MODELING LEAF APPEARANCE IN MAIZE

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Apresentado no XVII Congresso Brasileiro de Agrometeorologia -18 a 21 de julho de 2011-SESC Centro de Turismo de Guarapari, Guarapari-ES.

ABSTRACT: The objective of this study was to evaluate and compare a linear model (the Phyllochron model) with a non-linear model (the Wang and Engel, WE, model) for simulating LAR in a maize variety. A field experiment was done in Santa Maria, RS, Brazil, with seven sowing dates during two growing seasons (2005/2006 and 2006/2007). The maize variety BRS Missões was used in a randomized block design, with six replications. Plant spacing was 0.8 m x 0.21 m. Three plants in the central row of each plot were tagged. The ligule (expanded) and tip leaf number was measured weekly on the tagged plants. The Phyllochron model, which assumes a linear response of LAR to temperature, and the WE model, which assumes a non-linear response of LAR to temperature, were used to calculate ligule and tip leaf number. Models coefficients were estimated using the data set collected in 2005/2006 and evaluation of the models was done with the data set collected in 2006/2007 using the statistic root mean square error (RMSE). The WE model was superior to the Phyllochron model for predicting leaf number.

KEY WORDS: Plant development, Modeling, Temperature, Phyllochron, *Zea mays*.

MODELAGEM DO SURGIMENTO DE FOLHAS EM MILHO

RESUMO: O objetivo deste trabalho foi avaliar e comparar um modelo linear (o modelo Filocrono) e um modelo não linear (o modelo Wang e Engel - WE) para a simulação da TAF em uma variedade de milho. Um experimento foi realizado em Santa Maria, RS, com sete datas de semeadura em dois anos agrícolas (2005/2006 e 2006/2007). A variedade de milho usada foi BRS Missões, no delineamento blocos ao acaso, com seis repetições. O espaçamento foi 0,8 m x 0,21 m. Em cada parcela foram marcadas três plantas na linha central nas quais se realizou semanalmente a contagem do número de folhas expandidas e totais. Os modelos usados foram o Filocrono, que usa uma relação linear entre taxa de aparecimento de folhas e temperatura, e o modelo WE que utiliza uma função de resposta não-linear de temperatura [f(T)]. A estimativa dos coeficientes dos modelos foi com dados coletados em 2005/2006 e a avaliação dos modelos foi com dados coletados em 2006/2007 usando-se a estatística raiz do quadrado médio do erro (RQME). O modelo WE model foi superior ao modelo Filocrono para simular o número de folhas.

PALAVRAS-CHAVE: Desenvolvimento vegetal, Modelagem, Temperatura, Filocrono, *Zea mays*.

INTRODUCTION: One crop that is particularly important for small farmers in Brazil is maize (*Zea mays* L.). The calculation of leaf appearance rate (LAR) is an important part of many crop simulation models (HODGES, 1991). The integration of LAR over time gives the number of accumulated or emerged leaves on the main stem (LN), which is an excellent measure of plant development.

Temperature is a major factor that drives leaf appearance in maize (WHITE, 2001). One approach to predict the appearance of individual leaves is the phyllochron concept, defined as the time interval between the appearances of successive leaves (WILHELM & MCMASTER, 1995). Time is often expressed as thermal time (TT), with units of °C day, and in this case, the phyllochron has units of ^{o}C day leaf^{-1}. The TT approach is open to criticism because there are different ways to calculate TT (MCMASTER & WILHELM, 1997), and because of a linear response of development to temperature, which is not realistic in all situations where plants develop and grow (XUE et al., 2004).

One way to overcome the disadvantages of the TT approach is to use non-linear temperature response functions and multiplicative models. The Wang and Engel (WE) model (WANG & ENGEL, 1998) is a an example, this model improved the predictions of leaf appearance compared to the Phyllochron model, which uses a linear response, in several crops such as winter wheat (XUE et al., 2004), potato (STRECK et al., 2007) and eucaliptus seedlings (MARTINS & STRECK, 2007), but not in maize.
The objective of this study was to evaluate and compare the Phyllochron model and the WE model for simulating LAR in a maize variety.

MATERIAL AND METHODS: The Phyllochron model (WILHELM & MCMASTER, 1995) using the thermal time approach was used in this study as the linear model. This model is widely used to simulate leaf appearance is grasses (MCMASTER, 2005). Daily values of thermal time (TT, ^oC day) were calculated as (ARNOLD, 1960; MATTHEWS & HUNT, 1994):

$TT= (T–T_{min}).$ 1 day (1)

when $T_{min}<T \leq T_{opt}$ and if $T<T_{min}$ then $T=T_{min}$,

$TT= [(T_{opt}–Tmin). (T_{max}–T)/ (T_{max}–T_{opt})].$ 1 day (2)

when $T_{opt}<T\leq Tmax$ and if $T>T_{max}$ then $T=T_{max}$, where T_{min}, T_{opt}, T_{max} are the cardinal (minimum, optimum, and maximum) temperatures for maize and T is the daily air temperature. The cardinal temperatures for LAR in maize were 8°C, 31°C, and 105, 80°F (YAN & HUNT, 1999). TT was calculated using daily minimum (TN) and daily maximum (TX) air temperature, and then averaged. The accumulated thermal time (ATT) from emergence was calculated by accumulating TT, i.e. ATT=∑TT. The phyllochron (^oC day $leaf^{-1}$) was estimated by the inverse of the slope of the linear regression of LN against ATT (XUE et al., 2004). The main stem number of emerged leaves (LN) was calculated by LN=ATT/phyllochron.
The WE model (WANG & ENGEL, 1998) for LAR in maize has the general form:

$LAR = LAR_{max}$ f (T) (3)

where LAR is the daily leaf appearance rate (leaves day^{-1}), LAR_{max} is the maximum daily leaf appearance rate (leaves day^{-1}), and f(T) varies from 0 to 1 for LAR, respectively. The f(T) is a beta function:

$f(T) = [2(T-T_{min})^{\alpha}(T_{opt}-T_{min})^{\alpha}-(T-T_{min})^{2\alpha}]/(T_{opt}-T_{min})^{2\alpha}$ for $T_{min} \leq T \leq T_{max}$ (4)

$f(T) = 0$

for $T < T_{min}$ or $T > T_{max}$ (5)

$\alpha = \ln2/\ln[(T_{max}-T_{min})/(T_{opt}-T_{min})]$ (6)

where T_{min}, T_{opt}, and T_{max} are the cardinal (minimum, optimum, and maximum) temperatures for LAR and T is the daily air temperature. Values of T_{min}, T_{opt}, and T_{max} have been previously defined and are the same used in equations (1) and (2). The f (T) was calculated using daily TN and TX, and then the resulting daily values of f (T) were averaged, corresponding to the daily average f (T).
The main stem number of emerged leaves (LN), was calculated by accumulating daily LAR values starting at emergence, i.e., LN=∑LAR. LN, LAR and LAR_{max} were also expressed both on a ligule and a tip leaf basis.
Data from a two-year (2005/2006 and 2006/2007) field experiment done at the research area, Plant Science Department, Federal University of Santa Maria, Santa Maria, RS, Brazil (29°43' S; 53º43' W; 95 m a.s.l.) were used in this study. The region has a sub-tropical climate Cfa according to Köppen's climate system (MORENO, 1961). Soil type at the experimental site was a Rhodic Paleudalf (USDA Taxonomy). The maize variety BRS-Missões was sown during the 2005/2006 growing season at seven sowing dates: 21/09/2005, 20/10/2005, 29/11/2005, 04/01/2006, 07/02/2006, 16/03/2006 and 12/04/2006, and in 2006/2007 the dates were: 23/08/2006, 27/09/2006, 30/10/2006, 30/11/2006, 08/01/2007, 13/02/2007 and 15/03/2007. BRS-Missões is a synthetic variety development by Embrapa Trigo and recommended for southern Brazil States (EMBRAPA, 2006). Plant density was 6 plants m^{-2} and plant spacing was 0.8 m among rows and 0.21 m among plants within rows. The experimental design was a randomized block, with seven treatments and six replications. Each

replication was a plot with three 5m rows. Fertilization rates at sowing were 700 kg ha^{-1} of a commercial 07-11-09 (NPK) fertilizer. Additional nitrogen was added as a side-dress application at V4, V7, V11, and VT (FORTSTHOFER et al., 2004) with urea at a rate of 89 kg of urea ha^{-1}.

The date of 50% emergence was calculated for each plot and averaged for each sowing date. One week after emergence, three plants in the center row of each plot were arbitrarily selected and tagged with colored wires. The number of fully expanded leaves (ligule LN) and the number of leaf tips (tip LN) on the tagged plants were counted once a week until flag leaf appearance. Daily minimum (TN) and maximum (TX) air temperature were measured by a standard meteorological station located at about 200 m from the plots.

The coefficients phyllochron and LAR_{max} (equation 3) were estimated using the NL data of the 2005/2006 growing season. The coefficient LAR_{max} was estimated by least square method. The phyllochron and LAR_{max} estimates were the average of the seven sowing dates. The values of LN (ligule LN and tip LN) predicted with the Phyllochron model and with the WE model were compared with the observed LN of the 2006/2007 growing season, which are independent data sets. The statistic used to evaluate model performance was the root mean square error (RMSE).

The RMSE was calculated as (JANSSEN & HEUBERGER, 1995):

$$RMSE = [\Sigma(Pi-Oi)^2/ N]^{0.5} \qquad (7)$$

where Pi = predicted LN values, Oi = observed LN values, and N = number of observations. The unit of RMSE is the same as P and O, i.e., leaves.

RESULTS AND DISCUSSION: The estimates (average of seven sowing dates in the 2005/2006 growing season) of the phyllochron were 51.2 and 42.7°C day $leaf^{-1}$ and the estimates of the LAR_{max} were 0.452 and 0.626 leaves day^{-1}, for ligule LN and tip LN, respectively. The results of these estimates indicate a greater rate of tip leaf appearance than ligule leaf appearance, which lead to an accumulation of the number of leaf tips at the whorl as plant developed until flag leaf appearance. When the first ligule was visible, there were about two leaf tips at the whorl, whereas when there were 15 leaf ligules there were 5-6 leaf tips at the whorl.

Predictions of ligule LN were very good with both models, mainly up to about 10 leaves (Figure 1a,c). The overall RMSE was smaller than one leaf and slightly lower with the WE model (0.80 leaves) than with de Phylochron model (0.84 leaves). Among sowing dates, predictions with the Phyllochron model were the worst for sowings on 30/10/2006 and 30/11/2006 whereas with the WE model, predictions were the worst for sowings on 13/02/2007 and 15/03/2007. The lowest RMSE was 0.61 leaves (sowing date: 30/10/2006) and 0.23 leaves (sowing date: 08/01/2006) with the Phyllochron and the WE model, respectively (Table 1).

Predictions of tip LN had slightly greater error compared to the ligule LN with both models (Figure 1b,d). The overall RMSE was one leaf lower with the WE model (1.29 leaves) than with the Phyllochron model (2.32 leaves). The lowest RMSE with the Phyllochron model was 1.10 leaves (sowing date: 15/03/2007) and the lowest RMSE with the WE model was 0.67 leaves (sowing date: 23/08/2006) (Table 1).

These results suggest that the WE model should be preferred to the Phyllochron model for predicting ligule and tip LN in maize. The WE model uses a non-linear temperature response function, which is more biologically sound to represent the LAR response to temperature than a linear response (XUE et al., 2004; STRECK et al., 2007). The coefficients of the WE model LAR_{max} and cardinal temperatures have biological meaning and operational definition. The non-linear effects of temperature on LAR combined in a multiplicative fashion are also biologically sound to represent the interaction of environmental factors on plant development observed in the field.

Errors in the predictions of ligule LN with the WE model were lower than one leaf in most of the sowing dates (Table 1). The predictions of tip LN were with an error of about one leaf in most of the sowing dates (Table1).

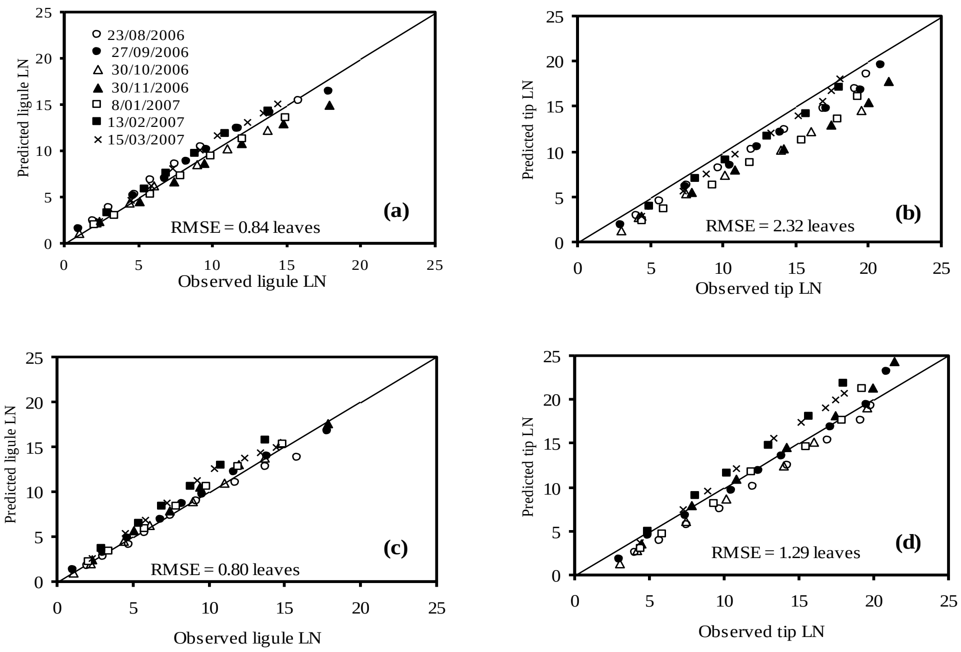

Figure 1. Predicted versus observed ligule and tip leaf number of maize variety BRS Missões in seven sowing dates (day/month/year), using the Phyllochron model (a) and (b) and the WE model (c) and (d).

Table 1. Root mean square error (RMSE) using the Phyllochron model and the WE model to predicted the ligule leaf number (LN) and the tip LN in the maize variety BRS Missões in seven sowing dates (day/month/year) during the 2006/2007 growing season. Santa Maria, RS, Brazil.

Sowing date	Statistic	Phyllochron model		WE model	
		Ligule LN	Tip LN	Ligule LN	Tip LN
23/08/2006	RMSE	0.82	1.59	0.57	0.67
27/09/2006	RMSE	0.66	1.77	0.59	0.85
30/10/2006	RMSE	0.61	3.09	0.35	1.43
30/11/2006	RMSE	1.37	3.37	0.67	0.87
08/01/2007	RMSE	0.68	3.26	0.23	1.36
12/02/2007	RMSE	0.71	1.16	1.31	1.67
15/03/2007	RMSE	0.84	1.10	1.23	1.85

Errors in the predictions of ligule LN with the WE model were lower than one leaf in most of the sowing dates (Table 1). An error lower than one leaf is acceptable for many practical applications. The predictions of tip LN were with an error of about one leaf in most of the sowing dates (Table1). An error of one leaf for tip LN has less impact than an error of one leaf for ligule LN, because there are two to five leaves unfolding and expanding at the whorl of a maize plant, and the uppermost visible leaf is small and has a minor contribution to the whole plant leaf area. Therefore, from a practical view point, the greater error for tip LN is of no concern.

CONCLUSIONS: The WE model is superior to the Phyllochron model to predict ligule and tip leaf number in maize. Better predictions of leaf number with the WE model are mainly due to more biologically sound representation of non-linear effects of temperature on LAR when air temperature is near beyond the optimum temperatures for LAR.

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