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SCIENTIFIC NOTE

Soybean development and thermal requirement under the climatic conditions of Paragominas, Pará state, Brazil

Soma térmica da soja nas condições climáticas de Paragominas-Pará

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ABSTRACT: The degree-days or thermal time theory has been widely used to simulate crop development because of its simplicity; in addition, it represents a good indicator of crop phenological evolution compared with the days after sowing scale. We investigated the development and thermal requirements of soybean (*Glycine max* (L.) Merrill), BRS Tracajá cultivar, grown in an agricultural border area of advance in eastern Amazon. The field experiment was carried out in the 2007 and 2008 growing seasons in the municipality of Paragominas, Pará state, in a completely randomized experimental design at six sowing dates with three replicates. The soybean thermal time required, from emergence to flowering, at cardinal temperatures of 10, 31 and 40 °C was 642±70 degree-days and the thermal time of the Ve-R8 stage was 1,753±16 degree-days.

RESUMO: *A teoria dos graus-dia ou tempo térmico tem sido amplamente utilizada para simular o desenvolvimento de culturas pela simplicidade do método, além de representar um bom indicativo da evolução fenológica da cultura quando comparado à escala de dias após a semeadura. Avaliaram-se o desenvolvimento e a necessidade térmica da soja [*Glycine max *(L.) Merrill], cultivar BRS Tracajá, em uma área de avanço de fronteira agrícola na Amazônia Oriental. O experimento foi realizado durante a safra de 2007 no município de Paragominas-PA, usando-se um delineamento inteiramente ao acaso em três datas de semeadura com três repetições cada. O tempo térmico necessário para a soja atingir o florescimento em Paragominas-PA, considerando-se as temperaturas cardinais de 10, 31 e 40 °C, foi de 642±7 graus-dia e, para completar o ciclo total, foi de 1.753±16 graus-dia.*

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1 Introduction

Many studies show the strong dependence of soybean phenology on weather conditions (SCHOFFEL; VOLPE, 2002; SETIYONO et al., 2007; SINCLAIR et al., 2005). The degree-days (or thermal time) theory represents the amount of heat accumulated to which the plant is submitted throughout the day, or the daily accumulation of energy that lies between the limits supported by the plant, expressed as a function of its cardinal temperatures.

The optimum air temperature values for soybean growth and development are around 30-31 °C (SETIYONO et al., 2007), and there are significant effects on the growth rate and retention of legumes when soybean is exposed to temperatures greater than 40 °C (AVILA et al., 2013). Some studies report lower thresholds of 10 °C (AVILA et al., 2013), 11 °C (SINCLAIR et al., 2005) and 14 °C (SCHOFFEL; VOLPE, 2002) for soybean in Brazil.

Under adverse weather conditions with high temperatures, it is often possible to observe a linear decrease in crop development rate and degree-day accumulation as from an optimum temperature, with null development at the upper threshold temperature (STRECK et al., 2007, 2008). Functions such as the sawtooth model (FERREIRA et al., 1997), the triangle method (SNYDER et al., 1999), and the nonlinear or curvilinear models (SETIYONO et al., 2007) are commonly used to describe the reductive effect of elevated temperatures on plant development under such adverse weather conditions.

Although the degree-days theory represents an empirical model based on a linear relation between temperature and crop development (STRECK et al., 2008), it has been widely disseminated and accepted by the scientific community (SETIYONO et al., 2007), mainly because temperature is the meteorological variable that best explains statistically the duration of plant development stages (FERREIRA et al., 1997). Crop growth and development models should reliably simulate plant development, considering that many of the processes involved occur according to phenology (STRECK et al., 2009). For the case of soybean grown under the climatic conditions of northeastern Pará state, the knowledge of its thermal needs may be used by researchers and farmers as a tool in crop management and identification of main phenological stages, assisting in the decision-making process. In this study, we aimed to determine the thermal time requirements and the duration of the main phenological stages of soybean grown in northeastern Pará state.

2 Materials and Methods

The experiment was carried out during the 2007/2008 growing season in the municipality of Paragominas in the northeast region of the state of Pará, distant approximately 320 km from the state capital city, Belém. The experimental field occupied a 200 ha continuous soybean planting area (2° 59’ 08’’ S latitude; 47° 19’ 57’’ W longitude; 122 m above sea level). The soil used was conventionally tilled during the rainy season and was later mechanically sown with the BRS Tracajá cultivar, which is the most recommended for this region. The soil was fertilized with 640 kg ha^{-1} of the NPK 2-20-18 formulation at sowing.

Prior to sowing, the seeds were properly treated with inoculant (*rhizobium*), fungicide, and insecticide. Sowing was performed at seed density of 27±1 seeds per m^{-2} on the following dates: 01/23/2007 (2007a), 02/02/2007 (2007b), and 02/23/2007 (2007c). Sowing was also performed on two other dates, 02/20/2007 (2007d) and 02/07/2008 (2008), aiming to generate independent data to validate the simulation of occurrences of phenological stages. Herbicides and pesticides were used when necessary in all experiments. Plant population was 200,000 plants per ha^{-1} at 0.50 m spacing.

A three-meter high micrometeorological tower equipped with thermo-hygrometers (Vaisala, HMP35A, PT100 resistors) was installed in the center of the experimental area. The sensors were connected to a CR10X datalogger (Campbell Scientific, Inc.) and an AM416 multiplexer (Campbell Scientific, Inc.). Measures of air temperature and rainfall were taken every 10 seconds throughout the experiment, providing totals and means every 10 min.

Phenological assessment was performed daily using the scale described by Fehr and Caviness (PEREIRA, 2002). We used a completely randomized experimental design with three replicates for each treatment, represented by the sowing dates (2007a, 2007b, 2007c). Each replicate consisted of 10 two-meter long rows selected at random, comprising 20 plants on average, which were continuously monitored since emergence. The beginning of a particular phenological stage was defined as the time when 50% or more plants in the row reached the stage of development in question.

Thermal time was calculated using the sawtooth model (FERREIRA et al., 1997), which considers the reductive effect of high temperatures. This model is similar to one of the methods (method 3) described by Trentin et al. (2008) and Streck et al. (2007) and to the thermal time method used by Streck et al. (2008), which consider the existence of an optimum temperature above which the rate of development is reduced. The effective temperature was obtained by a reductive function of the upper developmental threshold when close to the optimum temperature, which causes null development for cases where air temperature different from the crop cardinal temperatures is observed (Equations 1 and 2):

$$T_e = T_t + f(T)(T_o - Tt) \tag{1}$$

$$f(T) = \begin{cases} \dfrac{T_{air} - T_t}{T_o - T_b} & T_t \le T_{air} \le T_o \\[2ex] \dfrac{T_T - T_{air}}{T_T - T_o} & T_o \le T_{air} \le T_T \\[2ex] 0 & \textit{Other cases} \end{cases} \tag{2}$$

where, T_{e} – effective temperature, T_t – lower threshold temperature, T_o – optimum temperature, T_T – upper threshold temperature, and T_{air} -mean air temperature.

The cardinal temperatures used were obtained from the literature (SETIYONO et al., 2007; AVILA et al., 2013), because environmental temperature variation was not sufficient to obtain values for the region studied. We adopted the following lower, optimum, and upper temperatures: 10, 31, and 40 °C, respectively. Thus, the thermal time accumulated (τ_T) in the daily scale was calculated as (Equation 3):

$$\tau_T = \sum_{i=1}^{n} \left(T_e - T_t\right) \quad (3)$$

The mean air temperature (T_{mean}) used in Equation 2 was obtained by the average between the maximum (T_{max}) and minimum (T_{min}) temperatures of the day because we consider that the daily extremes are an approximation of the trend of diurnal temperature (SNYDER et al., 1999), describing this way the temperature range to which the plant was subjected throughout the day.

Phenological and climatic data obtained in the two independent experiments were used to validate the occurrence of soybean phenological stages (in days of the year) simulated by a thermal time method similar to those from the studies conducted by Setiyono et al. (2007) and Streck et al. (2008). The root-mean-square error (RMSE) and the index of agreement (d) were the statistical criteria used to evaluate the performance of soybean development simulation.

3 Results and Discussion

According to the climatology of the area for the months of the experiment, rainfall ranges from 218 mm in January to a maximum of 366 mm in March, with a continuous decline in the following months, 331 mm in April and 184 mm in May (SOUZA et al., 2009). The 2007 experiments were subjected to less rainfall than the 2008 experiments (Table 1). Rainfall accumulated during the 2008 cycle was 1,253 mm, while the 2007 treatments were subjected to rainfall amounts 33 and 52 % smaller (Table 1). Despite this reduction in water supply in the 2007 treatments, total rainfall during crop cycle varied between 410 and 650 mm; these values are very similar to the minimum demand required for soybean – approximately 450 mm according to Avila et al. (2013), suggesting absence of severe water stress.

According to the climatology of air temperature for the region of Paragominas, maximum values of 32.7, 22.6 and 22.2 °C are found for the months of January, March and February, respectively; whereas the minimum values for the same months are 22.3, 22.6 and 22.2, respectively (SOUZA et al., 2009). Air temperature was higher in 2007 than in 2008, presenting mean values of approximately 25-26 °C and maximum values always below 32 °C. At all sowing dates, the values of air temperature were consistent with the limits borne by soybean – between 10 and 40 °C (AVILA et al., 2013). On the other hand, we often observed maximum temperatures above the 31 °C optimum temperature considered for this study (SETIYONO et al., 2007).

Results reported by Streck et al. (2007) show a reduction in plant growth in some phases of potato crop when subjected to supra-optimal thermal conditions, but they also show the significant influence of the photoperiod in this process. In spite of the high values of air temperature, the mean temperature throughout the experiment never exceeded the optimum temperature for soybean culture.

In northeastern Pará state, thermal time requirements ranged from 604 to 680 degree-days and from 1,685 to 1,770 degree-days for soybean flowering and harvest, respectively. Schoffel and Volpe (2002), when investigating different soybean cultivars in Jaboticabal, São Paulo state, obtained thermal time requirements between 1,211 and 1,598 degree-days from sowing to physiological maturity (R7), a variation below the one obtained for the region studied (1,635 to 1,694 degree-days).

This difference may have occurred because the authors worked with longer cycle (112 to 148 days) cultivars considering the period comprised between pre-emergence and maturation, and most importantly, they used a different T_t value (14 °C), which caused lower thermal time accumulation compared with this experiment. Although the mean temperature observed by Schoffel and Volpe (2002) in the different sub-periods varied between 23.6 and 25.3 °C, maximum values of 32.9 °C were observed and were limited to 32 °C by the method used by the authors.

Results obtained by Pereira (2002) under different conditions of water availability showed that soybean completed its cycle with thermal time requirement ranging between 1,455 and 1,600 degree-days, presenting lower requirement when subjected to water stress in both sub-periods - vegetative and reproductive. It is worth mentioning, though, that under water stress, the calculation method used in the degree-days theory needs to be modified to suit such situations (MASSIGNAM; ANGELOCCI, 1993); this detail was not considered by the author. On the other hand, this relation loses its reliability only in cases of prolonged or extreme water stress (SENTELHAS et al., 1994); therefore, this fact did not occur in this experiment considering that rainfall totals in the cycle were always above the minimum required by the culture.

Table 1. Average weather conditions during the harvest-sowing period and degree-days accumulated by soybean under each treatment for the Emergence-Flowering (Em-Flo) and Emergence-R7 (Em-R7) periods.

Stages	Meteorological variables				Accumulation of thermal time	
	Rainfall (mm)	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	(Em–Flo) (degree-days)	(Em–R7) (degree-days)
2007a	603	25.31 (±0.06)*	31.11 (±0.01)	22.41 (±0.01)	647.73 (±22.61)	1,639.36 (±2.25)
2007b	573	25.30 (±0.06)	30.84 (±0.12)	22.21 (±0.06)	647.66 (±0.002)	1,693.57 (±0.25)
2007c	410.4	25.37 (±0.06)	31.10 (±0.10)	21.92 (±0.08)	630.59 (±5.69)	1,647.12 (±5.65)
2007d	431.8	25.36 (±0.06)	31.00 (±0.11)	22.00 (±0.07)	613.82 (±5.54)	1,617.64 (±20.88)
2008	1,253	25.16 (±0.07)	31.09 (±0.12)	21.94 (±0.06)	575.26 (±7.37)	1,601.45 (±4.83)

*Standard error of estimate.

Hydric and thermal conditions were appropriate for crop development during the entire period of soybean growth in the field. Although water availability was reduced in 2007, the values for fraction of transpirable soil water were always above 0.5 (SOUZA et al., 2009), which indicates that water restriction was not enough to cause serious physiological impacts on the culture (SINCLAIR; MUCHOW, 2001).

Excluding the effects of water stress and possibly of high temperatures, it is assumed that the linear relation between growth rate and temperature remains crescent; but, actually, a decrease in this growth rate is observed above optimum temperature (FERREIRA et al., 1997; STRECK et al., 2008). Despite the differences between the various experiments presented, if we consider the distinct methods used, the empiricism behind these methods, and the strong dependence of this theory on the thermal regime to which the plant is subjected, we realize that it is coherent to compare experiments with similar thermal conditions (BONHOMME, 2000).

Table 2 shows the mean thermal time required for some phenological stages of soybean grown in northeastern Pará state. It is possible to observe that the greatest variation is found in the very beginning of plant development. The likely reason for this is associated with to the fact that the ground is still bare and the main controlling element of development in this period is soil temperature (TRENTIN et al., 2008). Under the climatic conditions of the region where the experiment was conducted, soybeans require around 642±7 degree-days to achieve flowering and, on average, 1,660±9 degree-days to reach physiological maturity. These outcomes can be used in simulation models of soybean growth and yield for eastern Amazon as identifiers of the development of this culture.

Mean duration (in days) of occurrence of the phases obtained in this study (Table 2) are in agreement with Xavier et al. (2008), who observed a period of 100.7 days for the maturation of cultivar BRS Tracajá in the municipality of Parnaiba, Piaui state in the 2005/2006 growing season. Flowering occurred 39±1.2 days after emergence (DAE), and 101±2.1 DAE, on average, were needed for physiological maturity. Despite the small variability of weather conditions throughout the days between the different sowing dates, air temperature was the main reason for the difference in days observed between dates, indicating the necessity to adopt thermal time instead of the days after sowing scale for identification of crop phenology.

The values of soybean (cultivar BRS Tracajá) thermal time requirement obtained in the experiments (2007a – 2007b – 2007c) were used in the simulation of soybean phenology and validation was performed with data from the independent experiments (2007d e 2008), whose results are shown in Figure 1 and Table 3.

Simulation based on thermal time requirement reproduced soybean phenology very well, presenting root-mean-square errors (RMSE) smaller than four days - close to those obtained with more complex models for different soybean cultivars (SETIYONO et al., 2007).

The fact that the 2008 experiment received greater amount of rainfall than the 2007 experiment may have contributed to this error, because the water surplus may have affected crop development (AVILA et al., 2013); nevertheless, several studies have suggested significant effects only under severe water stress (MASSIGNAM; ANGELOCCI, 1993; SENTELHAS et al., 1994). Although simulations of the stages of grain filling and physiological maturation have presented

Table 2. Statistics of thermal time accumulation and duration (in days after emergence) of occurrence of some phenological stages of soybean grown in Paragominas, Pará state.

Stages	Accumulation of thermal time (duration in days after emergence)			
	Mean	Standard deviation	Standard error	CV (%)
V_1	137.60 (8.18)	10.72 (0.4)	3.57 (0.64)	7.79 (4.94)
V_5	397.63 (24.17)	40.88 (2.08)	13.63 (0.85)	10.28 (8.61)
R_1	641.99 (39.00)	21.91 (1.21)	7.30 (0.51)	3.41 (3.09)
R_3	843.17 (51.50)	34.99 (2.20)	11.66 (0.60)	4.15 (4.26)
R_5	1,066.66 (65.25)	43.32 (2.22)	14.44 (0.53)	4.06 (3.40)
R_6	1,442.40 (87.17)	22.49 (1.34)	7.49 (0.36)	1.56 (1.53)
R_7	1,660.02 (100.83)	25.93 (2.08)	8.64 (0.41)	1.56 (2.06)
R_8	1,740.86 (106.11)	34.31 (2.93)	11.43 (0.48)	1.97 (2.77)

Table 3. Statistical performance of soybean cycle simulation during the validation process.

Duration	Statistical parameters				
	$\overline{O}$ (days)	n	$\overline{P}$ (days)	d	dif(%)
Em-V_5	24.0±1.0	7	24.67±0.58	0.66	+2.8
Em-R_1	37.0±1.5	7	39.57±0.53	0.32	+6.9
Em-R_3	51.14±1.6	7	51.57±0.53	0.57	+0.84
Em-R_5	63.71±3.0	7	65.57±0.53	0.32	+2.9
Em-R_7	98.14±1.5	7	100.86±0.38	0.42	+2.8
Em-R_8	106.43±1.5	7	106.86±0.38	0.82	+0.94

$\overline{O}$ = observed mean ± standard deviation; $\overline{P}$ = simulated mean ± standard deviation; n = number of data; dif=(P-O)/O; d = index of agreement.

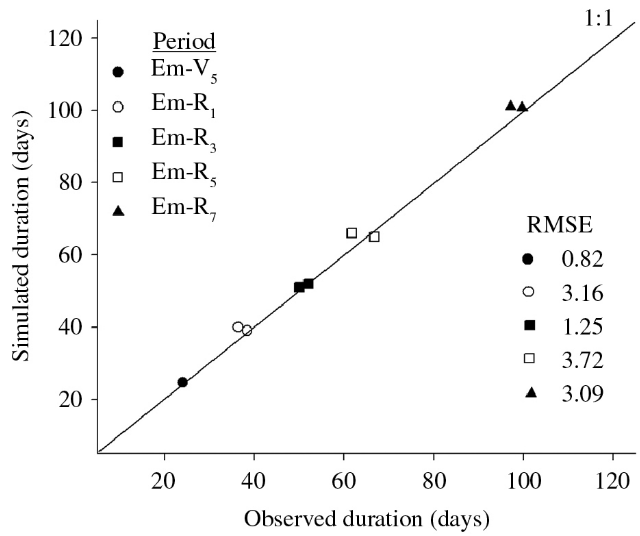

Figure 1. Soybean phenology observed and simulated during the experiment - 2007d and 2008.

RMSE of 3.5 days (Figure 1), this error corresponds to an over-estimation of less than 3% (Table 3).

Simulation of soybean development according to meteorological variables, either by simple linear models or more complex ones, has been conducted very efficiently and results are satisfactory in predicting its phenology (SETIYONO et al., 2007; STRECK et al., 2009). A good estimate of this phase by the model is important, because some models of soybean growth and yield adopt this phase as a starting point for the growth of grains through the linear increase in harvest index. Thus, the more accurate the simulation the more precise the duration of the grain filling phase, contributing to a better estimate of crop final yield.

4 Conclusions

Soybean BRS Tracajá cultivar required between 1,685 and 1,770 degree-days until harvest in the northeast region of Pará state considering cardinal temperatures of 10, 31 and 40 °C. Validation of soybean phenology simulation by the thermal time theory has proved to be an efficient method for the conditions of the area studied.

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