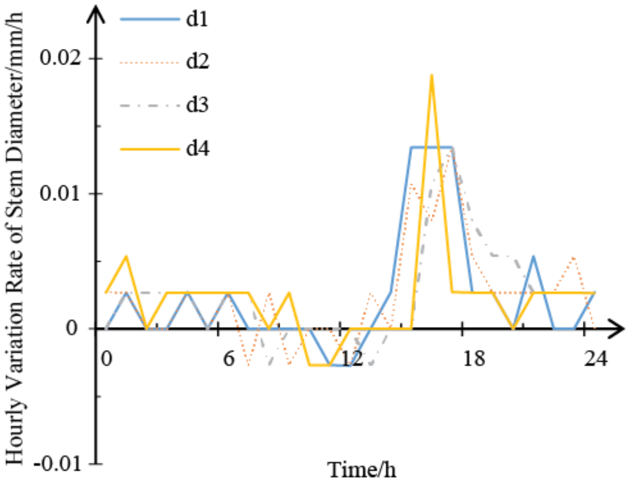

Fig. 4. Hourly variation rate of stem diameter in tomato grown under normal conditions for four individual day. The d1, d2, d3 and d4 is the first, second, third and fourth day of the period from 31st of December 2015 to 3rd of January 2016. d, day.

SDV response to radiation: Fig. 5 shows the SDV rate of tomato plants under different light intensities. The light intensity was the solo factor of environmental condition and the irrigation was all the same among these treatments. The trend of SDV rate was similar during the 10 days' experimental period. This indicates that the variation of stem diameter is closely related to the growth environment (King *et al.*, 2013). The plants under the non-shading control had the highest SDV rate, followed by 10% shading treatment, while the lowest SDV rate was found in 19% shading treatment. It was documented that under a given growth temperature, a positive correlation was found between increase rate of stem diameter and light intensity. This was mainly resulted by the enhanced photosynthetic rate under higher light intensity, and increased photosynthetic assimilates contribute to the stem growth (Downes *et al.*, 2009).

SDV response to temperature: The SDV during 10 days' experimental period in tomato plants under different temperature treatments were shown in Fig. 6. A similar trend in SDV was found among these three temperature treatments. The highest SDV rate was found in the plants grown under 29ºC, followed by the ones under 26ºC, while the lowest SDV rate was in the tomato plants under 23ºC. This indicated that the SDV rate was closely related to the environmental factors. A positive correlation between SDV rate and growth temperature was found in this temperature range. In agreement with the previous study, higher growth temperature enhances the stem diameter growth in tomato (Uzun, 2006; Duchesne & Houle, 2011).

Establishment of SDV model: Some SDV models have been developed depending on the response of trees to environmental factors, including temperature and radiation, for precise irrigation (summarized by Fernández & Cuevas, 2010). The SDV rate was positively correlated to both light intensity and growth temperature, which is related to the physiological responsiveness (PR) of tomato plants. A significant positive linear relationship was found between SDV rate and PR value (Fig. 7). In addition, the SDV model based on PR was established by linear regression equation:

$$y = 0.1051x - 0.0139 \tag{7}$$

where y is simulated SDV rate (mm d^{-1}) and x is PR value (ºC μmol m^{-2} s^{-1}).

Validation test: The root mean square error (RMSE) and relative error (RE) were used to test the correlation between measured and modeled SDV (Yan *et al.*, 2000). The RMSE and RE were calculated according to Yan *et al.* (2014).

$$RMSE = \sqrt{\sum_{i=1}^{n}(O_i - S_i)^2 / n} \tag{8}$$

$$RE = (RMSE / \bar{O}_i) \times 100\% \tag{9}$$

where O_i is measured SDV (mm d^{-1}), S_i is the modeled SDV (mm d^{-1}), *n* is number of replicate, here it is 8, and O_i is the average of measured SDV (mm d^{-1}).

The root mean square error (RMSE) and the relative error (RE) between the predicted and the measured values were 0.0014 (mm d^{-1}) and 5.55%, and the maximal relative error, average relative error, maximal absolute error, average absolute error shoes were 10.10%, 5.39%, 0.0019 (mm d^{-1}) , and 0.0011 (mm d^{-1}) , respectively. It showed that the model had a good prediction for tomato stem diameter growth rate at vegetative growth stage (Table 1).

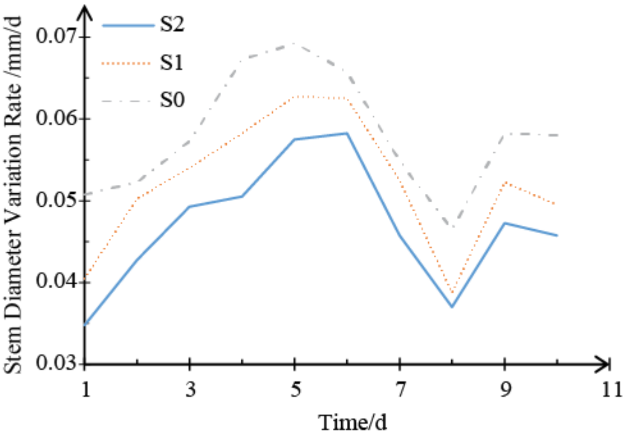

Fig. 5. Growth rate of stem diameter in tomato under different light intensity. S0, S1 and S2 is the non-shading control, 10% and 19% shading treatments, respectively.

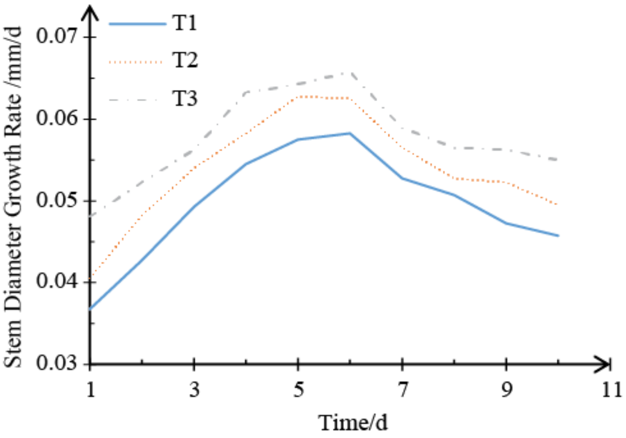

Fig. 6. Growth rate of stem diameter in tomato under different temperature. T1, T2 and T3 is the treatment with 23ºC, 26ºC and 29ºC, respectively.

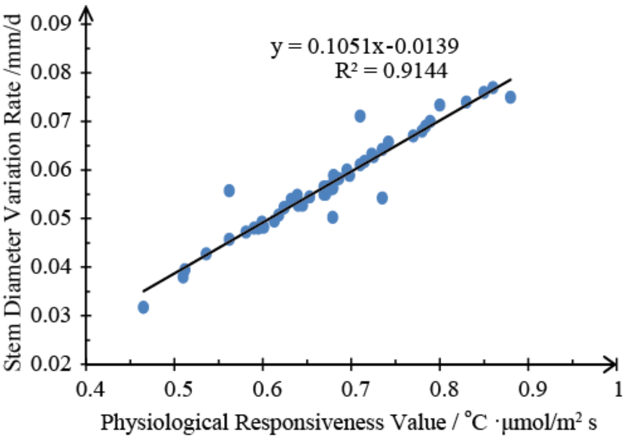

Fig. 7. Correlation between physiological responsiveness and the stem diameter variation rate in tomato. PR, physiological responsiveness.

Table 1. The observed and simulated PR of eight tomato plants for model validation.

PR °C· μmol/m^2·s	Simulated value mm/d	Observed value mm/d	Absolute error mm/d	Relative error %
0.5534	0.0443	0.0457	-0.0014	-3.15
0.468	0.0353	0.0349	0.0004	1.11
0.392	0.0273	0.0296	-0.0023	-7.77
0.2524	0.0126	0.0115	0.0011	9.80
0.4119	0.0294	0.0296	-0.0002	-0.71
0.3292	0.0207	0.0188	0.0019	10.10
0.2943	0.0170	0.0178	-0.0008	-4.32
0.2676	0.0142	0.0134	0.0008	6.15

Conclusion

In this study, the stem diameter growth model was developed to predict the response of plant growth under different conditions. The root mean square error and relative error were used to test the correlation between measured and modeled stem diameter variations. It was documented that the model can be used in prediction for stem diameter growth rate at vegetative growth stage in tomato. The root mean square error and the relative error between the predicted and the measured values were 0.0014 (mm d^{-1}) and 5.55%, and the maximal relative error, average relative error, maximal absolute error and average absolute error were 10.10%, 5.39%, 0.0019 (mm d^{-1}), and 0.0011 (mm d^{-1}), respectively. The improved stem diameter growth model can be used to improve the environmental control for better plant growth and lower cost.

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