Scientific article

Evaluation of different methods for estimating thermal time requirements for phenological phases of Norteño chickpea (*Cicer arietinum* L.) cultivar

Evaluación de diferentes métodos para la estimación del requerimiento en tiempo térmico de fases fenológicas de garbanzo (*Cicer arietinum* L.) cv. Norteño

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Abstract

Expressing the duration of the phenological phases of crops as thermal time, more specifically as growing degree-days (GDD), is a widely used method. Its advantage derives from the fact that GDD data is independent from the temperature variations normally recorded during crop cycles. Even though more modern tools are currently available, traditional methods continue to be used to estimate GDD. This work aimed to: i) propose a new alternative for estimating GDD, called “actual curve”; and ii) estimate the thermal time required for the development of the phenological phases of a cultivar grown in Argentina. Kabuli-type Norteño chickpea cultivar was sown according to a completely randomized design with 4 replications, on the following sowing dates: April 15, May 23, June 14, July 7, and August 5, 2016. The new methodology was compared to 6 traditional methods for estimating GDD, which presented different accuracy and complexity levels. The actual curve method proved to be adequately precise and highly simple, and led to GDD results that differed from those obtained by means of the other methodologies. With this new alternative, it was found that the thermal time required for Norteño chickpea to reach emergence, the beginning of flowering, pod formation, grain filling, and physiological maturity amounted to 110.6, 784.1, 1002.4, 1161.1, and 1746.8 °C/days, respectively.

Keywords: Actual curve; Growing degree-days; Predictive model.

Resumen

Expresar la duración de las fases fenológicas de un cultivo en tiempo térmico, medido en grados días de desarrollo (GDD), es un método ampliamente utilizado. La importancia que representa el dato de los GDD radica en su independencia de las variaciones de temperatura registradas durante el ciclo del cultivo. A pesar de su gran utilidad, se continúan empleando metodologías tradicionales para su estimación, aunque en la actualidad se dispone de nuevas herramientas. Los objetivos de este trabajo fueron: i) proponer una nueva alternativa para la estimación de los GDD, llamada “curva actual”; y ii) estimar el requerimiento en tiempo térmico de las fases fenológicas de una variedad de garbanzo utilizada en Argentina. Se sembró garbanzo tipo kabuli, cultivar Norteño, según un diseño completamente aleatorizado con 4 repeticiones, en las siguientes fechas: 15 de abril, 23 de mayo, 14 de junio, 7 de julio y 5 de agosto de 2016. La nueva metodología fue comparada con 6 metodologías tradicionales de estimación de los GDD, con diferentes niveles de complejidad y precisión. El método “curva actual” presentó adecuados niveles de precisión y elevada simpleza, con diferencias en la estimación de los GDD con respecto a los métodos tradicionales. Utilizando esta nueva alternativa de estimación de los GDD, el cv. Norteño presentó un requerimiento en tiempo térmico de 110,6; 784,1; 1002,4; 1161,1 y 1746,8 °C/días para alcanzar las fases fenológicas de emergencia, inicio de floración, formación de vaina, llenado de grano y madurez fisiológica, respectivamente.

Palabras clave: Curva actual; Grados días de desarrollo; Modelo predictor.

Introduction

Argentina produced about 137.244 t of chickpea in 2019, ranking 13th among the main producing countries worldwide (FAOSTAT, 2019; De Bernardi, 2020). In recent years, chickpea became the third legume in economic importance in the country, which has contributed to Argentina becoming a reference country, and to the consolidation of chickpea production and marketing structures (De Bernardi, 2020). Eight cultivars are available in our country, including Norteño, which is chosen for its seed size and tolerance to cold.

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In the main chickpea production areas in the world, it has been observed that among the environmental variables that affect crop development, temperature, soil humidity, and photoperiod have an outstanding impact (Singh and Virmani, 1996; Soltani *et al.*, 1999; Verghis *et al.*, 1999; Daba *et al.*, 2016; Ray *et al.*, 2020). Soltani *et al.* (2006a) and Ahmed *et al.* (2011) found a good association between the emergence-flowering stage and temperature combined with photoperiod in chickpea. They also discovered that photoperiod had no effect on the rate of progress of phenological stages that follow the beginning of flowering. Likewise, Daba *et al.* (2016) reported a different response to photoperiod, classifying groups of chickpea as highly sensitive, moderately sensitive, and insensitive to photoperiod.

However, it was found that some chickpea varieties show the best correlation between the rate of progress of different phenological stages and temperature (Singh and Virmani, 1996; Krishnamurthy *et al.*, 1999; Verghis *et al.*, 1999; Soltani *et al.*, 2006b; Chand *et al.*, 2010; Purushothaman *et al.*, 2014).

In the case of crops whose development is not affected by photoperiod, temperature is the environmental condition that regulates the rate of progress of phenological phases (Roberts *et al.*, 1985; Atkinson and Porter, 1996; Soltani *et al.*, 1999; Verghis *et al.*, 1999; Trudgill *et al.*, 2005; Soltani *et al.*, 2006a; Unigarro *et al.*, 2017; Bas-Nahas and Romero, 2020).

The duration of the different phenological phases of a crop can be expressed in either calendar days or thermal time. When expressed in calendar days (e.g. days after sowing - DAS), information characteristic of the place and year in which data was obtained is generated, since temperature variations registered among different sites or years of production modify the rate of progress of phenological phases and, consequently, different DAS values are obtained.

When expressing the duration of phenological phases in thermal time (e.g. growing degree-days - GDD), values are independent from temperature variations recorded during crop development, which results in information that can be valuable for production in different areas, and when different sowing dates (SD) are chosen (Zalom *et al.*, 1983; Atkinson and Porter, 1996; McMaster and Wilhelm, 1997; Verghis *et al.*, 1999; Trudgill *et al.*, 2005; Gan *et al.*, 2006; Soltani *et al.*, 2006b). Likewise, GDD data allows estimating the duration of each phenological phase or cycle length, which in turn is useful for deciding on crop management practices.

Currently, there are various GDD estimation methods available, but they show differing accuracy and complexity levels depending on which cyclical pattern they use to simulate daily temperature variation (i.e., rectangular, triangular or sinusoidal) (Allen, 1976; Zalom *et al.*, 1983; McMaster and Wilhelm, 1997; Soltani *et al.*, 2006b; Rodríguez Caicedo *et al.*, 2012; Unigarro *et al.*, 2017).

Nowadays, most research and production centers have automatic weather stations that allow obtaining accurate data about environmental variables every 15 to 30 minutes. In addition, there are software programs, which calculate the area under the curve quickly and with high accuracy, following Midpoint, Trapezoid or Simpson's rule.

In spite of the usefulness of thermal time requirement data, little information is available about new alternatives for its estimation. Therefore, this work aimed to evaluate the accuracy of a new alternative for estimating thermal time, apart from determining thermal time requirements for different phenological stages of chickpea cv. Norteño.

Materials and methods

Agricultural management and experimental design

Our trials were conducted in an experimental field in Finca El Manantial, which belongs to Facultad de Agronomía y Zootecnia (Universidad Nacional de Tucumán), and is located in Tucumán, Argentina (26º 50' 6.9'' S – 65º 16' 44.6'' W).

The field was sown with kabuli-type chickpea seeds of Norteño cultivar (59 g/100 seeds), which is characterized by having a semi-erect and indeterminate growth habit, imparipinnate leaves, white flowers, and cream colour seeds (Reginatto *et al.*, 2016). No information is available on the effect of photoperiod on the progress of the phenological stages of this cultivar.

The seeds were treated with Carbendazim + Thiram (625 cc/100 kg of seeds) and inoculated with *Mesorhizobium ciceri* (200 cc/50 kg of seeds), before being sown by hand in plots of six 13-meter-long rows, spaced 0.5 m apart, with a

5 cm sowing depth and a 26 seed/m^2 density. A completely randomized design with 4 replications was followed in setting the trial, and the SD were April 15, May 23, June 14, July 7, and August 5, 2016, which were thus selected to create different temperature regimes.

In order to avoid water stress, which would modify the rate of progress of the phenological phases (Singh, 1991; Bonhomme, 2000), the trial was conducted under irrigation, and the weight of an undisturbed soil sample at field capacity was used as a reference.

The lowest photoperiod value recorded at the experimental site (11.5 h) was higher than the base photoperiod reported for chickpea by Soltani *et al*. (2006a) and Verghis *et al*. (1999), whose values are 10.27 h and 10 h, respectively. Likewise, the sowing dates chosen for the trial registered a photoperiod variation of 1.5 h (during the phenological phase that is sensitive to this environmental variable). For this reason, temperature was considered as the variable that influences the rate of progress of phenological phases.

During the trial, daily ambient temperature was recorded from April to December with an automatic Davis Vantage Pro2 weather station with wireless transmission, which was located 1000 meters away from the experimental site. This station recorded temperature every 30 minutes, so 48 daily values were registered, and these were used to calculate daily mean temperature (Tm) (Figure 1a).

Crop development

Three 1-meter linear samples were randomly selected from the central rows in each plot, and subjected to phenological evaluations every two days, from sowing to physiological maturity. The emergence phenological stage (Ve) was established as the time the plumular hook elongated over the ground. The beginning of flowering (R1) was determined when the first flower bloomed, regardless of its location in the plant. The beginning of pod formation (R3) was taken to be signaled by the development of the first 1 cm pod anywhere in the plant. The beginning of pod filling (R5) was established when at least one pod on the plant changed from a slightly flattened and not very rigid shape to a globular and rigid shape. Finally, it was considered that physiological maturity (R7) had been reached when 50% of pods on each plant had changed their color from green to yellow.

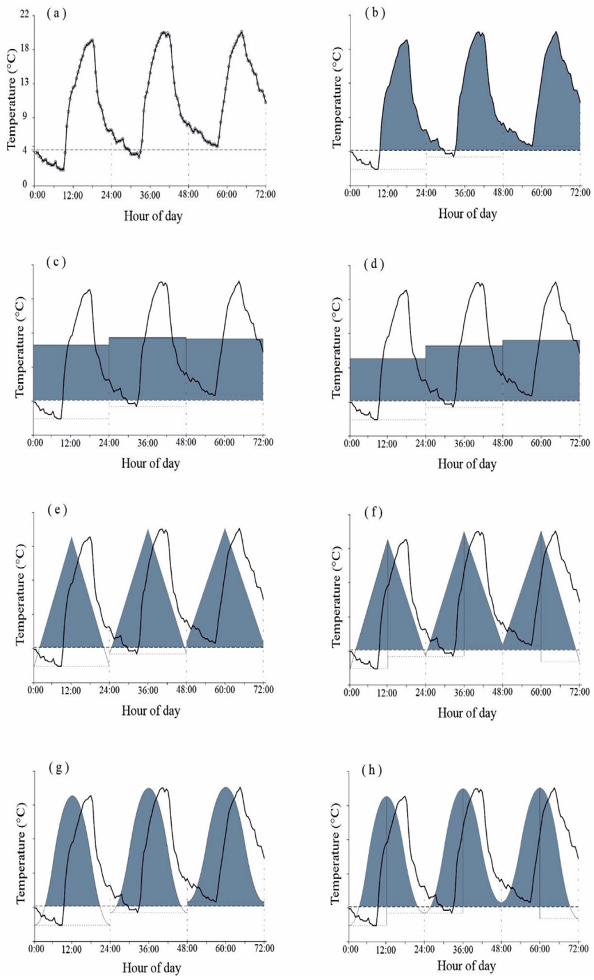

Figure 1. Temperature evolution over three days in June, based on records from the automatic weather station located near the trial site (a). Images b, c, d, e, f, g, and h represent the actual curve, average, modified average, single triangle, double triangle, single sine, and double sine methods, respectively. The dashed line shows base temperature for the Norteño cultivar (4.79 °C), and the dotted line shows minimum daily temperature.

Each sample was considered as having reached a phenological stage when 50% of the plants were observed as effectively being at that stage. Furthermore, the duration of each of the following phenological phases was recorded: sowing-emergence (S-Ve), sowing-beginning of flowering (S-R1), sowing-beginning of pod formation (S-R3), sowing-beginning of pod filling (S-R5), and sowing-physiological maturity (S-R7).

Thermal time

In order to determine the thermal time required for the different phenological phases of chickpea to develop, seven methods for estimating accumulated GDD were used, which are based on different temperature management criteria. Among the methods used, a new alternative for estimating GDD is presented, using Origin software. This new method is called "actual curve" (AC).

When estimating GDD, the base temperature (Tb) was taken to be 4.79 °C (Bas Nahas *et al.*, 2019) and was considered the lower threshold, whereas 40 °C was the upper threshold (Soltani *et al.*, 2006b).

Tm calculation criteria were as follows:

$Tm_{1\ i}$: day i mean temperature, as calculated with the average value of the 48 measurements made by the automatic weather station.

$Tm_{2\ i}$: day i mean temperature, calculated as the average value of the 48 daily measurements made by the automatic weather station. When the registered temperature was lower than Tb, such value was replaced with Tb (McMaster and Wilhelm, 1997), and if it was higher than the upper threshold, it was replaced with 40 °C.

$Tm_{3a\ i}$: day i mean temperature, calculated as the average value of the 24 daily measurements made by the automatic weather station during the first half of the day.

$Tm_{3b\ i}$: day i mean temperature, calculated with the average value of the 24 daily measurements made by the automatic weather station during the second half of the day. Tm_3 corresponds to mean Tm_{3a} and Tm_{3b} values.

All $T_{min\ i}$ and $T_{max\ i}$ values corresponded to minimum and maximum temperatures on day i, respectively. $T_{min(a,b)\ i}$ were the lowest temperatures recorded in the first (a) and second (b) half of the day.

The value of accumulated growing degree-days (ΣGDD, °C/d) in a period of n days was estimated incorporating the Tm criteria previously mentioned into the equations presented by Zalom *et al.* (1983). The equations were selected according to the thermal conditions at the site of the trial.

The average method (A) (Figure 1-c):

$$\Sigma GDD = \sum_{i=1}^{n}(T_{m1i} - T_b) \quad (1)$$

The modified average method (Am) (Figure 1-d):

$$\Sigma GDD = \sum_{i=1}^{n}(T_{m2i} - Tb) \quad (2)$$

The simple triangle method (ST) (Figure 1-e):

$$\Sigma GDD = \sum_{i=1}^{n} \frac{1}{12}\left(\frac{6\left((T_{max\,i} - Tb)^2\right)}{T_{max\,i} - T_{min\,i}}\right) \quad (3)$$

In this method, equation 1 was used for days on which Tmin i was not lower than Tb, and equation 3 was used when Tmin i dropped below Tb.

The double triangle method (DT) (Figure 1-f):

$$\Sigma GDD = \sum_{i=1}^{n} \frac{1}{2}[(T_{m3a\,i} - Tb) + (T_{m3b\,i} - Tb)] \quad (4)$$

$$\Sigma GDD = \sum_{i=1}^{n} \frac{1}{24}\left[\left(\frac{6\left((T_{max\,i} - Tb)^2\right)}{T_{max\,i} - T_{min\_a\,i}}\right) + \left(\frac{6\left((T_{max\,i} - Tb)^2\right)}{T_{max\,i} - T_{min\_b\,i}}\right)\right] \quad (5)$$

In this method, equation 4 was used when day i temperature was not lower than Tb, whereas equation 5 was considered when a temperature record at any time of day i was lower than Tb. For any day with a temperature record below Tb during either the first or second half, the first and second terms of equations 4 and 5 were combined.

The simple sine method (SS) (Figure 1-g):

$$\Sigma GDD = \sum_{i=1}^{n} \frac{1}{\pi}\left[(Tm_{1\,i} - Tb)\left(\frac{\pi}{2} - \theta\right) + \alpha\cos\theta\right] \quad (6)$$

Where:

$$\theta = \sin^{-1}\left[\frac{(Tb - Tm_{1\,i})}{\alpha}\right]; \alpha = \frac{T_{max\,i} - T_{min\,i}}{2}; \pi = 180°$$

In this method, equation 1 was employed when any temperature recorded during the day was not lower than Tb, whereas equation 6 was considered to deal with days when any temperature value was lower than Tb.

The double sine method (DS) (Figure 1-h):

$$\Sigma GDD = \sum_{i=1}^{n} \frac{1}{2\pi}\left\{\left[(Tm_{3a\,i} - Tb)\left(\frac{\pi}{2} - \theta_a\right) + \alpha_a\cos\theta_a\right] + \left[(Tm_{3b\,i} - Tb)\left(\frac{\pi}{2} - \theta_b\right) + \alpha_b\cos\theta_b\right]\right\} \quad (7)$$

Where:

$$\theta_{(a,b)} = \sin^{-1}\left[\frac{(Tb - Tm_{3(a,b)\,i})}{\alpha}\right]; \alpha_{(a,b)} = \frac{T_{max\ i} - T_{min(a,b)\,i}}{2}; \pi = 180°$$

In this method, equation 4 was used when temperature recorded at any time during the day was not inferior to Tb, whereas equation 7 was employed for days with temperature records below Tb. In the case of days with any temperature lower than Tb, during either the first or second half of the day, the first and second terms of equations 4 and 7 were combined.

The actual curve method (AC) (Figure 1-b):

The area under the real temperature evolution curve was determined by calculating its integral over the studied periods, using Origin software. A graph was built up using the daily temperature values recorded every 30 minutes on those n days required to reach each phenological phase, thus accurately illustrating the thermal evolution curve. The integral of the curve was then calculated, and the area beneath it was determined, without including spaces beyond development thresholds (Figure 1). Thus the ΣGDD of each phenological phase was obtained.

Days after sowing:

Fitted DAS (DASf) were obtained with the following equation:

$$\mathrm{DASf} = \frac{\overline{\Sigma\mathrm{GDD}}}{(\mathrm{Tm}-\mathrm{Tb})} \tag{8}$$

Mean ΣGGD ($\overline{\Sigma\mathrm{GDD}}$) values were calculated for each method and phenological phase. Mean temperature in equation 8 corresponded to $Tm_{1,2,3}$ depending on the method used for estimating $\overline{\Sigma\mathrm{GDD}}$. In other words, if $\overline{\Sigma\mathrm{GDD}}$ value was obtained with the double triangle method, Tm_3 was considered when calculating DASf by means of equation 8. When making this calculation using the AC method, Tm_2 had to be considered instead.

Data analysis

Data analysis was run using InfoStat software (Di Rienzo *et al*., 2020). An analysis of variance was carried out with general and mixed linear models, and the DGC test with (α = 0.05) was used to compare the means of the $\overline{\Sigma\mathrm{GDD}}$ values obtained with each method. Furthermore, a linear regression analysis was made between mean observed DAS ($\overline{\mathrm{DASo}}$) and fitted DAS ($\overline{\mathrm{DASf}}$) values. In all the cases, the statistical assumptions of each analysis were verified. The most accurate method was selected considering the refined index of agreement (dr) proposed by Willmott *et al.* (2012), the root mean square error (RMSE), the coefficient of determination (R^2), and the linear regression coefficients α and β.

Results

When the trial started, temperatures were high, but declined till July. Once this month was over, temperature began to rise until December. Days with minimum temperatures below the lower temperature threshold (4.79 °C) were registered, but there were no days with maximum temperatures rising over the upper threshold (40 °C) (Figure 2).

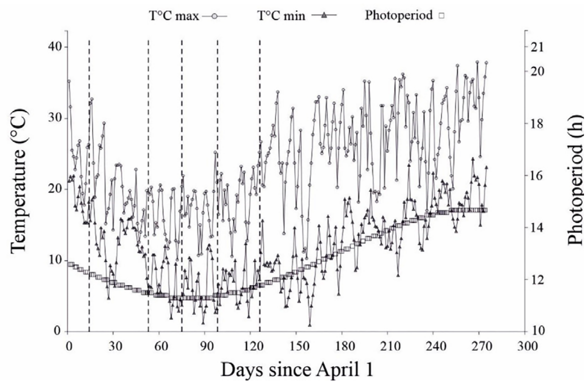

Figure 2. Maximum and minimum daily temperatures, and daily photoperiod recorded between April and December 2016, in Tucumán, Argentina. The dashed lines represent the five sowing dates selected for this study.

The mean thermal requirement value to reach the sowing-emergence phenological phase (S-Ve) ranged between 109.16 ± 1.76 and 116.34 ± 1.76 °C/d for the simple sine and double triangle methods, respectively (Table 1). No significant differences were found among the tested methods (F = 1.82; df_{error} = 129; P_{value} = 0.1010). Nor were there any significant differences among the methods with respect to $\overline{\Sigma\mathrm{GDD}}$ required for the S-R1 phase (F = 1.80; df_{error} = 129; P_{value} = 0.1038) (Table 1).

By contrast, significant differences were observed among the evaluated methods when estimating accumulated GDD necessary to reach S-R3, S-R5 and S-R7 phases (F = 35.10; df_{error} = 129; P_{value} < 0.0001) (F = 10.24; dferror = 129; Pvalue < 0.0001) (F = 8.85; df_{error} = 129; P_{value} < 0.0001) (Table 1). The average, modified average, simple triangle, and double triangle methods led to $\overline{\mathrm{DASf}}$ values slightly superior to mean DASo values for all these phenological phases (Table 2).

Mean DASf values obtained with the simple sine method were slightly inferior to $\overline{\mathrm{DASo}}$ with respect to number of days necessary to reach the phenological stages considered. The methods that gave mean DASf values similar to $\overline{\text{DASo}}$ in all the phenological stages were double sine and actual curve (Table 2).

Table 1. Mean accumulated growing degree-days values ($\overline{\Sigma \text{GDD}}$) ± standard error, required by Norteño chickpea to reach different phenological phases. These values correspond to an average of five sowing dates, from April to December in Tucumán (Argentina), and were obtained by different estimation methods.

Phenological phases	Accumulated $\overline{\Sigma \text{GDD}}$						
	Average (A)	**Modified average (Am)**	**Simple triangle (ST)**	**Double triangle (DT)**	**Simple sine (SS)**	**Double sine (DS)**	**Actual curve (AC)**
S-Ve	110.57 ± 1.76 a	111.88 ± 1.76 a	112.80 ± 1.76 a	116.34 ± 1.76 a	109.16 ± 1.76 a	113.59 ± 1.76 a	110.66 ± 1.76 a
S-R1	748.11 ± 13.83 a	756.94 ± 13.83 a	761.91 ± 13.83 a	787.79 ± 13.83 a	736.19 ± 13.83 a	768.48 ± 13.83 a	784.11 ± 13.83 a
S-R3	1000.98 ± 3.42 d	1010.37 ± 3.42 c	1015.68 ± 3.42 c	1049.41 ± 3.42 a	987.93 ± 3.42 e	1028.67 ± 3.42 b	1002.43 ± 3.42 d
S-R5	1159.68± 7.09 c	1169.61 ± 7.09 c	1175.08 ± 7.09 c	1213.77 ± 7.09 a	1145.89 ± 7.09 c	1192.05 ± 7.09 b	1161.10 ± 7.09 c
S-R7	1745.66 ± 9.63 b	1755.60 ± 9.63 b	1761.07 ± 9.63 b	1813.26 ± 9.63 a	1731.88 ± 9.63 b	1791.54 ± 9.63 a	1746.79 ± 9.63 b

S-Ve: sowing to emergence; S-R1: sowing to beginning of flowering; S-R3: sowing to beginning of pod formation; S-R5: sowing to beginning of grain filling; S-R7: sowing to physiological maturity.
Means followed by the same letter in each row are not significantly different according to the DGC test ($P > 0.05$).

RMSE and dr values were in agreement with a good fit between mean values of observed and fitted DASo in all the evaluated methods. The method that led to the lowest RMSE value and a dr close to 1 was double sine. The coefficient of determination R^2 presented high values (≈ 0.94) in all the methods, and with minimal variations among them.

Values of α were not significantly different from 0 in all the cases (A: T = 1.27; df_{error} = 98; P_{value} = 0.2231; Am: T = 1.27; df_{error} = 98; P_{value} = 0.2078; ST: T = 1.32; df_{error} = 98; P_{value} = 0.1915; DT: T = 1.34; df_{error} = 98; P_{value} = 0.1820; SS: T = 1.06; df_{error} = 98; P_{value} = 0.2910; DS: T = 1.15; df_{error} = 98; P_{value} = 0.2541; AC: T = 1.58; df_{error} = 98; P_{value} = 0.1185). β values were significantly different from 0 in all the cases (A: T = 38.66; df_{error} = 98; $P_{value} < 0.0001$; Am: T = 39.19; df_{error} = 98; $P_{value} < 0.0001$; ST: T = 38.60; df_{error} = 98; $P_{value} < 0.0001$; DT: T = 39.98; df_{error} = 98; $P_{value} < 0.0001$; SS: T = 39.24; df_{error} = 98; $P_{value} < 0.0001$; DS: T = 40.05; df_{error} = 98; $P_{value} < 0.0001$; AC: T = 38.85; df_{error} = 98; $P_{value} < 0.0001$).

Discussion

The estimation methods evaluated in this work led to significantly different $\overline{\Sigma \text{GDD}}$ results, and the contrasts were even bigger when lengthy periods were considered (S-R7). These divergences could be attributed to the fact that the methods use different daily cyclical patterns (rectangular, triangular, and sinusoidal) to simulate daily temperature evolution, and the formulae used in estimating GDD are based on these patterns (Zalom *et al*., 1983). In contrast, from S to Ve (approximately 12 days) no significant differences were revealed among $\overline{\Sigma \text{GDD}}$ values, possibly because during that period there was a minimal frequency of days with a temperature below Tb. Hence, the formulae used in estimating GDD gave similar values.

The average method (A) presented a good fit and, among the equations used in this study, it is the simplest one. Nonetheless, in places where days with a Tm lower than Tb are highly frequent, this method may lead to errors, as its GDD estimation includes temperatures at which plants may not present any activity, thus resulting in an overestimation of ΣGDD (McMaster and Wilhelm, 1997; Rodríguez Caicedo *et al*., 2012). Am, ST, and SS methods do not consider temperature values lower than Tb when estimating GDD, and Tm is calculated as an average of daily temperature

Table 2. Mean observed days after sowing ($\overline{\text{DASo}}$) and fitted days after sowing ($\overline{\text{DASf}}$) values ± standard error, required by Norteño chickpea to reach different phenological stages. These values correspond to an average of five sowing dates, from April to December in Tucumán (Argentina).

Phenological phases	$\overline{\text{DASo}}$	$\overline{\text{DASf}}$						
		Average (A)	Modified average (Am)	Simple triangle (ST)	Double triangle (DT)	Simple sine (SS)	Double sine (SD)	Actual curve (AC)
S-Ve	12.65 ± 0.84	12.82 ± 0.06	12.77 ± 0.03	12.88 ± 0.03	12.96 ± 0.04	12.46 ± 0.03	12.66 ± 0.03	12.63 ± 0.03
S-R1	84.25 ± 3.08	84.73 ± 0.83	84.68 ± 0.81	86.30 ± 0.84	85.83 ± 0.81	82.36 ± 0.79	83.73 ± 0.79	87.72 ± 0.84
S-R3	102.80 ± 4.04	103.79 ± 0.17	103.69 ± 0.14	105.32 ± 0.20	104.82 ± 0.16	101.39 ± 0.17	102.74 ± 0.16	102.88 ± 0.14
S-R5	114.10 ± 4.55	115.34 ± 0.27	115.23 ± 0.25	116.87 ± 0.29	116.35 ± 0.26	112.89 ± 0.26	114.27 ± 0.25	114.39 ± 0.25
S-R7	150.70 ± 3.92	151.74 ± 0.29	151.67 ± 0.27	153.08 ± 0.30	152.67 ± 0.27	149.62 ± 0.28	150.85 ± 0.27	150.91 ± 0.28
RMSE		1.21	1.192	1.233	1.184	1.187	1.162	1.198
dr		0.871	0.872	0.865	0.872	0.88	0.878	0.87
R^2		0.938	0.939	0.938	0.942	0.94	0.942	0.938
α		3.23 ± 2.63 *	3.29 ± 2.60 *	3.51 ± 2.67 *	3.45 ± 2.56 *	2.71 ± 2.55 *	2.90 ± 2.53 *	4.01 ± 2.47 *
β		0.97 ± 0.03	0.97 ± 0.03	0.98 ± 0.03	0.98 ± 0.03	0.96 ± 0.02	0.97 ± 0.02	0.96 ± 0.03

S-Ve: sowing to emergence; S-R1: sowing to beginning of flowering; S-R3: sowing to beginning of pod formation; S-R5: sowing to beginning of grain filling; S-R7: sowing to physiological maturity. RMSE: root mean square error; dr: refined index of agreement; R^2: coefficient of determination; α and β: linear regression coefficients. (*) indicates that β and α are not significantly different from 0 (P > 0.05).

records. DT and DS do not take temperature values that are below Tb, and when estimating GDD, Tm represents an average between the first and second half of the day, allowing for the possibility that minimum temperatures at dawn and nightfall might be different.

The AC methodology allows estimating GDD without including temperatures outside the development thresholds. Moreover, unlike the methods mentioned in the previous paragraph, the AC method estimates GDD using actual temperature variation values recorded in a certain period, since its calculations include temperature data supplied by automatic weather stations.

The $\overline{\Sigma\text{GDD}}$ values obtained in this work for the different phenological stages were similar to those reported by Verghis *et al*. (1999) for the Hernández chickpea variety. The differences might be due to Tb values themselves, and the methods used for estimating GDD. Furthermore, Gan *et al.* (2002) found a similar ΣGDD requirement for S-VE and R1-R7 phases in the Sanford variety, a kabuli-type chickpea cultivar, when using a Tb value of 5 °C.

Singh (1991), Chand *et al.* (2010), and Ray *et al.* (2020) obtained GDD values that differ from those presented in this article. Moreover, Thangwana and Ogola (2012) estimated a thermal requirement of 1150 °C/d to reach physiological maturity on summer and winter sowing dates. In both cases, the differences in ΣGDD values could be attributed to the use of a high Tb value in the estimation, and to the fact that a desi-type chickpea variety had been evaluated. This chickpea type differs from kabuli concerning the duration of reproductive and vegetative phases (Purushothaman *et al*., 2014).

When comparing fits between $\overline{\text{DASo}}$ and $\overline{\text{DASf}}$, it could be observed that all the evaluated methods had a good performance in predicting the number of days necessary to reach the phenological stages studied, but the DT, DS, and AC methods further contemplated physiological aspects (thermal thresholds) and temperature fluctuations between sunrise and nightfall.

It is necessary to point out that, among the evaluated methodologies, the AC method has proven to be an innovative alternative, which uses a software program to estimate thermal requirements. This estimation is made quickly, accurately, and following a simple procedure, based on calculating the area under the curve plotted with actual temperature data, which was recorded during a certain period.

Further research involving different environmental conditions and other chickpea varieties is necessary, so that the performance of the AC method can be evaluated in different thermal scenarios. In addition, it will be essential to validate fitted DAS against independent temperature data.

Conclusions

The methods considered in this study had a satisfactory performance as potential models for predicting days after sowing for the phenological phases of Norteño chickpea. However, if other factors are taken into account, such as procedural simplicity, quickness, and the reliance on the combination of a software tool and data provided by an automatic weather station, the actual curve method could be recommended for estimating accumulated growing degree-days. In this study, this estimation method revealed that, after sowing, the Norteño cultivar required 110.66 °C/d, 784.11 °C/d, 1002.43 °C/d, 1161.10 °C/d, and 1746.79 °C/d for the S-Ve, S-R1, S-R3, S-R5, and S-R7 phenological phases, respectively.

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References

Ahmed F., Islam M.N., Jahan M.A., Rahman M.T., Ali M.Z. (2011). Phenology, growth and yield of chickpea as influenced by weather variables under different sowing dates. Journal of Experimental Biosciences 2 (2): 83-88.

Allen J.C. (1976). Modified sine wave method of calculating degree days. Environmental Entomology 5: 388-96.

Atkinson D., Porter J.R. (1996). Temperature, plant development and crop yields. Trends in Plant Science 1 (4): 119-124.

Bas Nahas S.S., Interdonato R., Romero E.R. (2019). Estimating base temperature and thermal time requirement for chickpea (*Cicer arietinum* L.) emergence. Revista Agronómica del Noroeste Argentino 39 (1): 37-44.

Bas-Nahas S.S., Romero E.R. (2020). Influence of thermal factor on chickpea (*Cicer arietinum* L.) development, yield and yield components. Revista Agronómica del Noroeste Argentino 40 (1): 39-50.

Bonhomme R. (2000). Bases and limits to using 'degree day' units. European Journal of Agronomy 13: 1-10.

Chand M., Singh D., Roy N., Kumar V., Singh R.B. (2010). Effect of growing degree days on chickpea production in Bundelkhand region of Uttar Pradeshet. Journal of Food Legumes 23 (1): 41-43.

Daba K., Tar'an B., Warkentin T.D. (2016). Flowering response of diverse chickpea (*Cicer arietinum* L.) accessions to photoperiod. Genetic Resources and Crop Evolution 63: 1161-1172.

De Bernardi L.A. (2020). Perfil del Garbanzo (*Cicer arietinum* L.). In: https://magyp.gob.ar/sitio/areas/ss_mercados_agropecuarios/publicaciones/_archivos/000101_Perfiles/999980_Perfil%20del%20Garbanzo%202020.pdf, accessed: April 2021.

Di Rienzo J.A., Casanoves F., Balzarini M.G., Gonzalez L., Tablada M., Robledo C.W. (2020). InfoStat versión 2020. Centro de Transferencia InfoStat, FCA, Universidad Nacional de Córdoba, Argentina. URL http://www.infostat.com.ar

FAOSTAT (2019). Organización de las Naciones Unidas para la Alimentación y la Agricultura. http://www.fao.org/faostat/es/#data/QC, accessed: March 2021.

Gan Y.T., Miller P.R., Liu P.H., Stevenson F.C., McDonald C.L. (2002). Seedling emergence, pod development, and seed yields of chickpea and dry pea in a semiarid environment. Canadian Journal of Plant Science 82: 531-537.

Gan Y.T., Wang J., Poppy L.B. (2006). Node and branch development of chickpea in a semiarid environment. Canadian Journal of Plant Science 86: 1333-1337.

Krishnamurthy L., Johansen C., Sethi S.C. (1999). Investigation of factors determining genotypic differences in seed yield of non-irrigated and irrigated chickpeas using a physiological model of yield determination. Journal of Agronomy and Crop Science 183: 9-17.

McMaster G.S., Wilhelm W.W. (1997). Growing degree-days: one equation, two interpretations. Agricultural and Forest Meteorology 87: 291-300.

Purushothaman R., Upadhyaya H.D., Gaur P.M., Gowda C.L.L., Krishnamurthy L. (2014). Kabuli and desi chickpeas differ in their requirement for reproductive duration. Field Crops Research 163: 24 - 31.

Ray M., Sahoo K.C., Mohanty T.R., Mishra P., Mishra M., Sahoo S.K., Tudu S. (2020). Effect of climate change on productivity and profitability of chickpea cultivars under various dates of sowing in rice fallows. Current Journal of Applied Science and Technology 39 (31): 116-124.

Reginatto L., Toscano M., Castro R., Carreras J.J. (2016). Producción de semillas de garbanzo. En: El cultivo de garbanzo (*Cicer arietinum* L.) en Argentina. Carrera J., Mazzuferi V., Karlin M. (Eds). Universidad Nacional de Córdoba, Argentina. Pp. 271-291.

Roberts E.H., Hadley P., Summerfield R.J. (1985). Effects of temperature and photoperiod on flowering in chickpeas (*Cicer arietinum* L.). Annals of Botany 55: 881-892.

Rodríguez Caicedo D., Cotes Torres J.M., Cure J.R. (2012). Comparison of eight degree-days estimation methods in four agroecological regions in Colombia. Bragantia 71 (2): 299-307.

Singh P. (1991). Influence of water-deficits on phenology, growth and dry-matter allocation in chickpea (*Cicer arietinum*). Field Crops Research 28: l-15.

Singh P., Virmani S.M. (1996). Modeling growth and yield of chickpea (*Cicer arietinum* L.). Field Crops Research 46: 41-59.

Soltani A., Ghassemi-Golezani K., Khooie F.R., Moghaddam M. (1999). A simple model for chickpea growth and yield. Field Crops Research 62: 213-224.

Soltani A., Hammer G.L., Torabi B., Robertson M.J., Zeinali E. (2006a). Modeling chickpea growth and development: phenological development. Field Crops Research 99: 1-13.

Soltani A., Robertson M.J., Torabi B., Yousefi-Daz M., Sarparast R. (2006b). Modelling seedling emergence in chickpea as influenced by temperature and sowing depth. Agricultural and Forest Meteorology 138: 156-167.

Thangwana N.M., Ogola J.B.O. (2012). Yield and yield components of chickpea (*Cicer arietinum*): Response to genotype and planting density in summer and winter sowings. Journal of Food, Agriculture & Environment 10 (2): 710-715.

Trudgill D.L., Honek A., Li D., Van Straalen N.M. (2005). Thermal time – Concepts and utility. Annal of Applied Biology 146 (1): 1-14

Unigarro C.A., Bermúdez L.N., Medina R.D., Jaramillo A., Flórez C.P. (2017). Evaluation of four degree-day estimation methods in eight Colombian coffee-growing areas. Agronomía Colombiana 35 (3): 374-381.

Verghis T.I., McKenzie B.A., Hill G.D. (1999). Phenological development of chickpeas (*Cicer arietinum*) in Canterbury, New Zealand. New Zealand Journal of Crop and Horticultural Science 27 (3): 249-256.

Willmott C.J., Robeson S.M., Matsuura K. (2012). A refined index of model performance. International Journal of Climatology 32: 2088-2094.

Zalom F.G., Goodell P.B., Wilson L.T., Barnett W.W., Bentley W.J. (1983). Degree-days: the calculation and use of heat units in pest management. Leaflet 21373. Division of Agriculture and Natural Resources. University of California, Berkeley, EEUU.