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Estimation of eggplant leaf number using thermal time model

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Abstract

A two-year investigation was carried out during 2006 (on three cultivars) and 2007 (on one cultivar) under open-field conditions, respectively, to test whether a model based on the thermal time approach could be developed to estimate the leaf number of eggplant (*Solanum melongena* L.) across cultivars. Thermal time (°Cd) was calculated using a base temperature of 11°C and a ceiling temperature of 32°C. Leaves that were beginning to unfold with a width of 2 cm or greater were counted every 3 to 4 days. A relationship between the leaf number and the thermal time was established in the calibration experiment (2006) on three cultivars, and data from another cultivar in 2007 growing season was used for model validation. Results indicated that a single equation could be used to predict leaf number of all cultivars in response to thermal time. The response of the leaf numbers to thermal time was curvilinear, with a lag over the first 450°Cd. After 450°Cd, the increase in the leaf number per plant was linearly related to the thermal time. These results would be useful in developing a model of leaf area development and eventually a crop growth model for eggplant.

Key words: Base temperature, growing degree units, leaf number, modelling, *Solanum melongena* L.

Introduction

Knowledge concerning the timing of crop phenological events is important for management decisions such as the timing of pesticide application, scheduling harvest of crops, selecting genotypes for optimum yields in varying climates and in irrigation scheduling [1]. Of particular importance to crop modelling efforts is the ability to predict leaf area development, since plant leaf area is an important determinant of light interception and consequently of transpiration, photosynthesis and plant productivity [2-5]. Crop leaf area depends on the leaf appearance rate, the leaf expansion rate, the duration of leaf expansion and leaf senescence rate [6]. The expansion of leaf area can be successfully predicted from leaf number [7]. Nevertheless, leaf appearance rates and the leaf numbers are affected by environmental factors such as temperature, photoperiod, radiation, water stress and composition of the nutrient solution [1, 6, 8, 9]. Of these, temperature is generally the primary consideration when developing models for predicting leaf area [1, 8], development [10], and appearance [11].

Reaumur introduced the concept of heat units (or thermal time) in 1730; since then, many methods for its calculation have been devised [12]. Heat units can be expressed as growing degree-days (GDD) or growing degree units (GDU), and are frequently used to describe the timing of biological processes [12].

The effect of temperature on leaf number has been studied for several grain crops [13-17]. These studies typically normalize time by temperature, resulting in a scale of thermal time (°Cd), also referred as heat units or growing degree days [8]. The normalization results in a linear [6, 18-20] or nonlinear [1, 10, 11] relationships between leaf number and thermal time over a wide range of environments.

While there has been considerable researches concerning the influence of temperature on leaf number of grain crops, there is much less information available [1, 21] for vegetable crops, in particular on eggplant (*Solanum melongena* L.).

Therefore, the aims of this study were (1) to develop a model for predicting leaf numbers of different eggplant cultivars based on thermal time approach and (2) to assess the robustness of the selected model on an independent data set coming from other cultivar.

Materials and Methods

Four eggplant (*Solanum melongena* L.) cultivars were used to develop the leaf number prediction model. Eggplant cultivars Beatrice, Luciana and Melana were grown in summer 2006 (30 June - 21 September), whereas cultivar Galina was grown in summer 2007 (6 July - 24 September) under field conditions at the Experimental Farm of Tuscia University, central Italy (latitude 42°25 N; longitude 12°08 E; altitude 310 m). These cultivars were selected as a representative sampling of many eggplants cultivated in Italy. In both years plants were grown in a randomized completely block design with 4 replications. The size of each plot was 4.8 m×10 m (four rows per plot). Row spacing was 1.20 m and the distance between plants in the row was 0.40 m providing a plant density of 2.1 plants m^{-2}. All plots received the same amount of total N (150 kg ha^{-1}), P (100 kg ha^{-1}), and K (200 kg ha^{-1}) fertilizers. All of the P and 40% of the N and K fertilizers were applied prior to planting and thoroughly mixed to the soil. The remaining 60% of N and K was added equally at weekly intervals through the drip irrigation system, starting 2 weeks after transplanting until the second harvest. Irrigation was scheduled twice weekly and applied with drip-irrigation system to ensure that water was non-limiting. Weeds were controlled by hand as needed and there was no problem related to diseases and insects.

In the preliminary calibration experiment (2006) coming from the three cultivars (Beatrice, Luciana and Melana), six plants were marked in the center rows of each experimental unit (plot) for leaf counts. Beginning at the second leaf, leaves were counted every 3 to 4 days. A small hole was punched in each leaf to facilitate counts. A leaf was counted if it had a width (perpendicular to the midrib) of at least 2 cm. The daily minimum and maximum air temperature was recorded at the weather station, 100 m apart from the experimental site.

The daily thermal time (TH_T) was calculated using the formula:

$$TH_T = \left[\left(T_{\max} + T_{\min}\right)/2 - T_B\right] \quad (1)$$

where T_{max} is the daily maximum air temperature, T_{min} the daily minimum air temperature and T_B the base temperature of 11°C. Two additional constraints are used in the thermal time calculations. If the T_{min} is less than T_B, then it is set to T_B, if the T_{max} exceeds 32°C (ceiling temperature), it is set to [32-2(T_{max}-32)]. The base temperature and the 32°C ceiling temperature were assumed for these calculations based on the results obtained by Jovanovic and Annandale [22].

To characterize the time evolution of the leaf number a sigmoidal model was used [23]:

$$Y = \frac{a}{\left(1 + e^{-\frac{1}{b}(x - x_0)}\right)} \quad (2)$$

where a is the maximal value of y, x is the time expressed in days after transplanting or accumulated thermal time after transplanting, x_0 represents the time period (days after transplanting or accumulated thermal time after transplanting) to reach 50% of the final maximal value a and b is the fitting parameter of the model.

In addition to validate the developed model and to increase practical applicability in different environmental conditions, a validation experiment was conducted in the summer 2007 on leaf samples of cv. Galina. Leaf number was predicted using the model from the calibration experiment and compared with the actual leaf number. The slope and intercept of the model were tested to see if they were significantly different from the slope and intercept of the 1:1 correspondence line [24]. Regression analyses were conducted using the SigmaPlot 8.0 package (SigmaPlot, Richmond, California, USA).

Results and Discussion

The minimum and maximum air temperatures in both growing seasons (2006 and 2007) are presented in Fig. 1 (A and B). In the calibration experiment (2006), the minimum air temperature ranged from 12.3 to 21.5°C and the maximum air temperature from 19.5 to 34.5°C. Moreover, a similar trend was recorded in the validation experiment (2007), where the minimum air temperature ranged from 11.8 to 20.6°C and the maximum air temperature from 23.8 to 38.6°C (Fig. 1).

The sigmoidal equation (Eq. (2)) was well adapted to the experimental data relative to the evolution of leaf number of the three cultivars Beatrice, Luciana and Melana during the 2006 growing season (Fig. 2). The coefficient of determination (r^2) was higher than 0.99 and the *P*-value was also significant ($P < 0.001$), which indicated a good fit. Fig. 2 shows the time course of leaf number during the two growing seasons. The maximum leaf number

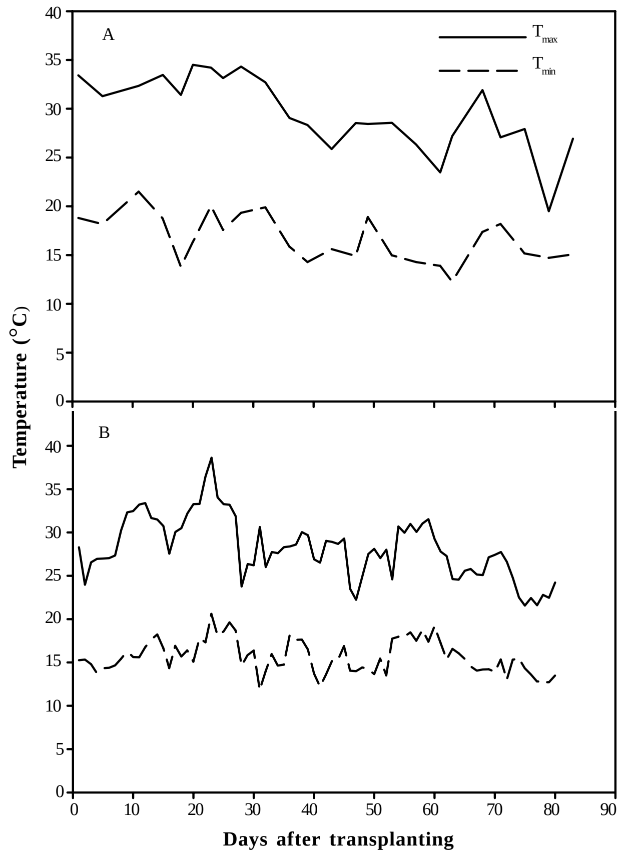

Figure 1. Daily maximum and minimum air temperature at the experimental farm of Tuscia University during the 2006 (A) and 2007 (B) growing seasons.

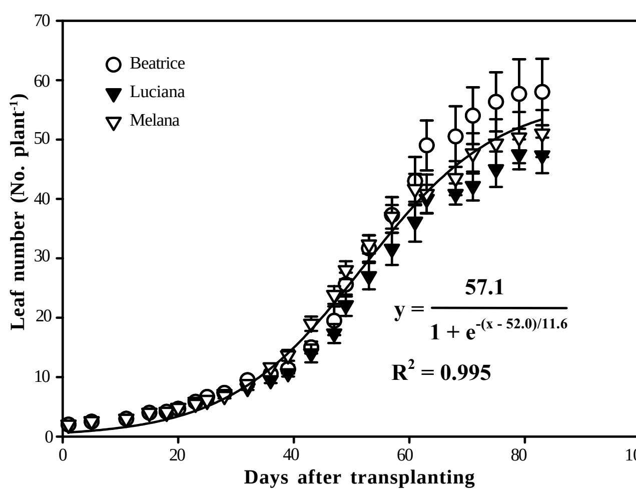

Figure 2. Number of leaves per plant as function of days after transplanting for three eggplant cultivars, during 2006 (calibration experiment).

Data are means of four replicates.Vertical bars indicate ± S.E. of means; their absence indicates the size was less than the symbol.

(*a*) recorded in the calibration experiment was 57, whereas the time required to reach 50% of the maximum value was 52 days.

Cultivars were pooled to examine the initial relationship between the leaf number and the thermal time after transplanting in 2006 (Fig. 3). A non-linear relationship was apparent between thermal time and leaf count, and regression revealed that the equation of Fig. 3 fit the data for all cultivars reasonably well. Similar result has been reported by NeSmith [1] on four summer squash (*Cucurbita pepo* L.) cultivars, where the response of leaf numbers to thermal time was non-linear. The equation reported in Fig. 3 implies a maximum leaf number of approximately 59 leaves, which is similar to the number of leaves observed during the calibration experiment. Moreover, the response of leaf numbers to thermal time was curvilinear, with a lag over the first 450°Cd, thereafter the increase in the leaf number per plant was linearly related to the thermal time. The reason for the apparent lag for the first 450°Cd is not clear. NeSmith [1] and Villalobos and Ritchie [25] revealed a similar relationship for summer squash and sunflower leaf numbers in response to thermal time. They hypothesized that there could be a different sensitivity to temperature during early growth. Additionally, an assimilate supply may limit the leaf appearance rate of very young plants. Possible genotype differences using the selected model were analyzed. However, when leaf number estimations using an equation derived for a single cultivar versus the overall model were compared, they were not significantly different. These results suggest that an universal leaf number estimation model for eggplant is plausible.

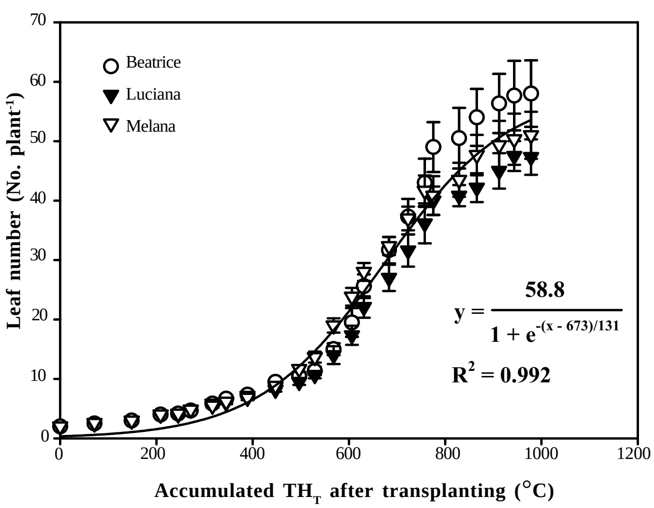

Figure 3. Relationship between leaf number per plant and the accumulated thermal time after transplanting for three eggplant cultivars, during 2006 (calibration experiment).

Data are means of four replicates. Vertical bars indicate ± S.E. of means; their absence indicates the size was less than the symbol.

Comparisons between measured versus calculated leaf number, using the following model (LN = $58.8/(1+e^{-(x-673)/131})$ for the validation set derived from 2007 experiment on 'Galina', showed a high degree of correlation and provided quantitative evidence of the validity of the leaf number estimation model (Fig. 4). The regression lines of the measured versus calculated values were not significantly ($P = 0.59$) different from the 1:1 correspondence. Moreover, the calculated values of leaf number were very close to the measured values, giving an overestimation of 1.5% in the prediction.

To summarize, we can conclude that the proposed model can provide accurate estimations of eggplant leaf number across cultivars and environments. These results should be useful in developing a model of leaf area development and eventually a crop growth model for eggplant.

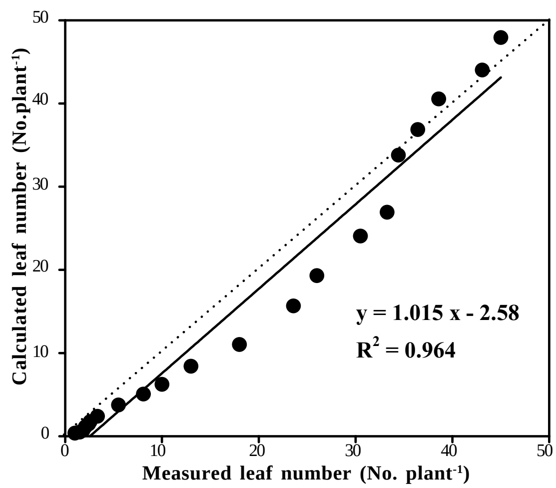

Figure 4. Measured vs. calculated number of leaves per plant of Galina cultivar, during 2007 (validation experiment)

The following model was used [LN = $58.8/(1+e^{-(x-673)/131})$, where LN is the number of leaves per plant and x the accumulated thermal time]. Solid line represents linear regression lines of the model. Dotted lines represent the 1:1 relationship between the measured and calculated values.

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