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A non-linear model to simulate node appearance in muskmelon (*Cucumis melo* L.) grown inside plastic greenhouse as a function of air temperature

Um modelo não linear para estimar o aparecimento de nós em meloeiro (*Cucumis melo* L.) cultivado em estufa plástica, baseado na temperatura do ar

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Abstract: The calculation of node appearance rate is an important part of simulation models of crops with decumbent growth habit like muskmelon (*Cucumis melo* L.). The objective of this study was to adapt and evaluate a multiplicative non-linear model for estimating node appearance in muskmelon under greenhouse conditions. A series of experiments were conducted inside a plastic greenhouse in Santa Maria, RS, Brazil, using the muskmelon hybrid HY-MARK. A total of eleven planting dates were performed during 2002, 2003, and 2004. The number of visible nodes (NN) on the main vine was evaluated twice a week. The NN data from three planting dates were used to estimate the coefficients of the non-linear model and the plastochron (linear model), used as a comparison model. The NN data from the other eight planting dates were used as independent data for evaluating the models. The non-linear model had a good performance in simulating the main vine node number in this muskmelon hybrid, with a root mean square error of 2.4 nodes. The non-linear model was superior to the linear model as deviations (predicted-observed) were greater with the latter compared to the former model.

Key words: Modeling, temperature, plant development, phenology.

Resumo: O cálculo da taxa de aparecimento de nós é uma parte importante de modelos de simulação de culturas com hábito de crescimento decumbente como o meloeiro (*Cucumis melo* L.). O objetivo deste trabalho foi adaptar e avaliar um modelo multiplicativo não linear para simular o aparecimento de nós em meloeiro cultivado em estufa plástica. Uma série de experimentos foram conduzidos no interior de uma estufa plástica em Santa Maria, RS, com o híbrido de meloeiro HY-MARK. Um total de onze épocas de plantio foram realizadas durante 2002, 2003 e 2004. O número de nós visíveis (NN) na haste principal foi medido duas vezes por semana. Dados de NN de três épocas de plantio foram usados para estimar os coeficientes do modelo não linear e do plastocrono, usado como modelo para comparação. Os dados de NN das outras oito épocas de plantio foram usados como dados independentes para avaliar os modelos. O modelo não-linear apresentou boa performance para simular o número de nós visíveis na haste principal deste híbrido de meloeiro, com um valor de raiz quadrada do quadrado médio do erro de 2,4 nós. O modelo não linear foi superior ao modelo linear pois os desvios (predito-observado) foram maiores no segundo comparado com o primeiro modelo.

Palavras-chave: Modelagem, temperatura, desenvolvimento vegetal, fenologia.

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Introduction

Muskmelon (*Cucumis melo* L.) is an important horticultural crop for sub-tropical and tropical countries. Brazil is the third largest muskmelon producer in South America, after Argentina and Chile (COSTA, 2001). The muskmelon harvested area in Brazil increased from 5,671 ha in 1980 to 15,000 ha in 2005 (FAO, 2006). About 90% of the Brazilian muskmelon production is concentrated in the Northeastern Region, with Rio Grande do Norte State being the largest producer (GRANGEIRO et al., 1999; COSTA, 2001). In Southern Brazil, muskmelon can be grown under field conditions only during the warmest season (from November to March), whereas during Spring and Fall, muskmelon can be grown only inside plastic greenhouses.

The calculation of node appearance rate (NAR) on the main and secondary vines is an important part of simulation models of crops with decumbent growth habit like muskmelon and other cucurbits (BAKER et al., 2001; STRECK, 2002). The integration of NAR over time gives the number of visible nodes (NN) on each vine, which is an excellent measure of plant development. The appearance and growth of leaves, and the timing of flowering of the first male and the first perfect (hermaphrodite) flowers are also related to NN in muskmelon (BAKER et al., 2001).

One approach to predict node appearance in muskmelon refers to the plastochron concept, defined as the time interval between the appearance of successive nodes on a stem (SINCLAIR, 1984; BAKER & REDDY, 2001). Time in the plastochron concept is usually expressed as thermal time (TT), measured in units of degree days ($^{\circ}\text{C day}$). Therefore, the plastochron has units of $^{\circ}\text{C day node}^{-1}$ (BAKER & REDDY, 2001). However, the thermal time approach has been criticized because there are different ways to calculate $^{\circ}\text{C day}$, which may result in different values when considering a same data set (McMASTER & WILHELM, 1997), and because of the assumption of a linear response of development to temperature (SHAYKEWICH, 1995; XUE et al., 2004; STRECK, 2004).

One way to overcome the disadvantages of the TT approach is to use non-linear temperature

response functions (STRECK, 2002; STRECK et al., 2003) and multiplicative models (WANG & ENGEL, 1998; XUE et al., 2004). STRECK (2002) demonstrated that a non-linear temperature response function (Beta function) described better the response of NAR to temperature than a two-stage linear function (thermal time). Non-linear functions also introduce elegant and smooth response functions rather than a combination of linear functions (step function) in the model (STRECK, 2002). WANG & ENGEL (1998) used a multiplicative model composed by non-linear response functions to temperature, photoperiod, and vernalization to model leaf appearance and phenology of winter wheat. The multiplicative model was more realistic than additive models to represent the interactive effects of environmental variables on wheat development (WANG & ENGEL, 1998).

No previous effort to model NAR with a non-linear multiplicative model was found in the literature. BAKER et al. (2001) proposed a developmental model in muskmelon, in which the timing of first male and perfect flowers occurs when the ninth and twelfth nodes, respectively, are visible on the main stem, and the NN is calculated using the plastochron concept. We propose here to use a multiplicative model with a non-linear temperature response function for modeling NAR in muskmelon, based on the model presented by WANG & ENGEL (1998).

The objective of this study was to adapt and evaluate a multiplicative non-linear model for estimating node appearance in muskmelon under greenhouse conditions.

Material and Methods

The WE model (WANG & ENGEL, 1998) was adapted to estimate node appearance in muskmelon considering its general form, since there is no photoperiod or vernalization response in muskmelon (BAKER & REDDY, 2001):

$$\text{NAR} = \text{NAR}_{\max} f(T) \quad (1)$$

where NAR is the daily node appearance rate (nodes day^{-1}), NAR_{\max} is the maximum daily node appearance rate (nodes day^{-1}) under optimum

temperature, and $f(T)$ is a dimensionless temperature response function (0-1) for NAR. The $f(T)$ is a beta function:

$$f(T) = [2(T-T_{\min})^a(T_{\text{opt}}-T_{\min})^a-(T-T_{\min})^{2a}]/(T_{\text{opt}}-T_{\min})^{2a} \quad (2)$$

$$a = \ln 2 / \ln[(T_{\max}-T_{\min})/(T_{\text{opt}}-T_{\min})] \quad (3)$$

where T_{\min} , T_{opt} , and T_{\max} are the cardinal temperatures (minimum, optimum, and maximum) for NAR and T is the mean daily air temperature. The cardinal temperatures for NAR are 0, 33, and 42°C, respectively for T_{\min} , T_{opt} , and T_{\max} (STRECK, 2002) and T is calculated from the average of minimum and maximum air temperatures. The curve generated by equations (2) and (3) with cardinal temperatures for NAR is presented in Figure 1.

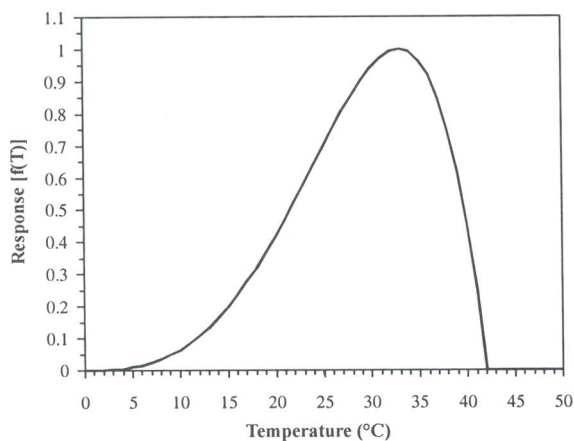


Figure 1. The beta function (equations 2 and 3) used as the temperature response function in the node appearance model of muskmelon with cardinal temperatures of 0 (minimum), 33 (optimum), and 42°C (maximum).

The number of visible nodes (NN) on the main vine is calculated by accumulating daily NAR values (i.e. at a one day time step) starting at transplanting date, i.e., $NN = HNAR$.

In order to compare predictions with the WE model, we also predicted the NN with the BAKER

et al. (2001) model, hereafter referred to as the BAKER model, which uses the plastochron concept with the thermal time approach. Thermal time in the BAKER model is calculated with a two-stage linear function, and cardinal temperatures of 10, 34, and 45°C, respectively for T_{\min} , T_{opt} , and T_{\max} .

The muskmelon hybrid HY-MARK was grown under a 10 x 25 m plastic greenhouse located at the field research area, Plant Science Department, Federal University of Santa Maria, RS, Brazil (29° 43' S latitude, 53° 43' W longitude, and 95m altitude). A total of eleven planting dates during 2002, 2003 and 2004 were performed and shown in Table 1. Seedlings were produced in a nursery and transplanted at the two-node stage to bags filled with commercial substrate (10 L) inside the plastic greenhouse. Plant spacing was 1.00 x 0.33 m. Plants were vertically single-vine conducted and pruned at 2 m height. Plants were irrigated daily with drip irrigation lines, and fertilized twice a week with macro and micronutrients. The experimental design was a complete randomized block design with three replications. Each replication had three rows of 5.6 m, with 17 plants per row. Four plants in the central row of each replication were tagged with colored wires, resulting in 12 tagged plants per planting date. The number of visible nodes on the main vine (NN) was counted on the tagged plants twice a week. A node was assumed visible when its associated leaf exceeded 3 cm in length (BAKER & REDDY, 2001).

The coefficient NAR_{\max} and the plastochron are genotype dependent. These two coefficients were estimated from the NN data collected during three planting dates (20 December 2002, 14 January 2003, and 27 March 2003). The NAR_{\max} for each planting date was estimated by minimizing the root mean square error (RMSE) (JANSSEN & HEUBERGER, 1995):

$$RMSE = [\sum(P_i - O_i)^2/n]^{0.5} \quad (4)$$

where P_i are predicted NN data, O_i are observed NN data, n is the number of observations, and i varies from 1 to n . The plastochron was estimated by the inverse of the slope of the linear regression between NN and TT accumulated from transplanting (BAKER & REDDY, 2001). The three estimated NAR_{\max} and plastochron values were then averaged resulting in a $NAR_{\max} = 1.01$ nodes day⁻¹ and a plastochron = 20.3 °C day node⁻¹.

Models evaluation was performed with independent data from eight different planting dates of the same genotype in the same plastic greenhouse: 17 September 2003, 12 November 2003, 17 December 2003, 26 January 2004, 20 February 2004, 14 July 2004, 20 August 2004, and 07 October 2004. Plants of these planting dates were grown as the ones in the planting dates used to estimate NAR_{max} and the plastochron. The RMSE (eq. 4) was calculated with the independent data and used as a measure of the models performance. The RMSE expresses the spread in $P_i - O_i$ and has the same units as the predicted and the observed data (in this study the unit is nodes). The lower the RMSE the better the model prediction. The method based on the deviations (prediction minus observation) proposed by MITCHELL (1997) was also used for assessing models performance. This method consists of plotting the deviations against the predicted data and defining a criteria for adequacy of the model based on an acceptable precision (envelope) and the proportion of points that must lie within it. We avoided using the regressing predicted vs. observed method, as this method has been proved not being appropriate for assessing models performance for several reasons (HARRISSON, 1990; MITCHELL, 1997).

Daily minimum and maximum air temperature were recorded inside the plastic house at 1.5 m height with a thermograph throughout the growing season of all planting dates.

Results and Discussion

Different planting dates resulted in different meteorological conditions during muskmelon growing seasons. Mean air temperature and sunshine hours varied from 18.0 to 25.7 °C and from 5.7 to 8.8 hours, respectively (Table 1). These different environmental conditions are important for plant growth and developmental studies, and for calibrating and evaluating the muskmelon NAR models.

The WE model predicted the NN in muskmelon quite well, with an overall RMSE of 2.4 nodes for the eight planting dates used as independent data (Figure 2a). A RMSE of 2.4 nodes is reasonable as during most of the planting dates, plants put a new node on a daily basis or every other day. Therefore, an error of 2-3 nodes is acceptable. The RMSE with the BAKER model was also 2.4 nodes (Figure 2c). Assuming a criteria of an error of 2 nodes in the approach proposed by MITCHELL (1997), the proportion of points with deviations (predicted minus observed) greater than or equal to 2 nodes was 0.46 (46 out of 100) and 0.45 (45 out of 100) for the WE model and the BAKER model, respectively, i.e., the performance of both models based on this statistic was also similar. However, both models performed differently if absolute deviations are compared; positive deviations (overpredictions) were lower with the WE model whereas negative deviations (underpredictions) were

Table 1. Mean air temperature and sunshine hours from transplanting to last node appearance during the eleven planting dates of muskmelon, hybrid HY-MARK, inside a plastic greenhouse. Santa Maria, RS, Brazil.

Planting date	Air temperature (°C)	Sunshine (h)
20 Dec 2002	25.4	8.8
14 Jan 2003	24.3	8.2
27 Mar 2003	19.8	6.2
17 Sep 2003	20.7	6.2
12 Nov 2003	23.7	7.5
17 Dec 2003	25.7	8.4
26 Jan 2004	25.6	8.6
20 Feb 2004	24.3	7.5
14 Jul 2004	18.0	5.7
20 Aug 2004	19.8	6.5
07 Oct 2004	22.0	7.9

higher with the WE model compared to the BAKER model (Figure 2b and 2d). The five greatest deviations were -5.8 , -5.5 , -5.1 , -4.9 and -4.8 nodes with the WE model, and $+6.7$, $+5.7$, $+5.2$, $+5.2$ and $+5.1$ nodes with the BAKER model. Greater negative deviations with the WE model occurred at an intermediate narrow range of NN values, from about 20 to 25 nodes (Figure 2b), while greater positive deviations with the BAKER model were at a higher and broader range of NN values, from 23 to 42 nodes (Figure 2d). These results indicate that the WE model is superior to the BAKER model.

We also noted that, although the plastochron was estimated easily from the three planting dates, the BAKER model was more difficult to implement for calculating NN. The difficulty has risen in the

following situation: when the thermal time at a given day is greater than de plastochron, should the difference be used in the accumulation of the thermal time of the following day or not? This information is not given in the literature that used the plastochron concept. Some internationally well-known authors were contacted and they advised us to use the first approach, but admitted that there is no consensus on this issue (W.W. Wilhelm & A. Weiss, personal communication), just like there is no consensus on the way to calculate thermal time (McMASTER & WILHELM, 1997).

On the other hand, we did not have such difficulty to implement the WE model for calculating NN. Also, the multiplicative nature and non-linear response function of the WE model are more realistic

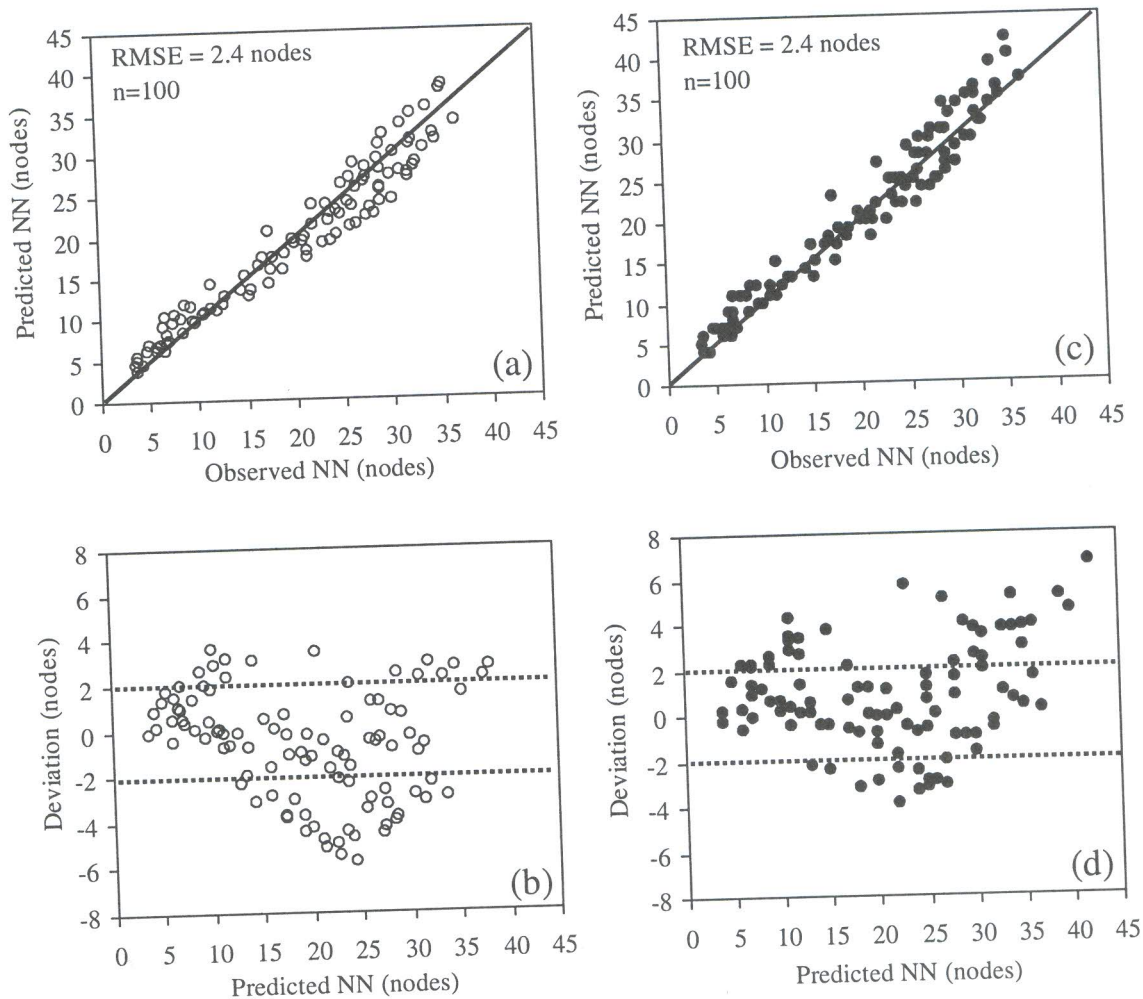


Figure 2. Predicted vs. observed (a, c), and deviations (predicted minus observed) vs. predicted (b, d) number of nodes on the main vine (NN) of muskmelon hybrid HY-MARK with the WE model (open circles) and with the BAKER model (closed circles). The solid line is the 1:1 line and the dashed line is the envelope of ± 2 nodes. Santa Maria, RS, Brazil, 2003-2004.

from a biological point of view (SHAYKEWICH, 1995; WANG & ENGEL, 1998; XUE et al., 2004). Another advantage of the WE model is that the Beta function has general nature as the cardinal temperatures were derived from another study with different muskmelon genotypes (STRECK, 2002) and worked well in this study with the hybrid HY-MARK. When using generalized response functions, we invoke Occam's Razor, which is encouraged in crop modeling (SINCLAIR & MUCHOW, 1999), i.e., the simplest theory is preferred to more complex ones or explanations of phenomena should be in terms of known quantities. This kind of philosophy in crop modeling assumes that similarities among genotypes are more important than the differences (MAJOR & KINIRY, 1991). Therefore, the WE model is more appropriated and should be preferred to the plastochron approach for estimating node appearance in muskmelon.

Conclusions

We adapted and evaluated a simple node appearance model in muskmelon that is realistic from a biological point of view because it uses a multiplicative approach and is composed by a non-linear temperature response function. The model had a good performance in simulating main vine node number of the muskmelon hybrid HY-MARK grown at different planting dates under plastic greenhouse condition, with a root mean square error of 2.4 nodes, which is an acceptable error. The non-linear model was superior to the linear model as deviations (predicted-observed) were greater with the latter compared to the former model.

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