ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.25, n.6, p.361-371, 2021
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v25n6p361-371

Calibration and validation of a node appearance model in soybean crop[1]

Calibração e validação de um modelo de aparecimento de nós na cultura da soja

Kelin P. Bexaira[2*], Nereu A. Streck[2], Alencar J. Zanon[2], Eduardo L. Tagliapietra[2], Gean L. Richter[2] & Patric S. Weber[2]

[1] Research developed at Rio Grande do Sul, Brazil
[2] Universidade Federal de Santa Maria/Departamento de Fitotecnia, Santa Maria, RS, Brazil

HIGHLIGHTS:

Improvement of the simulation by calculating a temperature function with the daily minimum and maximum temperatures.
Equation to determine the maximum rate of node appearance of soybean cultivars recommended for Southern Brazil.
Maximum node appearance rate varies with the maturity group and not with the type of growth of soybean cultivars.

ABSTRACT: Agricultural models that simulate the appearance of nodes are tools that describe the vegetative stages of soy and help to understand the physiological processes of the plant. This study aimed to calibrate and validate a non-linear node appearance model for soybean cultivars recommended for Southern Brazil. Data from 47 experiments carried out in the Rio Grande do Sul between 2010 and 2018 were used, with 35 soybean cultivars of determined and indeterminate growth type and relative maturity groups ranging from 3.9 to 8.3. The calibration of the node appearance model was performed using the least-squares method of the residue, between the number of observed and simulated nodes, for three versions of the model regarding the temperature function calculation [f(T)]. The performance of the model was validated with data on the number of nodes in experiments and crops, with irrigated and non-irrigated water regimes, highland and lowland environments. The simulation of the number of nodes is improved when a temperature function is calculated with the minimum daily air temperature and another with the maximum daily air temperature. Then the average of the two functions is calculated (Tmm version). Also, the general equation, which does not consider the growth type of the cultivar, can calculate the maximum rate of nodes appearance (NAR_{MAX}) without loss of precision in the simulation.

Key words: *Glycine max*, agricultural models, stages of development, phenology, plastochron

RESUMO: Os modelos agrícolas que simulam o aparecimento de nós são ferramentas que descrevem os estágios vegetativos da soja e auxiliam a compreender os processos fisiológicos da planta. O objetivo deste estudo foi calibrar e validar um modelo não linear de aparecimento de nós para as cultivares de soja recomendadas para o Sul do Brasil. Foram utilizados dados de 47 experimentos realizados no Rio Grande do Sul entre 2010 e 2018, com 35 cultivares de soja de tipo de crescimento determinado e indeterminado e grupo de maturidade relativa variando de 3,9 a 8,3. A calibração do modelo de aparecimento de nós foi realizada por meio do método dos mínimos quadrados do resíduo, entre o número de nós observados e simulados, para três versões do modelo no que se refere ao cálculo da função de temperatura [f(T)]. O desempenho do modelo foi validado com dados de número de nós de experimentos e lavouras, com regime hídrico irrigado e não irrigado, ambientes de terras altas e baixas. A simulação do número de nós é melhorada quando é calculada uma função de temperatura com a temperatura mínima diária do ar e outra com a temperatura máxima diária do ar e, em seguida, calculada a média das duas funções (versão Tmm). Além disso, a equação geral, que não leva em consideração o tipo de crescimento da cultivar, pode ser utilizada para o cálculo da taxa máxima de aparecimento de nós (NAR_{MAX}), sem perda de precisão na simulação.

Palavras-chave: *Glycine max*, modelos agrícolas, estágios de desenvolvimento, fenologia, plastocrono

• Ref. 228904 – Received 18 Sept, 2019
* Corresponding author - E-mail: kelin_bexaira@hotmail.com
• Accepted 03 Feb, 2021 • Published 10 Mar, 2021
Edited by: Carlos Alberto Vieira de Azevedo

Introduction

The node appearance rate (NAR) is an important parameter of the simulation models of soybean growth, development, and yield (Sinclair et al., 2005). Integrating NAR over time gives the accumulated number of nodes (NN), which is a morphological indicator of plant development (Sinclair et al., 2005), as it is through NN that the vegetative phase of the plant is determined, according to the scale of Fehr & Caviness (1977).

Soydev (Setiyono et al., 2007) is the most recent and modern model of soybean phenology and was developed in the United States for cultivars of semi-determinate and indeterminate growth type, with relative maturity groups (RMG) from 0.8 to 4.2 grown at high latitudes and under irrigation (Setiyono et al., 2007). However, the cultivars currently used in Southern Brazil have an RMG from 4.5 to 7.0 and an indeterminate growth type (Zanon et al., 2015).

According to Setiyono et al. (2007), the key parameters of a soybean phenology model can be estimated from traits such as the relative maturity group and growth type. The relative maturity group is defined as the duration of the soybean development cycle (from sowing to physiological maturity, in days) (Zanon et al., 2018). The growth type indicates the duration of flowering, in which cultivars with a specific type will flower in a short period, so that, after the R1 stage, the plant grows little and the appearance of nodes ceases around the R3 stage (Zanon et al., 2016). Indeterminate cultivars have the longest flowering, and after the R1 stage, the plant continues to produce nodes until the R5 stage (Zanon et al., 2016).

The node appearance model included in the Soydev model needs to be calibrated and validated for the Brazilian environmental conditions and cultivars currently used in Brazil. Also, the air temperature input data for calculating the temperature function of the node appearance model is the arithmetic mean of the maximum and minimum daily temperature values (Setiyono et al., 2007). However, when soybeans are grown in tropical and subtropical conditions, like most crops in Brazil, the air temperature during the growing season is greater than in the conditions in which the Soydev was calibrated. Therefore, this study aimed to calibrate and validate a non-linear node appearance model for soybean cultivars recommended for Southern Brazil.

Material and Methods

For the calibration and validation of the node appearance model, data from 47 experiments conducted in the State of Rio Grande do Sul (RS), Brazil, were used during eight growing seasons (2010/2011, 2011/2012, 2012/2013, 2013/2014, 2014/2015, 2016/2017, 2017/2018, and 2018/2019). In five locations, the experiments were carried out in research institutes or universities (Santa Maria, Cachoeirinha, Júlio de Castilhos, Itaqui, and Frederico Westphalen), the rest being conducted in commercial fields (Água Santa, Restinga Seca, Tupanciretã, Cruz Alta, and Júlio Castilhos).

In Cachoeirinha, Itaqui, and some locations in Santa Maria, the experiments were conducted in areas traditionally cultivated with irrigated rice (lowlands). The data included irrigated and non-irrigated experiments and sowing before (from the end of September to the beginning of October), during (from the end of October to December), and after (from December) the period recommended by the Agricultural Climate Risk Zoning for the State of Rio Grande do Sul (Table 1). Thirty-five soybean cultivars were sown with determined and indeterminate growth type and RMG ranging from 3.9 to 8.3 (Table 2).

Table 1. Sowing dates, water regime, and cultivation environments of the experiments in nine locations from the Rio Grande do Sul during eight growing seasons

Growing season	Local	Sowing date	Water regime
2010/2011	Santa Maria	12/10 – 01/08	Irrigated
2011/2012	Santa Maria	09/24 – 11/19* - 01/28*	Irrigated
2012/2013	Santa Maria	09/22* – 11/03* – 12/02* – 02/06*	Irrigated
2013/2014	Santa Maria	09/27 – 11/15 – 02/19	Irrigated
	Frederico Westphalen	11/23	Non-irrigated
	Júlio de Castilhos	11/18	Non-irrigated
	Tupanciretã	11/17	Non-irrigated
	Água Santa	11/18 – 12/03	Non-irrigated
	Restinga Seca	11/14	Non-irrigated
2014/2015	Santa Maria	11/15	Non-irrigated
	Água Santa[1]	11/08	Non-irrigated
	Restinga Seca[1]	11/13	Non-irrigated
	Tupanciretã[1]	10/27	Non-irrigated
	Cachoeirinha[2]	10/04 – 11/19 - 12/12	Non-irrigated
2016/2017	Itaqui[2]	11/04 – 12/02 – 01/03 – 01/19	Non-irrigated
2017/2018	Santa Maria	08/05 – 09/02 – 10/17 – 11/21 – 12/19 – 01/16 – 02/16 – 03/22	Irrigated
	Santa Maria[2]	10/05 - 11/30 – 01/10	Non-irrigated
	Júlio de Castilhos[1]	10/30	Irrigated
	Cruz Alta[1]	11/03	Irrigated
	Itaqui[2]	11/08 – 12/19 – 01/18	Non-irrigated
2018/2019	Santa Maria	08/17 – 10/23 – 01/24	Irrigated
	Santa Maria[2]	10/24	Non-irrigated
	Júlio de Castilhos[1]	10/20	Irrigated
	Cruz Alta[1]	11/20	Non-irrigated

*Experiments used for calibration; [1]Experiments conducted in commercial crops; [2]Lowlands. The other locations are highlands

Table 2. Soybean cultivars used in the calibration/validation of the node appearance model

Cultivar	RMG[1]	Growth-type	Location
HO 3998 STS	3.9	Indeterminate	Santa Maria
NS 4823 RR*	4.8	Indeterminate	Santa Maria, Restinga Seca, Frederico Westphalen, Júlio de Castilhos, Cachoeirinha, Itaqui, Tupanciretã, Água Santa
BMX Raio IPRO	5.0	Indeterminate	Santa Maria, Júlio de Castilhos
TMG 7161 RR INOX	5.4	Indeterminate	Santa Maria, Restinga Seca, Tupanciretã, Água Santa, Frederico Westphalen, Júlio de Castilhos
DM 53I54 IPRO	5.4	Indeterminate	Júlio de Castilhos
TEC 5936 IPRO	5.5	Indeterminate	Santa Maria, Restinga Seca, Água Santa, Frederico Westphalen, Júlio de Castilhos, Cachoeirinha, Tupanciretã
BMX Energia RR*	5.5	Indeterminate	Santa Maria, Restinga Seca, Frederico Westphalen, Júlio de Castilhos, Tupanciretã, Água Santa
Pionner 95R51 RR	5.5	Indeterminate	Água Santa, Júlio de Castilhos
BMX Elite IPRO	5.5	Indeterminate	Santa Maria, Itaqui
BMX Ativa RR	5.6	Determinate	Júlio de Castilhos
DM 5958 IPRO	5.8	Indeterminate	Santa Maria
BMX Lança IPRO	5.8	Indeterminate	Itaqui, Cruz Alta
Fundacep 65 RR	5.9	Determinate	Cachoeirinha
BMX Delta IPRO	5.9	Indeterminate	Santa Maria
BMX Turbo RR*	6.0	Indeterminate	Santa Maria, Restinga Seca, Frederico Westphalen, Tupanciretã
NS 6262 RG	6.2	Indeterminate	Restinga Seca
TMG 7062 IPRO	6.2	Semi-determinate	Santa Maria, Itaqui
NA 5909 RG*	6.3	Indeterminate	Santa Maria, Restinga Seca, Água Santa, Frederico Westphalen, Júlio de Castilhos, Tupanciretã
TEC IRGA 6070 RR	6.3	Indeterminate	Cachoeirinha, Itaqui
NIDERA 6411 RG	6.4	Determinate	Cachoeirinha
IAS 5*	6.4	Determinate	Santa Maria, Água Santa, Frederico Westphalen, Júlio de Castilhos, Tupanciretã
BS IRGA 1642 IPRO	6.4	Indeterminate	Itaqui
BMX Compacta IPRO	6.5	Indeterminate	Cruz Alta
Igra RA 518 RR*	6.6	Semi-determinate	Santa Maria, Restinga Seca, Água Santa, Frederico Westphalen, Júlio de Castilhos, Tupanciretã
BMX Potência RR*	6.7	Indeterminate	Santa Maria, Restinga Seca, Água Santa, Frederico Westphalen, Júlio de Castilhos, Tupanciretã
BMX Valente RR	6.7	Indeterminate	Cachoeirinha
BMX Ícone IPRO	6.8	Indeterminate	Santa Maria, Itaqui
CD 2694 IPRO	6.9	Determinate	Itaqui
Fepagro 36 RR*	7.2	Determinate	Santa Maria, Restinga Seca, Água Santa, Frederico Westphalen, Júlio de Castilhos, Tupanciretã
BRS 246 RR*	7.2	Determinate	Santa Maria, Restinga Seca, Água Santa, Frederico Westphalen, Júlio de Castilhos, Tupanciretã
BRAGG*	7.3	Determinate	Santa Maria, Água Santa, Frederico Westphalen, Júlio de Castilhos, Tupanciretã
TEC 7849 IPRO	7.8	Indeterminate	Santa Maria, Itaqui
SYN 1378	8.0	Determinate	Itaqui
CD 219 RR*	8.2	Determinate	Santa Maria, Restinga Seca, Água Santa, Frederico Westphalen, Júlio de Castilhos, Tupanciretã, Cachoeirinha
MONSOY 8372 IPRO	8.3	Indeterminate	Santa Maria

*Cultivars used for calibration; [1]RMG - Relative maturity group of the cultivar

The experiments were designed in randomized blocks, with four replicates, and the cultivars were the treatments. The row spacing was 0.45 m, and the plant density was 30 plants m^{-2} in all locations. The management followed the recommended practices for soybeans in Southern Brazil. Weeds, diseases, and pests have been controlled to keep the crop free from biotic stresses.

The emergence date (VE) was considered in each plot when 50% of the total plants had cotyledons above the ground. In each plot, from five to eight plants were randomly selected right after the first pair of unifoliate leaves was visible. These plants were identified, and the number of visible nodes was counted. A visible node was considered when the trifoliolate above it no longer had the edges of the leaflets touching (Fehr & Caviness, 1977). The number of nodes accumulated and the vegetative stages on the main stem followed Fehr & Caviness (1977) scale.

The node appearance in Soydev is simulated with a multiplicative model and a non-linear response functions to temperature and chronology, following the approach of the Wang & Engel (1998) model, with two components: genotype and environment. The number of nodes (NN) of the main stem (Eq. 1) is calculated by accumulating the values of the daily rate of nodes appearance (NAR) (Eq. 2), starting on the date of the emergence.

$$NN = \sum NAR \quad (1)$$

$$NAR = NAR_{MAX} f(T) CF \quad (2)$$

where:

NAR - daily node appearance rate on the main stem (nodes per day);

NAR_{MAX} - maximum daily node appearance rate on the main stem (nodes per day);

f (T) - non-linear temperature response function (0-1); and,

CF - chronological function to reduce the appearance rate.

The NAR equation (Eq. 2) was simplified by Streck et al. (2009) so that the chronology function was considered 1. The non-linear temperature response function [f (T)] in the node appearance model is a beta function (Eq. 3).

$$f(T) = \frac{\left[2(T_{MED} - T_{MIN})^{\alpha}(T_{OPT} - T_{MIN})^{\alpha} - (T_{MED} - T_{MIN})^{2\alpha}\right]}{(T_{OPT} - T_{MIN})^{2\alpha}} \quad (3)$$

$$\alpha = \frac{\ln 2}{\ln\left[\left(T_{MAX} - T_{MIN}\right) / \left(T_{OPT} - T_{MIN}\right)\right]} \quad (4)$$

where:

T_{MIN} - minimum temperature, below which the development rate is zero (°C);

T_{MAX} - maximum temperature, above which the development rate is zero (°C);

T_{OPT} - optimal temperature, at which the development rate is optimal (°C);

T_{MED} - average daily air temperature (°C); and,

α - shape factor of the beta function (Eq. 4).

Cardinal temperatures T_{MIN}, T_{MAX}, and T_{OPT}, are 7.6, 40, and 31 °C, respectively (Setiyono et al., 2007). The node appearance model was calibrated for three versions regarding the calculation of f(T) (Eq. 3):

Version 1 (Tmean) - the average daily air temperature (T_{MED}) used in f(T) is the arithmetic mean of the minimum and maximum daily air temperature;

Version 2 (Tmm) - separately calculated an f(T) with the minimum daily air temperature [f(T)min] and a function with the maximum daily air temperature [f(T)max] and then the average of the f(T)min and f(T)max was calculated;

Version 3 (Thmean) - the average daily air temperature (T_{MED}) in the calculation of f(T) was obtained by averaging the minimum and maximum hourly air temperatures.

For the calibration of the node appearance model, the maximum daily node appearance rate (NAR_{MAX}), which is the genetic coefficient dependent on the cultivar, was calibrated for 11 cultivars (Table 2) and for six sowing dates from September to February (Table 1). The NAR_{MAX} calibration was performed using the least-squares method of the residue, between the number of observed and simulated nodes (Xue et al., 2004), in the three versions of the node appearance model.

From the specific calibration of the cultivars, three equations were generated to calculate the NAR_{MAX} according to the relative maturity group (RMG): a general equation that does not consider the type of growth, an equation for cultivars with a determinate growth type, and another equation for cultivars with indeterminate growth type, for each version of the node appearance model. The simulations of NN with each equation were compared with independent data (not used for model calibration) of NN from experiments and crops, under irrigated and non-irrigated conditions, high and lowland environments, and different sowing dates (Table 1) and RMG (Table 2).

Six statistics were used to validate the performance of the node appearance model and its versions: Root Mean Square Error (RMSE) (Janssen & Heuberger, 1995) (Eq. 5), Normalized Root Mean Square Error (NRMSE) (Janseen & Heuberger, 1995) (Eq. 6), Systematic Mean Square Error (MSEs) (Eq. 7) and Unsystematic Mean Square Error (MSEu) (Willmott, 1981) (Eq. 8), “BIAS” index (Wallach, 2006) (Eq. 9), and correlation coefficient (r) (Schneider, 1998) (Eq. 10).

$$RMSE = \left[\frac{\sum (S_i - O_i)^2}{n}\right]^{0.5} \quad (5)$$

$$NRMSE = \frac{\sqrt{\frac{\sum (S_i - O_i)^2}{n}}}{\sum \frac{O_i}{n}} 100 \quad (6)$$

$$MSEs = \left[\frac{\sum (\hat{S} - O_i)^2}{n}\right] \cdot \frac{100}{\left[\frac{\sum (S_i - O_i)^2}{n}\right]} \quad (7)$$

$$MSEu = \left[\frac{\sum (S_i - \hat{S})^2}{n}\right] \cdot \frac{100}{\left[\frac{\sum (S_i - O_i)^2}{n}\right]} \quad (8)$$

$$BIAS = \frac{\left(\sum S_i - \sum O_i\right)}{\sum O_i} \quad (9)$$

$$r = \frac{\left[\sum (O_i - \bar{O})(S_i - \hat{S})\right]}{\left\{\left[\sum (O_i - \bar{O})^2\right]\left[\sum (S_i - \hat{S})^2\right]\right\}^{0.5}} \quad (10)$$

where:

S_i - simulated value;

O_i - observed value;

$\hat{S}$ - mean of simulated values;

$\bar{O}$ - mean of observed values; and,

n - number of observations.

Results and Discussion

The variation in weather conditions among years and sowing dates is shown in Figure 1. For the Tmean version, the general equation, the equation for cultivars with indeterminate growth type, and the equation for cultivars with determinate growth type are in Eqs. 11, 12, and 13, respectively. For the Tmm version, the three equations can be seen in Eqs. 14, 15, and 16; for the Thmean version, they are Eqs. 17, 18, and 19.

a) Tmean version

General equation (Eq. 11):

$$NAR_{MAX} = -0.0048x^2 + 0.0749x + 0.0524 \quad (11)$$

(R^2 = 0.4450, p-value for the angular coefficient = 0.364 and p-value for the linear coefficient = 0.277)

Equation for the cultivars with indeterminate growth type (Eq. 12):

$$NAR_{MAX} = 0.0112x + 0.2536 \quad (12)$$

(R^2 = 0.3053 and p-value = 0.3342)

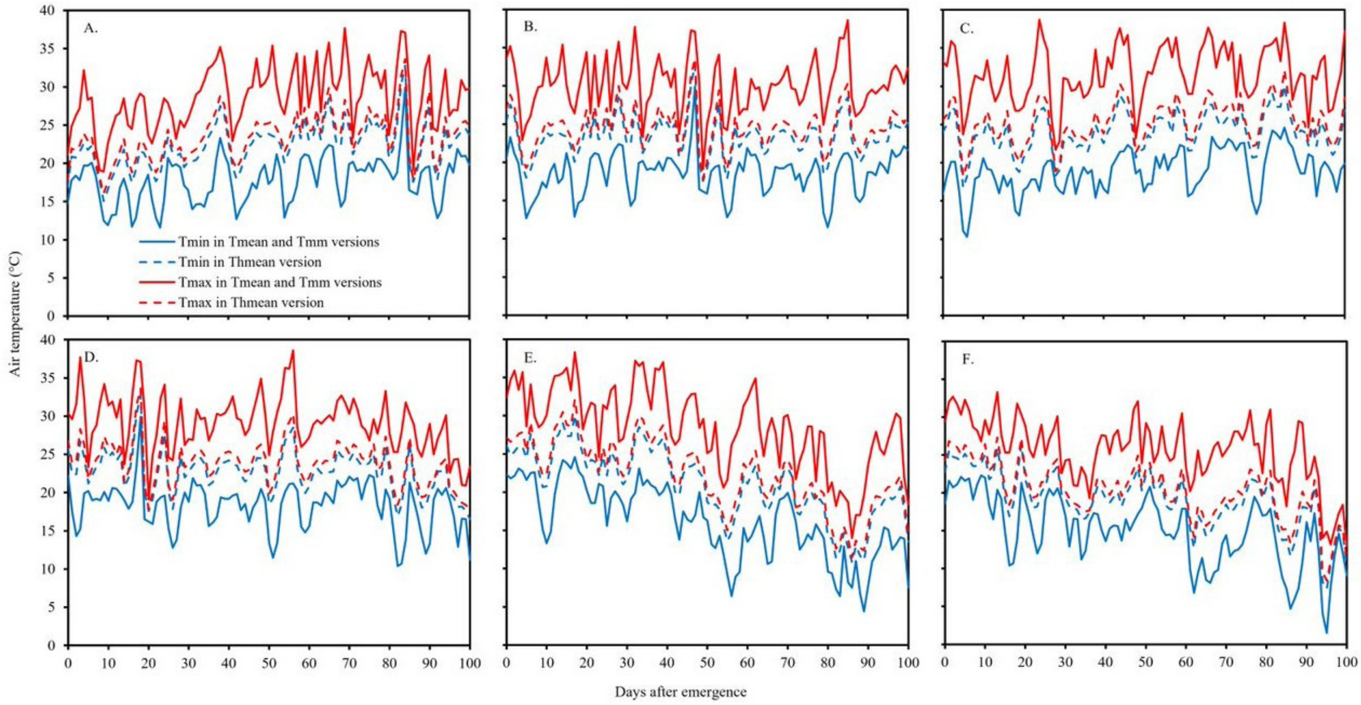


Figure 1. Minimum and maximum daily air temperature during the vegetative phase at sowing on 22/09/12 (A), 03/11/12 (B), 19/11/11 (C), 02/12/2012 (D), 28/01/12 (E), and 02/06/13 (F) used in the calibration of the three versions of the model, Santa Maria, RS, Brazil

Equation for the cultivars with determinate growth type (Eq. 13):

$$NAR_{MAX} = -0.0071x + 0.4000 \quad (13)$$

(R^2 = 0.1384 and p-value = 0.4678)

b) Tmm version

General equation (Eq. 14):

$$NAR_{MAX} = -0.0061x^2 + 0.0935x + 0.0331 \quad (14)$$

(R^2 = 0.4614, p-value from the angular coefficient = 0.283 and p-value from the linear coefficient = 0.212)

Equation for the cultivars with indeterminate growth type (Eq. 15):

$$NAR_{MAX} = 0.0144x + 0.2775 \quad (15)$$

(R^2 = 0.3619 and p-value = 0.2832)

Equation for the cultivars with determinate growth type (Eq. 16):

$$NAR_{MAX} = -0.0086x + 0.4548 \quad (16)$$

(R^2 = 0.1633 and p-value = 0.4268)

c) Thmean version

General equation (Eq. 17):

$$NAR_{MAX} = -0.0048x^2 + 0.0759x + 0.0599 \quad (17)$$

(R^2 = 0.4492, p-value for the angular coefficient = 0.380 and p-value from the linear coefficient = 0.288)

Equation for the cultivars with indeterminate growth type (Eq. 18):

$$NAR_{MAX} = 0.0114x + 0.2643 \quad (18)$$

(R^2 = 0.2964 and p-value= 0.3427)

Equation for the cultivars with determinate growth type (Eq. 19):

$$NAR_{MAX} = -0.0070x + 0.4235 \quad (19)$$

(R^2 = 0.1357 and p-value = 0.4725)

where, x is the relative maturity group (RMG) of the cultivar.

A summary of the maximum, minimum, and average temperature, during the vegetative phase, in each location used to validate the model versions is in Table 3.

Among the model versions, Tmm had the lowest RMSE and NRMSE, both for the general equation (RMSE = 1.15 nodes and NRSME = 14.79%), and for the equation according to the type of growth (RMSE = 1.19 nodes and NRMSE = 15.34%) (Figure 2B and 2E). Decomposing the SME into systematic (MSEs) and unsystematic (MSEu) of the Tmm version and general equation, the MSEs was 28.41%, and the MSEu was 71.59% (Figure 2B), indicating that random errors prevail. Cera et al. (2017) found RMSE for the number of soybean nodes from 0.60 to 0.70 nodes. Setiyono et al. (2007) reported RMSE from 0.30 to 1.50 nodes for 22 cultivars using specific cultivar calibration. Uhlmann et al. (2017) found RMSE from 0.30 to 0.70 leaves to simulate the number of gladiolus leaves, which indicates that the three versions of the model have the RMSE

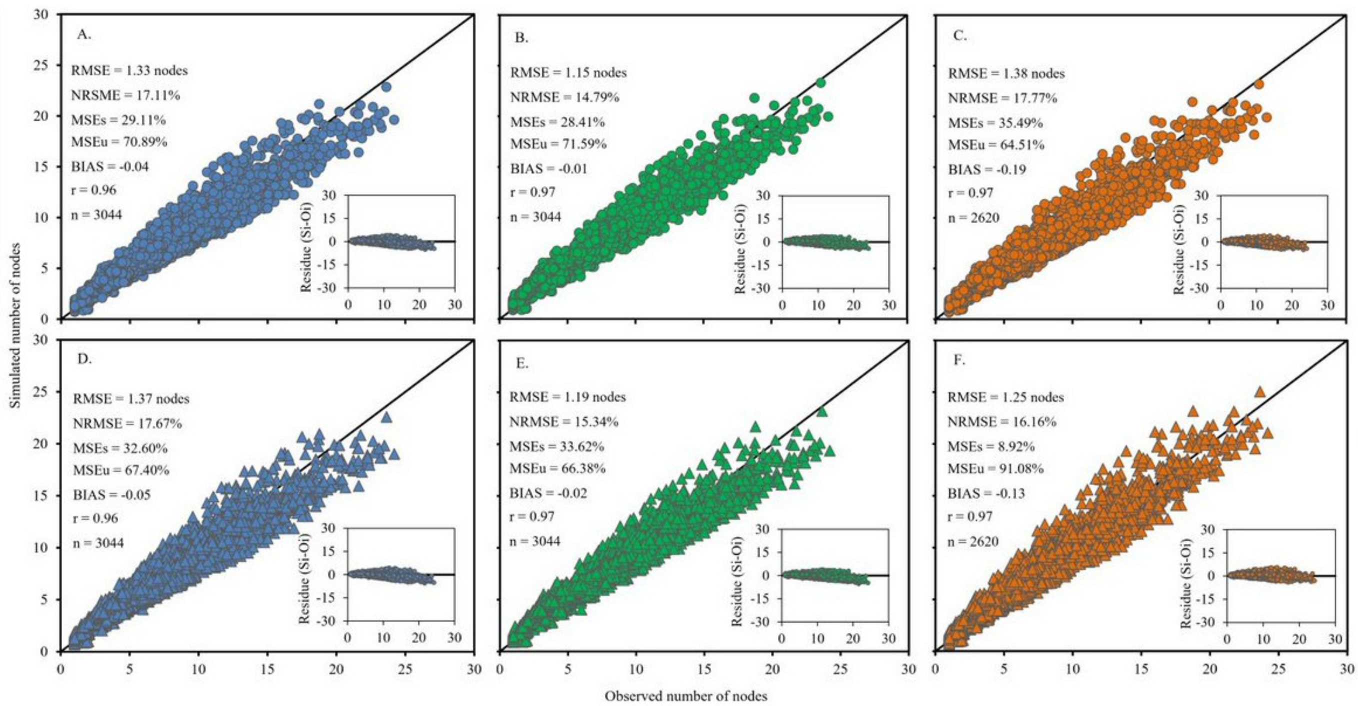
Table 3. Maximum (TMA), minimum (TMI), and mean (TM) air temperature, rainfall, and irrigation during the vegetative phase of soybean cultivars in the experiments from 2010 to 2018 used to validate the three versions of the model (Tmean, Tmm, Thmean)

Location	Sowing date	Tmean and Tmm			Thmean			Rainfall (mm)	Irrigation (Mm)	Weather station
		TMA	TMI	TM	TMA	TMI	TM			
		(°C)								
Água Santa	18/11/2013	35.90	12.60	24.25	28.47	16.64	22.55	410.80	-	INMET[1]
	03/12/2013	35.90	12.60	24.25	28.47	16.64	22.55	472.20	-	
	08/11/2014	34.51	9.46	21.98	25.93	15.78	20.86	715.40	-	
Cachoeirinha	12/10/2014	37.68	11.36	24.52	29.71	17.79	23.75	499.40	-	UFSM
	24/11/2014	37.46	12.58	25.02	29.71	18.96	24.34	540.00	-	
	12/12/2014	37.46	12.58	25.02	29.71	18.96	24.34	524.80	-	
Cruz Alta	03/11/2017	35.50	7.90	21.70	28.20	14.75	21.48	630.00	30.00	INMET
	20/11/2018	36.22	9.11	22.67	29.99	15.50	22.75	583.20	-	UFSM
Frederico Westphalen	23/11/2013	36.80	12.30	24.55	29.58	17.51	23.55	564.60	-	INMET
Itaqui	04/11/2016	36.90	9.20	23.05	-	-	-	550.40	-	UFSM
	12/12/2016	36.90	12.80	24.85	-	-	-	578.60	-	
	13/01/2017	35.50	12.80	24.15	-	-	-	885.40	-	
	30/01/2017	35.30	12.80	24.05	-	-	-	1048.60	-	
	08/11/2017	38.60	10.70	24.65	-	-	-	364.80	-	
	19/12/2017	35.40	11.90	23.65	-	-	-	479.80	-	
	18/01/2018	35.20	11.90	23.55	-	-	-	333.60	-	
Júlio de Castilhos	18/11/2013	37.50	11.00	24.25	-	-	-	369.25	-	INMET
	30/10/2017	35.70	8.00	21.85	29.28	14.73	22.01	569.00	30.00	INMET[2]
	20/10/2018	36.40	8.50	22.45	30.19	15.14	22.66	864.20	27.80	INMET[2]
Restinga Seca	14/11/2013	40.00	14.90	27.45	32.60	18.57	25.59	374.80	-	INMET[3]
	20/11/2014	36.20	13.40	24.80	29.59	18.72	24.15	649.80	-	
Santa Maria	10/12/2010	36.20	12.30	24.25	28.85	17.37	23.11	402.6	0.00	INMET
	08/01/2011	36.20	7.00	21.60	28.85	12.53	20.69	479.4	0.00	
	24/09/2011	39.00	9.00	24.00	30.35	14.52	22.43	265.20	140.00	
	27/09/2013	38.80	8.30	23.55	31.01	14.67	22.84	600.40	7.40	
	15/11/2013	40.00	14.90	27.45	32.60	18.57	25.59	373.40	109.70	
	19/02/2014	34.70	4.70	19.70	27.47	8.31	17.89	637.40	0.00	
	15/11/2014	36.20	13.40	24.80	29.59	18.72	24.15	646.00	0.00	
	05/08/2017	36.50	2.30	19.40	29.00	8.17	18.59	640.20	0.00	
	02/09/2017	38.60	7.10	22.85	29.50	13.88	21.69	455.60	19.05	
	05/10/2017	38.60	7.10	22.85	29.50	14.08	21.79	422.20	-	
	17/10/2017	38.60	8.80	23.70	29.50	16.07	22.78	339.80	75.33	
	21/11/2017	38.60	13.00	25.80	29.50	19.18	24.34	355.00	110.29	
	30/11/2017	38.60	10.30	24.45	29.82	17.76	23.79	395.60	-	
	19/12/2017	36.60	10.30	23.45	29.82	16.46	23.14	473.60	105.84	
	10/01/2018	36.60	10.30	23.45	29.82	16.46	23.14	470.40	-	
	16/01/2018	36.60	10.30	23.45	29.82	16.46	23.14	556.80	52.86	
	16/02/2018	36.60	2.40	19.50	29.82	8.48	19.15	437.00	56.19	
	22/03/2018	35.20	-0.90	17.15	29.81	4.45	17.13	264.00	2.72	
	17/08/2018	35.20	7.50	21.35	29.27	12.33	20.80	598.00	23.96	
	17/08/2018	35.20	7.50	21.35	29.27	12.33	20.80	598.00	16.67	
	23/10/2018	38.60	10.00	24.30	31.53	16.61	24.07	616.00	17.82	
	24/10/2018	38.60	10.00	24.30	31.53	16.61	24.07	616.00	-	
	24/01/2019	37.10	10.50	23.80	31.09	16.17	23.63	517.80	13.89	
Tupanciretã	17/11/2013	37.50	11.00	24.25	-	-	-	358.50	-	INMET[4]
	27/10/2014	35.09	9.32	22.20	28.03	16.12	22.08	430.20	-	UFSM

[1]Weather station located in Passo Fundo; [2]Weather station located in Tupanciretã; [3]Weather station located in Santa Maria; [4]Weather station located in Júlio de Castilhos; INMET - National Institute of Meteorology; UFSM - Federal University of Santa Maria. Tmean - Version 1 of the model where the average daily air temperature (T_{MED}) used in the temperature function [f(T)], was obtained by the arithmetic mean of the minimum and maximum daily air temperature values; Tmm - Version 2 of the model, where a temperature function with the minimum daily air temperature [f(T)min] and a function with the maximum daily air temperature [f(T)max] were calculated separately and then made the mean of the f(T) min and f(T)max; Thmean - Version 3 of the model, in which the average daily air temperature (T_{MED}) used to calculate the temperature function [f(T)], was obtained by averaging the minimum and maximum hourly air temperatures

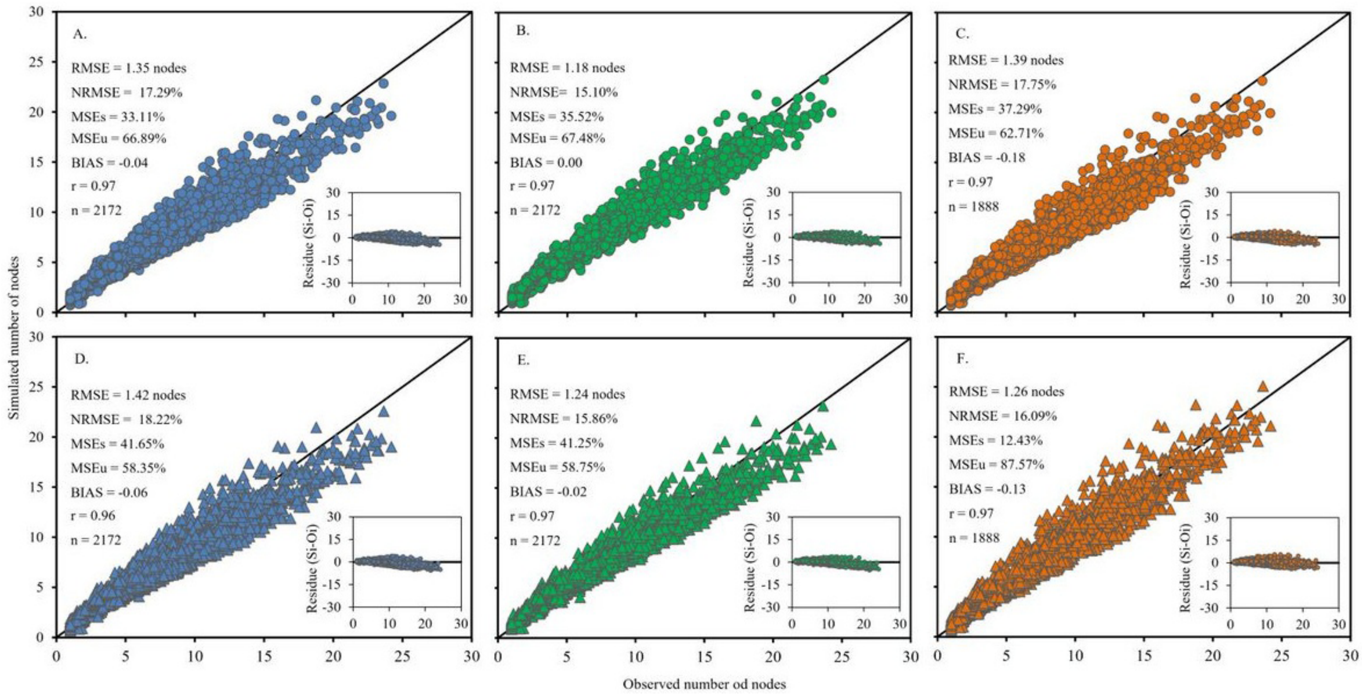
close to those found in the literature. The BIAS index that came closest to zero (-0.01) was that of the Tmm version of the model using the general equation (Figure 2B). The correlation coefficient (r) among versions and equations ranged from 0.96 to 0.97 (Figure 2). Despite the little difference in the simulation of the number of nodes between the model versions, there is an average gain of 0.20 nodes when using the Tmm version. The Tmm version uses the same database (maximum and minimum temperature) as the Tmean version; that is, the Tmm version of the model has a gain in precision in the NN simulation by calculating the f(T).

The response of the model versions and equations was the same for cultivars with indeterminate growth type. The Tmm version (Figures 3B and E) performed better (RMSE = 1.18 and 1.24 nodes; NRMSE = 15.10 and 15.86%) when compared to the Tmean version (RMSE = 1.35 and 1.42 nodes; NRMSE = 17.29 and 18.22%) (Figures 3A and D) and the Thmean version (RMSE = 1.39 and 1.26 nodes;



The blue color is the Tmean version (A, D), the green color is the Tmm version (B, E), and the orange color is the Thmean version (C, F). The circles are the numbers of nodes simulated with NAR_{MAX} obtained through the general equation (A, B, C), and the triangles are the numbers of nodes simulated by the equation according to the type of growth (D, E, F). The solid line is the 1:1 line. The inserts are the residues between the simulated and observed (Si - Oi)

Figure 2. Simulated versus the observed number of nodes for 35 soybean cultivars with indeterminate and determinate growth type, relative maturity group from 3.9 to 8.3, in seven harvests and nine locations from the Rio Grande do Sul, Brazil

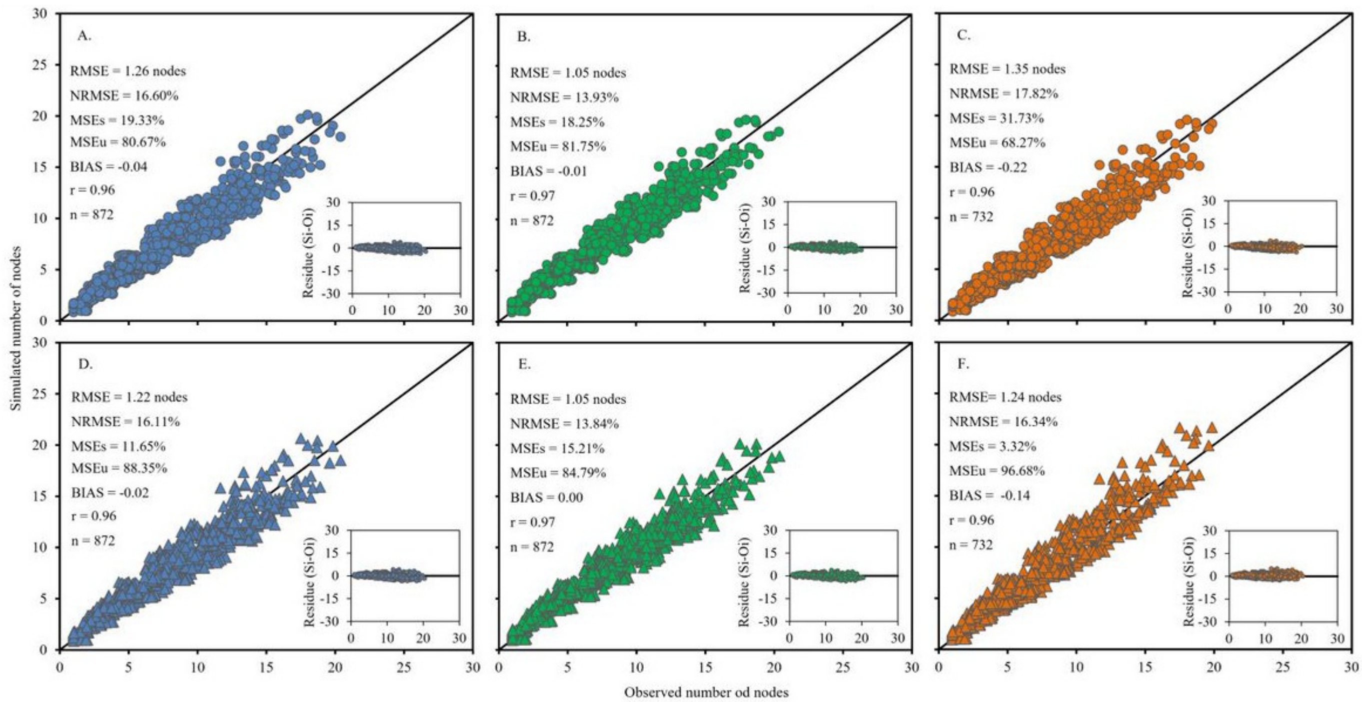


The blue color is the Tmean version (A, D), the green color is the Tmm version (B, E), and the orange color is the Thmean version (C, F). The circles are the numbers of nodes simulated with NAR_{MAX} obtained through the general equation (A, B, C), and the triangles are the numbers of nodes simulated by the equation according to the type of growth (D, E, F). The solid line is the 1:1 line. The inserts are the residues between the simulated and observed (Si – Oi)

Figure 3. Simulated versus the observed number of nodes for 24 soybean cultivars with indeterminate growth type, relative maturity group from 3.9 to 8.3, in seven harvests and nine locations from the Rio Grande do Sul, Brazil

NRMSE = 17.75 and 16.09%) (Figures 3C and F). In the Tmm version, the general equation (Figure 3B) had a better response than the equation for the indeterminate growth type (Figure 3E) in all statistical indexes; also, the BIAS index of 0.00 was obtained in the Tmm version and equation general (Figure 3B), indicating the model performance in simulating the number of nodes has no trend to overestimate or underestimate the simulation.

For cultivars with determinate growth type, the Tmm version (Figures 4B and E) showed the lowest RMSE and NRMSE (RMSE = 1.05 and 1.05 nodes; NRMSE = 13.93 and 13.84%). There was no difference between the RMSE in



The blue color is the Tmean version (A, D), the green color is the Tmm version (B, E), and the orange color is the Thmean version (C, F). The circles are the numbers of nodes simulated with NAR_{MAX} obtained through the general equation (A, B, C), and the triangles are the numbers of nodes simulated by the equation according to the type of growth (D, E, F). The solid line is the 1:1 line. The inserts are the residues between the simulated and observed (Si – Oi)

Figure 4. Simulated versus the observed number of nodes for 11 soybean cultivars with determinate growth type, relative maturity group from 3.9 to 8.3, in seven harvests and nine locations from the Rio Grande do Sul, Brazil

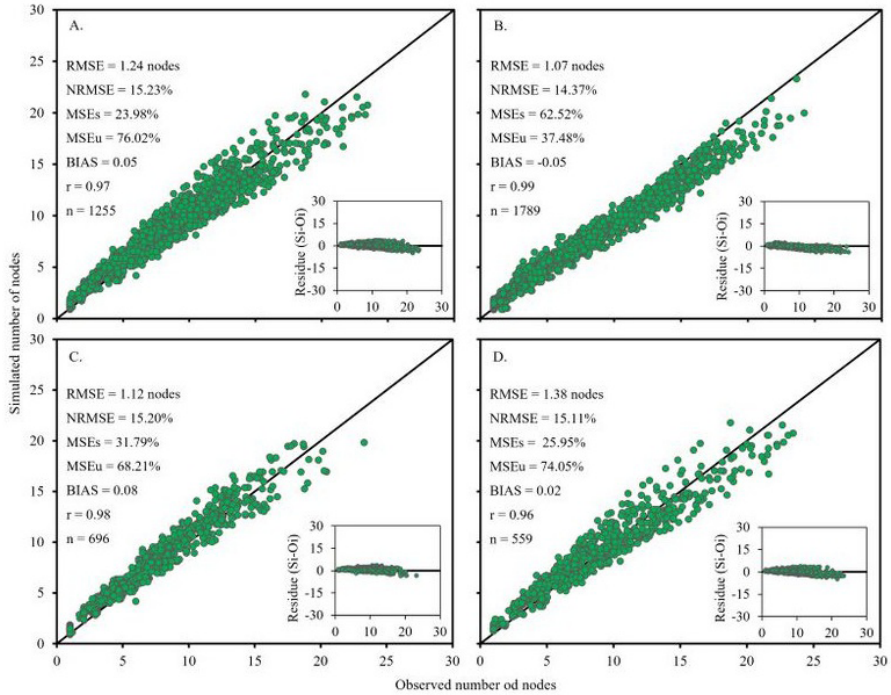
the Tmm version when comparing general and growth type equations. Streck et al. (2009) found an RMSE of 0.80 to 2.40 nodes for soybean cultivars of determinate growth, indicating that the RMSE in this study is following the literature. The systematic (MSEs) and unsystematic (MSEu) errors were 11-20 and 89-80%, respectively, for the Tmean and Tmm versions in both equations (general and growth type).

The results indicate that the NN simulation in soybean plants is improved using the Tmm version, when calculating a temperature function using only the minimum daily air temperature and a temperature function using only the maximum daily air temperature and then calculating the average of the two functions, instead of using the average air temperature as an input to the temperature function. Therefore, the hypothesis that calculating the temperature function in the node appearance model can improve the soybean NN simulation in Brazilian conditions is confirmed. Similar results have been reported for winter wheat (Xue et al., 2004), corn (Streck et al., 2008), and soybean (Streck et al., 2009).

Comparing the non-irrigated and irrigated experiments, the RMSE and NRMSE were 1.24 nodes and 15.24%, respectively, when not irrigated (Figure 5A) and 1.07 nodes and 14.37% when the system is irrigated (Figure 5B). The highest RMSE in the non-irrigated system may be related to the cultivation environment and not the water regime. In the studied data set, the non-irrigated system had both cultivation environments (highlands and lowlands), and the irrigated system had only data from the highland environment. When divided into non-irrigated in highlands (Figure 5C) and non-irrigated in lowlands (Figure 5D), the RMSE was 1.12 and 1.38 nodes, respectively, confirming that the highest RMSE refers to the growing environment of lowlands when not irrigated. Lowland soils have specificities, poor drainage compared to highland environments (Rocha et al., 2017). The cultivation of soybean in hydromorphic soils exposes plants to water stress, even in years with well-distributed rainfall during the growing season, due to the low water storage capacity of these soils (Rocha et al., 2017). Also, soils traditionally cultivated with irrigated rice present higher bulk density in the superficial layer, impairing the root growth of soybeans and decreasing their capacity to tolerate short periods of water deficit (Drescher et al., 2011). As a result, there is greater variability in the development of soybean plants in lowlands.

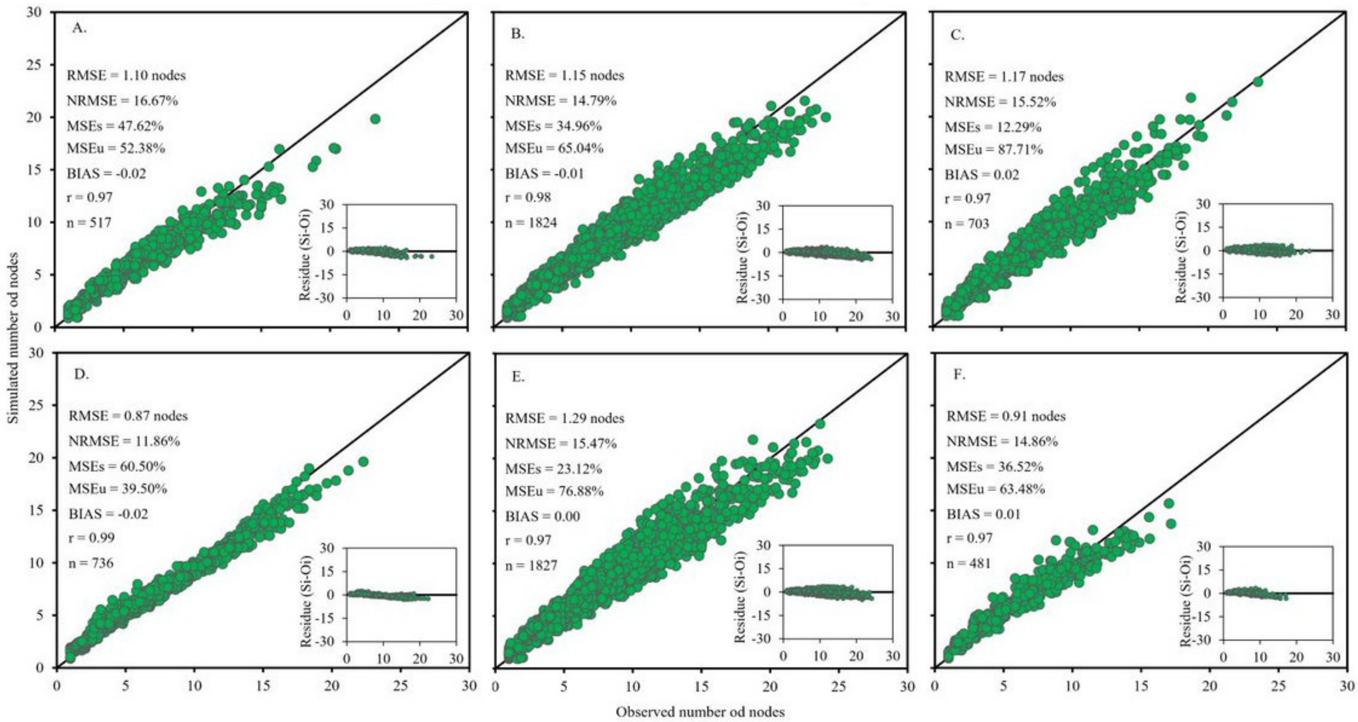
Although the non-irrigated (Figure 5C) and irrigated (Figure 5B) experiments in highlands show no difference in the RMSE, the systematic error (MSEs) was 62.52% in the irrigated experiments and 31.79% in the non-irrigated experiments in highlands, revealing an error that is not random in irrigated experiments, which must be further investigated and corrected. Besides, the negative BIAS index of -0.05 indicates an underestimation of the model, which may be associated with an excess of irrigation in the vegetative phase, quickly stimulating vegetative development and, consequently, causing plants to emit more nodes. Even with this variation in the RMSE among cultivation environments and water regime, the model shows satisfactory performance for both conditions and environments, within the range found by Setiyono et al. (2007) for 22 cultivars with specific cultivar calibration (RMSE from 0.30 to 1.50 nodes).

The cultivars were divided into three groups: RMG ≤ 5.5; 5.5 < RMG < 7 and RMG ≥ 7 to evaluate the simulation in the wide range of RMG (3.9 to 8.3). Cultivars with RMG ≤ 5.5 (Figure 6A) had the lowest RMSE (1.10 nodes) and cultivars



The solid line is the 1:1 line. The inserts are the residues between the simulated and observed (Si - Oi)

Figure 5. Number of simulated soy nodes with the Tmm version and general equation versus the number of nodes observed in non-irrigated experiments in low and high lands (A), irrigated experiments in high lands (B), non-irrigated experiments in high lands (C), and non-irrigated experiments in lowlands (D), in seven harvests and nine locations from the Rio Grande do Sul, Brazil



Cultivars with RMG ≤ 5.5 (A), 5.5 < RMG < 7 (B), RMG ≥ 7 (C). Soybean sowing in August/September (D), October/November/December (E), and January/February/March (F). The solid line is the 1:1 line. The inserts are the residues between the simulated and observed (Si - Oi)

Figure 6. Number of simulated soybean nodes with the Tmm version and general equation versus the number of observed nodes, grouped by RMG and sowing time

with RMG ≥ 7 (Figure 6C) had the highest RMSE (1.17 nodes), with little variation in the range of RMG, indicating the adequate performance of the general equation in calculating NAR_{MAX} by RMG.

There is a satisfactory response of the model in the simulation of the appearance of nodes in sowing from August to March, with the RMSE of 0.87 to 1.29 nodes (Figures 6D, E, and F). Even in sowing outside the calibration range, the model has an adequate response in the appearance of nodes, differing from the original version of Soydev. According to Cera et al. (2017), the errors increase considerably for sowing outside the calibration range.

The Tmm version of the model and the general equation used to calculate the NAR_{MAX} for each cultivar showed an adequate performance in simulating the appearance of nodes for cultivars with RMG from 3.9 to 8.3 in a subtropical environment, highland and lowland seasons, sowing times, and water regimes. The RMSE between the number of nodes observed and simulated by the Tmm model and general equation was 1.15 nodes. Considering that the NAR ranges according to the sowing season, this difference of 1.15 nodes in early sowing (September/October, NAR = 0.17 nodes per day) represents seven days and in later sowing (November/December/January, NAR = 0.24 nodes per day) this difference is five days.

The results indicate the robustness and adequate performance of the node appearance model using a general equation to calculate the NAR_{MAX} of the cultivars, which is important because it shows its reduced need for cultivar specific calibration. The node appearance model allows estimating the vegetative stage of the plant, thus being able to assist in the proper management at a given stage of soybean development. Also, the simulation of the number of nodes in soybean helps to identify characteristics such as optimum NN (Zanon et al., 2018) and optimum leaf area index (LAI) (Tagliapietra et al., 2018), which are important for choosing the best cultivars for each environment and sowing dates, aiming to achieve high yields.

Conclusions

1. The simulation of the number of nodes in soybean cultivars recommended for Southern Brazil is improved with the Tmm version, using a temperature function with the minimum daily air temperature and another with the maximum daily air temperature and then calculating the average of the two functions, instead of using the average air temperature.

2. In the Tmm version, the maximum daily node appearance rate (NAR_{MAX}) can be estimated by a general equation, regardless of the growth type, for cultivars with relative maturity group from 3.9 to 8.2, and determinate and indeterminate growth type, not requiring a specific cultivar calibration.

Literature Cited

Cera, J. C.; Streck, N. A.; Yang, H.; Zanon, A. J.; Lago, I. Extending the evaluation of the SoySim model to soybean cultivars with high maturation groups. Field Crops Research, v.201, p.162-174, 2017. https://doi.org/10.1016/j.fcr.2016.11.006

Drescher, M. S.; Eltz, F. L. F.; Denardin, J. E.; Faganello, A. Persistência do efeito de intervenções mecânicas para a descompactação de solos sob plantio direto. Revista Brasileira de Ciência do Solo, v.35, p.1713-1722, 2011. https://doi.org/10.1590/S0100-06832011000500026

Fehr, W. R.; Caviness, C. E. Stages of soybean development. Ames: Iowa State University of Science and Technology, 1977. 15p. Special Report, 80

Janssen, P. H. M.; Heuberguer, P. S. C. Calibration of process - Oriented models. Ecological Modelling, v.83, p.55-56, 1995. https://doi.org/10.1016/0304-3800(95)00084-9

Rocha, T. S. M. da; Streck, N. A.; Zanon, A. J.; Marcolin, E.; Petry, M. T.; Tagliapietra, E. L.; Balest, D. S.; Bexaira, K. P. Performance of soybean in hydromorphic and nonhydromorphic soil under irrigated or rainfed conditions. Pesquisa Agropecuária Brasileira, v.52, p.293-302, 2017. https://doi.org/10.1590/s0100-204x2017000500002

Schneider, P. R. Análise de regressão aplicada à engenharia florestal. 2. ed. Santa Maria: Ed. UFSM/CEPEF, 1998. 236p.

Setiyono, T. D.; Weiss, A.; Specht, J.; Bastidas, A. M.; Cassman, K. G.; Dobbermann, A. Understanding and modeling the effect of temperature and day length on soybean phenology under high-yield conditions. Field Crops Research, v.100, p.257-271, 2007. https://doi.org/10.1016/j.fcr.2006.07.011

Sinclair, T. R.; Neumaier, N.; Farias, J. R. B.; Nepomuceno, A. L. Comparison of vegetative development in soybean cultivars for low-latitude environments. Field Crops Research, v.92, p.53-59, 2005. https://doi.org/10.1016/j.fcr.2004.08.008

Streck, N. A.; Lago, I.; Gabriel; L. F.; Samboranha, F. K. Simulating maize phenology as a function of air temperature with a linear and a nonlinear model. Pesquisa Agropecuária Brasileira, v.43, p.449-455, 2008. https://doi.org/10.1590/S0100-204X2008000400002

Streck, N. A.; Paula, G. M. de; Oliveira, F. B.; Schwantes, A. P.; Menezes, N. L. Improving node number simulation in soybean. Pesquisa Agropecuária Brasileira, v.44, p.661-668, 2009. https://doi.org/10.1590/S0100-204X2009000700002

Tagliapietra, E. L.; Streck, N. A.; Rocha, T. S. M. da; Richter, G. L., Silva, M. R. da; Cera, J. C.; Guedes, J. V. C.; Zanon, A. J. Optimum leaf area index to reach soybean yield potential in subtropical environment. Agronomy Journal, v.110, p.932-938, 2018. https://doi.org/10.2134/agronj2017.09.0523

Uhlmann, L. O.; Streck, N. A.; Becker, C. C.; Schwab, N. T.; Benedetti, R. P.; Ccharão, A. S.; Ribeiro, B. S. M. R.; Silveira, W. B.; Backes, F. A. A. L.; Alberto, C. M.; Muttoni, M.; Paula, G. M.; Tomiozzo, R.; Bosco, L. C.; Becker, D. PhenoGlad: A model for simulating development in Gladiolus. European Journal of Agronomy, v.82, p.33-49, 2017. https://doi.org/10.1016/j.eja.2016.10.001

Wallach, D. Evaluating crop models. In: Wallach, D.; Makowski, D.; Jones, J. (eds.) Working with dynamic crop models: Evaluation, analysis, parameterization, and applications. Amsterdam: Elsevier, 2006. p.11-50.

Wang, E.; Engel, T. Simulation of phenological development of wheat crops. Agricultural Systems, v.58, p.1-24, 1998. https://doi.org/10.1016/S0308-521X(98)00028-6

Willmott, C. J. On the validation of models. Physical Geograph, v.2, p.184-194, 1981. https://doi.org/10.1080/02723646.1981.10642213

Xue, Q.; Weiss, A.; Baenziger, P. S. Predicting leaf appearance in field-grown winter wheat: Evaluating linear and non-linear models. Ecological Modelling, v.175, p.261-270, 2004. https://doi.org/10.1016/j.ecolmodel.2003.10.018

Zanon, A. J.; Silva, M. R. da; Tagliapietra, E. L.; Cera, J. C.; Bexaira, K. P.; Richter, G. L.; Duarte Júnior, A. J.; Rocha, T. S. M. da; Weber, P. S.; Streck, N. A. Ecofisiologia da soja: Visando altas produtividades. Santa Maria: Palloti, 2018. 136p.

Zanon, A. J.; Streck, N. A.; Richter, G. L.; Becker, C. C.; Rocha, T. S. M. da; Cera, J. C.; Winck, J. E. M.; Cardoso, A. P.; Tagliapietra, E. L.; Weber, P. S. Development of soybean cultivars as a function of maturation group and growth type in high lands and in lowlands. Bragantia, v.74, p.400-411, 2015. https://doi.org/10.1590/1678-4499.0463

Zanon, A. J.; Streck, N. A.; Rocha, T. S. M. da; Alberto, C. M.; Bartz, A. C.; Paula, G. M.; Tomiozzo, R. Costa, L; C. Fensterseifer, C. A.; Tagliapietra, E. L.; Cardoso, A. P.; Weber, P. S.; Bexaira, K. P. Growth habit effect on development of modern soybean cultivars after beginning of bloom in Rio Grande do Sul. Bragantia, v.75, p.445-458, 2016. https://doi.org/10.1590/1678-4499.535