Evaluation of four degree-day estimation methods in eight Colombian coffee-growing areas

Evaluación de cuatro métodos para estimar grados-día en ocho zonas cafeteras colombianas

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ABSTRACT

Methods to estimate the accumulation of degree-days based on maximum and minimum temperaturesare are commonly used to determine relationships or to adjust phenological models based on the "physiological time". Degree-days are obtained indirectly by these methods, this information is not generally available on hourly or shorter time scales due to the type of equipment used to record data or a data loss in historical time series. To compare the performance of such methods, degree-days were estimated with four indirect methods in eight Colombian locations during 1 year. Each indirect method was evaluated in comparison to the numerical integration method by the trapezoidal rule (reference method) using temperatures recorded every 5 min. Based on the percent bias error, the methods proposed by Arnold, Ometto and Snyder tend to overestimate thermal time, whereas the Villa-Nova method underestimates this time, but with a lower performance as regards to the previous ones.

Key words: thermal time, temperature, numerical integration, linear regression, bias.

RESUMEN

Los métodos que estiman la acumulación de los grados-día basados en datos de temperatura máxima y mínima diaria son comúnmente usados para determinar relaciones o hacer ajustes en modelos fenológicos basados en "tiempo fisiológico". La obtención de los grados-día con estos métodos se hace de manera indirecta, dado a que en general no se dispone de información de temperaturas a escala horaria e incuso menor, debido al tipo de equipo utilizado para tomar registros o por la pérdida de datos en series históricas. Con el objetivo de determinar el desempeño de estos métodos, se estimaron los grados-día con cuatro métodos indirectos en ocho localidades colombianas durante 1 año. Cada uno de los métodos se evaluó con respecto al método de integración numérica por regla del trapecio (método de referencia) usando las temperaturas registradas cada 5 min. El desempeño de los métodos se evaluó a partir de un modelo de regresión lineal y sus respectivos errores. Los métodos de Arnold, Ometto y Snyder, según el porcentaje de sesgo, tienden a sobrestimar el tiempo térmico, mientras el método de Villa-Nova lo subestima, pero con un menor desempeño respecto a los anteriores.

Palabras clave: tiempo térmico, temperatura, integración numérica, regresión lineal, sesgo.

Introduction

Temperature affects several physiological processes in plants. Generally, this influence is due to a thermal action on enzymatic activity, with temperature inducing changes in the conformation of enzymes and consequently on their functionality (Sharpe and DeMichele, 1977; Johnson and Thornley, 1985; Higley *et al.*, 1986; Bonhomme, 2000). The phenological response of plants to temperature is observed as changes in developmental rates (the occurrence of certain phenological events per time unit) (Raworth, 1994). Jaramillo and Guzmán (1984) found that a significant correlation exists among the number of days elapsed from planting to first harvest, the average air temperature (°C) and the thermal units.

Heat accumulation is referred to as "heat units", "thermal time", "cumulative growing degree days" or "physiological time" and reflects the concept of a quantifiable relationship between temperature and the rate of crop development (Gordon and Bootsma, 1993; McMaster and Wilhelm, 1997; Bonhomme, 2000; Snyder *et al.*, 2013). This relationship has been successfully used in agricultural science to predict and quantify the time between the plant phenological stages (Gilmore and Rogers, 1958; Cross and Zuber, 1972; McMaster, 1993; Cardina *et al.*, 2007).

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In the study of phenology and crop development, the concept "physiological time" can be expressed in quantifiable terms, with this time measured in growing degree-days (GDD, °C-days) (McMaster and Wilhelm, 1997; Rodríguez *et al.*, 2012) and representing the thermal units recorded between the minimum (Tb) and maximum (TB) threshold temperatures at the hours of a day (Snyder *et al.*, 2013). Mathematically, the daily GDD are obtained by the integration of growing degree-hours (GDH, °C-hours) for each hour of the day divided by the number of hours in a day (24 h) (Roltsch *et al.*, 1999; Cesaraccio *et al.*, 2001; Souza *et al.*, 2011; Rodríguez *et al.*, 2012; Snyder *et al.*, 2013).

However, hourly data are not always available, for example,when historical records are used or automatic weather stations are scarce. In such cases, the GDD are estimated using mathematical methods that use only daily maximum (TM) and minimum (Tm) temperatures (Snyder *et al.*, 1999). Among the methods most frequently used for calculating degree-days are the rectangle (Arnold, 1959), triangle (Lindsey and Newman, 1956) and sine wave (Baskerville and Emin, 1969) methods, including their variants (Villa-Nova *et al.*, 1972; Ometto, 1981; Snyder, 1985).

According to Roltsch (1999), when the TM exceeds the TB, these methods can use two approximations of accumulated thermal units: (1) the vertical cutoff, which assumes that there has been no accumulation of thermal units and (2) the horizontal cutoff, which assumes that the thermal units continue to accumulate until the Tb is reached. The threshold temperatures are the values under which (Tb) or above which (TB) the development rate is zero.

However, the threshold temperature is only a statistical value, which may be distant from the "physiological temperature" for which the development rate is close to zero, essentially because its value may vary depending on the method used for its calculation, on the growth stage or on the physiological process analyzed (Wang, 1960; Durand *et al.*, 1982; Bonhomme, 2000; Litschmann *et al.*, 2008).

In crops such as Brussels sprouts, cabbage, parsley, legumes, fodder, corn, soybeans and tomatoes, the Tb may oscillate between 0 and 10°C (Gordon and Bootsma, 1993). For *Coffea arabica* L. in Brazil, Lima and Silva (2008) estimated the Tb and TB at 12.9 and 32.4°C, respectively, from transplanting to the first flowering event, whereas Pezzopane *et al.* (2008) obtained a Tb value of 10.2°C from flowering to harvesting based on several harvest cycles using the "Mundo Novo" variety. For most tropical plants, including coffee, the Tb and TB values have been defined, respectively, as 10°C (Pedro-Junior *et al.*, 1977; Jaramillo and Guzmán, 1984) and 32°C (Jaramillo and Guzmán, 1984; Hatfield andPrueger, 2015).

Roltsch *et al.* (1999), Souza *et al.* (2011), Rodríguez *et al.* (2012) and Kean (2013) have found variation in performance when comparing different methods to estimate GDD based on maximum and minimum daily temperatures and when applying those methods to different growing regions. These disparities become relevant, for example, should the estimated accumulation of degree-days be greater than the "real" accumulation; this example would imply that a shorter chronological time than estimated would be necessary to reach a certain phenological stage, or *vice versa* (Bryant *et al.*, 1998), which can affect the predictions of phenological models based on "physiological time" (Kean, 2013).

Given the importance of the degree-day calculation in phenological models, the objective of the present research was to evaluate the performance of four horizontal cutoff methods in estimating degree-days within eight Colombian coffee-producing areas, using thermal thresholds associated with tropical plants.

Materials and methods

Study area and meteorological data

Eight localities with contrasting environmental conditions were selected, espatial distribution and economic importance for Colombian coffee crop was considered. Each locality was equipped with an automatic, RAWS-F, Fire Weather, Campbell Scientific® Remote Automated Weather Station from the Coffee Meteorological Network, a part of the Colombian National Federation of Coffee Producers (Federación Nacional de Cafeteros de Colombia) (Tab. 1, Fig. 2). The air temperature was recorded 24 h a day between February 1, 2014, and January 31, 2015, with five-minute intervals between measurements. The differences in the number of daily logs for the meteorological stations, due to the days with missing data are shown in Table 1. The temperature sensors were previously calibrated, by means of the homologation in parallel between conventional and authomatic stations, with amaximum error of ± 0.5 °C.

Degree-day calculation

For all the developed methods, the Tb and TB values were considered as 10 and 32°C, respectively, following the proposal by Pedro-Junior *et al.* (1977), Jaramillo and Guzmán, (1984), Camargo and Pereira (1994) and Hatfield and Prueger, (2015) for coffee cultivation.

TABLE 1. Geographic location of the weather stations used in the study; average annual historical values for precipitation (**P**), maximum temperature (**T_{max}**), temperature (**T_{med}**), minimum temperature (**T_{min}**) and mean relative humidity (**RH**); and the number of days used in calculating the degree-days for each locality (**ND**).

Weather station	Department	Elevation (m)	Latitude	Longitude	P (mm)	T_{max} (°C)	T_{med} (°C)	T_{min} (°C)	RH (%)	ND
El Sauce	Nariño	1609	01°37´	77°07´	1853	25.7	19.9	16.1	77.5	292
Jorge Villamíl	Huila	1420	02°20´	75°31´	1337	24.5	19.8	16.2	76.6	365
Julio Fernández	Valle del Cauca	1381	03°49´	76°32´	1094	25.7	19.9	16.4	78.3	337
Paraguaicito	Quindío	1203	04°24´	75°44´	2179	28.1	21.7	17	78.5	365
Naranjal	Caldas	1381	04°58´	75°39´	2795	26.8	20.9	16.6	76.9	337
Bertha	Boyacá	1677	05°53´	73°34´	1999	26.1	18.8	13.2	77.3	337
El Rosario	Antioquia	1635	05°58´	75°42´	2645	24.9	20.1	16.2	75.3	281
Pueblo Bello	Cesar	1134	10°25´	73°34´	2043	27.2	21.0	15.7	81.1	337

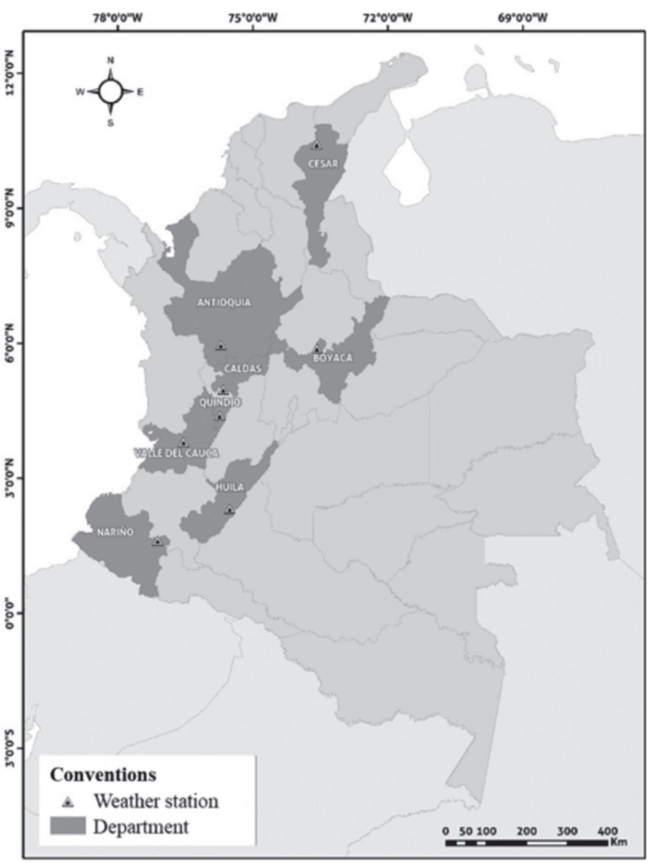

FIGURE 1. Location in Colombia of the weather stations of the Coffee Meteorological Network used in the study.

Numerical integration by trapezoidal rule (reference method)

The integration method was used as the reference method against which the indirect methods were evaluated due to its greater estimation precision and its comparatively frequent data collection at relatively short intervals (Cesaraccio *et al.*, 2001; Souza *et al.*, 2011; Rodríguez *et al.*, 2012).

The estimate of GDD using the reference method (GDD_r) was calculated as follows:

$$GDD_r = GDD_{TT} - (GDD_{TB} + GDD_{Tb}) \quad (1)$$

Where GDD_r = degree-days of the reference method (°C-days), GDD_{TT} = total degree-days (°C-days), GDD_{TB} = degree-days above TB (°C-days), and GDD_{Tb} = degree-days below Tb (°C-days).

To obtain the values that compose expression (1), we used expression (2), in which the areas of individual trapezoids constructed from the temperature records were calculated to apply the "trapezoid rule". These areas were integrated into an area under the curve (AUC), which was divided by the total number of seconds per day (86400), thus obtaining the daily thermal units, representing the total degree-days per day (GDD_{TT}) in this case. To calculate the GDD_{TB} and GDD_{Tb}, the AUC was integrated, assuming that the temperatures (the m_i values in expression 2) were, respectively, higher than or equal to the TB and below or equal to the Tb at corresponding times (Fig. 2).

$$TU = \frac{\sum_{i=2}^{n} 0,5 * (m_i + m_{i-1}) * (t_i - t_{i-1})}{86400} \quad (2)$$

Where **TU** = thermal units, $\mathbf{m}_i$ = temperature in the i^{th} measurement, and $\mathbf{t}_i$ = i^{th} time in the daily logs.

Indirect methods evaluated

The daily "cumulative growing degree days" or "physiological time" in GDD was estimated using the daily maximum and minimum temperature and four indirect methodologies formerly described in the literature (Arnold, 1959; Villa-Nova *et al.*, 1972; Ometto, 1981; Snyder, 1985) (Tab. 2), some of them previously applied to coffee production (Lima and Silva, 2008).

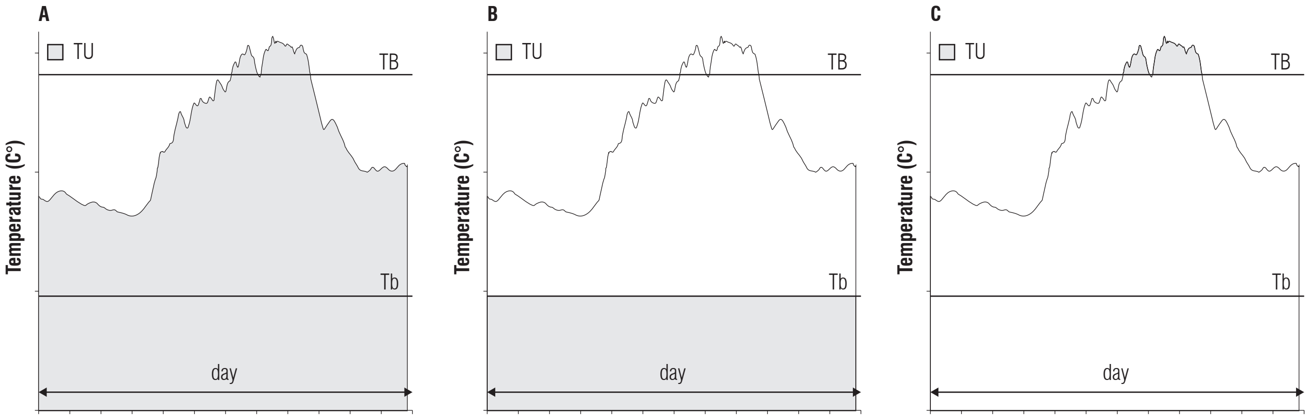

FIGURE 2. Description of thermal units (**TU**) integrated in the **AUC** for $\mathbf{GDD_{TT}}$ (a), $\mathbf{GDD_{Tb}}$ (b) and $\mathbf{GDD_{TB}}$ (c).

TABLE 2. Indirect methods of degree-day estimation used in the analysis.

Method	Use context	Equation	
Arnold (1959)	General	$GDD = \left(\frac{TM + Tm}{2}\right) - Tb$	(3)
Villa-Nova *et al.* (1972)	Tb ≥ Tm	$GDD = \frac{(TM - Tb)^2}{2(TM - Tm)}$	(4)
	Tb < Tm	$GDD = \frac{(Tm - Tb) + (TM - Tm)}{2}$	(5)
	Tb ≥ TM	$GDD = 0$	(6)
Ometto (1981)	TB > TM > Tm > Tb	$GDD = \left(\frac{TM - Tm}{2}\right) + (Tm - Tb)$	(7)
	TB > TM > Tb > Tm	$GDD = \frac{(TM - Tb)^2}{2(TM - Tm)} \quad (8)$	(8)
	TB > Tb > TM > Tm	$GDD = 0$	(9)
	TM > TB > Tm > Tb	$GDD = \frac{\left(2(TM - Tm)(Tm - Tb)\right) + (TM - Tm)^2 - (TM - TB)^2}{2(TM - Tm)}$	(10)
	TM > TB > Tb > Tm	$GDD = \frac{1}{2}\left(\frac{(TM - Tb)^2 - (TM - TB)^2}{(TM - Tm)}\right)$	(11)
Snyder (1985)		$M = \left(\frac{TM + Tm}{2}\right)$	(12)
		$W = \left(\frac{TM - Tm}{2}\right)$	(13)
		$\theta = arcsin\left(\frac{Tb - M}{W}\right)$	(14)
		$\varphi = arcsin\left(\frac{TB - M}{W}\right)$	(15)
	Tb < Tm	$GDD = \left(\frac{TM + Tm}{2}\right) - Tb$	(16)
	Tb > Tm	$GDD = \frac{\left[(M - Tb)\left(\frac{\pi}{2} - \theta\right) + (W \cos\theta)\right]}{\pi}$	(17)

Continue

TABLE 2. *Continuation*

Method	Use context	Equation	
Snyder (1985)	Tm > Tb; TM > TB	$GDD_1 = \left(\frac{TM + Tm}{2}\right) - Tb$	(18)
		$GDD_2 = \frac{\left\lfloor (M - TB)\left(\frac{\pi}{2} - \varphi\right) + (W \cos\varphi) \right\rfloor}{\pi}$	(19)
		$GDD = GDD_1 - GDD_2$	(20)
	Tb > Tm; TM > TB	$GDD_1 = \frac{\left[(M - Tb)\left(\frac{\pi}{2} - \theta\right) + (W \cos\theta)\right]}{\pi}$	(21)
		$GDD_2 = \frac{\left[(M - TB)\left(\frac{\pi}{2} - \varphi\right) + (W \cos\varphi)\right]}{\pi}$	(22)
		$GDD = GDD_1 - GDD_2$	(23)

Where: TM = maximum daily temperature (ºC), Tm = minimum daily temperature (ºC), Tb = minimum threshold temperature (ºC), TB = maximum threshold temperature (ºC), GDD = growing degree-days according to the indirect method (°C-days), GDD_1 = degree-days above Tb (°C-days), and GDD_2 = degree-days above TB (°C-days).

Statistical analysis

A linear regression model of the observed values was adjusted to each locality and indirect method, fitting the reference method data (dependent variable, Y) as a function of the data obtained with the indirect method (independent variable, X). The significance of the regression coefficients was evaluated using a t-test with α=5%. To identifying the best adjustment, we also evaluated whether the regression slope coefficient (β_1) differed statistically from one to determine whether the indirect method overestimated or underestimated the GDD. Additionally, the coefficient of determination (R^2) was calculated.

The bias of the degree-days accumulated by each conventional method was estimated as the percent bias (PB) of the residual (expressed as percentage), as shown by expression (24).

$$\text{PB} = \left(\frac{\sum_{i=1}^{n}(GDD - GDD_r)}{\sum_{i=1}^{n} GDD_r}\right) * 100 \qquad (24)$$

Where: GDD_r = degree-days of the reference method (°C-days); GDD = growing degree-days according to the indirect method (°C-days).

The statistical analyses were performed using SAS software version 9.4 (SAS Institute, 2012).

Results and discussion

The results of adjusting the regression model with the data from the reference method expressed as a function of the data obtained from each of the indirect methods are presented in Table 3 for each weather station. The regression coefficients (β_1) were significantly different from zero for all the methods by the t-test at the 5% probability level, indicating that the values obtained with each of the indirect methods help explain the results observed with the reference method. The proportion of the data variability observed with the reference method that was explained by the indirect method varied from 32 to 82%, according to the coefficients of determination (Tab. 3).

The regression coefficient was equal to one (it means, a 1:1 ratio existed between the indirect method and the reference method) for the indirect method of Villa-Nova *et al.* (1972) and for the localities of Naranjal (β_1 = 0.960°C-days) and El Rosario (β_1 = 1.053°C-days) (t-test, α = 5%). The coefficient was significantly different from 1 for all the other localities.

Regarding goodness-of-fit, R^2 for the methods proposed by Arnold (1959), Ometto (1981) and Snyder (1985) exceeded 0.73 for the El Rosario, El Sauce, Jorge Villamíl, Naranjal and Paraguaicito localities and varied between 0.59 and 0.68 for Julio Fernández and Pueblo Bello. For every locality assessed, the R^2 obtained for the method of Villa-Nova *et al.* (1972) was lower compared to all the other methods. The lowest adjustment values for R^2 were recorded for a locality in Bertha (between 0.32 and 0.44).

The PB showed that when the degree-day errors accumulated, for the methods of Arnold (1959), Ometto (1981) and Snyder (1985) overestimated the GDD relative to the reference method by between 8.3 and 17.2% at all eight

TABLE 3. Regression coefficient (β_1), standard error (STE), coefficient of determination (R^2) and percent bias (PB) obtained in the relation between accumulated degree-days in each indirect method and the accumulated degree-days estimated by numeric integration during the evaluated period in eight coffee-growing areas of Colombia.

Station and degree-days accumulated (reference method)	Indirect method	Regression coefficient $\beta_1 \pm$ SE			R^2	Accumulated (indirect method) (°C-day)	PB (%)
Bertha (ΣGDDr= 3148°C-día)	Arnold(1959)	0.566 ± 0.035	a	b	0.44	3685.4	17.08
	Ometto(1981)	0.569 ± 0.035	a	b	0.44	3686.3	17.11
	Snyder(1985)	0.572 ± 0.035	a	b	0.44	3687.8	17.16
	Villa *et al.* (1972)	0.529 ± 0.042	a	b	0.32	3085.1	-1.99
El Rosario (ΣGDDr= 2907°C-día)	Arnold(1959)	0.908 ± 0.028	a	b	0.79	3264.5	12.31
	Ometto(1981)	0.908 ± 0.028	a	b	0.79	3264.5	12.31
	Snyder(1985)	0.908 ± 0.028	a	b	0.79	3264.5	12.31
	Villa *et al.* (1972)	1.053 ± 0.038	a		0.73	2334.6	-19.68
El Sauce (ΣGDDr= 3004°C-día)	Arnold(1959)	0.798 ± 0.027	a	b	0.75	3490.3	16.20
	Ometto(1981)	0.798 ± 0.027	a	b	0.75	3490.3	16.20
	Snyder(1985)	0.798 ± 0.027	a	b	0.75	3490.3	16.20
	Villa *et al.* (1972)	0.864 ± 0.037	a	b	0.66	2541.0	-15.41
Jorge Villamil (ΣGDDr= 3711°C-día)	Arnold(1959)	0.810 ± 0.020	a	b	0.82	4161.0	12.12
	Ometto(1981)	0.810 ± 0.020	a	b	0.82	4161.0	12.12
	Snyder(1985)	0.810 ± 0.020	a	b	0.82	4161.0	12.12
	Villa *et al.* (1972)	0.826 ± 0.027	a	b	0.73	2946.4	-20.61
Julio Fernández (ΣGDDr= 3650°C-día)	Arnold(1959)	0.677 ± 0.026	a	b	0.68	4183.0	14.61
	Ometto(1981)	0.677 ± 0.026	a	b	0.68	4183.0	14.60
	Snyder(1985)	0.678 ± 0.026	a	b	0.68	4182.9	14.60
	Villa *et al.* (1972)	0.728 ± 0.038	a	b	0.52	3021.3	-17.22
Naranjal (ΣGDDr= 3828°C-día)	Arnold(1959)	0.926 ± 0.023	a	b	0.82	4354.8	13.76
	Ometto(1981)	0.926 ± 0.023	a	b	0.82	4354.8	13.76
	Snyder(1985)	0.926 ± 0.023	a	b	0.82	4354.8	13.76
	Villa *et al.* (1972)	0.960 ± 0.029	a		0.76	3196.8	-16.49
Paraguaicito (ΣGDDr= 4465°C-día)	Arnold(1959)	0.869 ± 0.026	a	b	0.76	5085.7	13.90
	Ometto(1981)	0.870 ± 0.026	a	b	0.76	5085.5	13.90
	Snyder(1985)	0.871 ± 0.026	a	b	0.76	5085.1	13.89
	Villa *et al.* (1972)	0.832 ± 0.027	a	b	0.72	3747.8	-16.06
Pueblo Bello (ΣGDDr= 3871°C-día)	Arnold(1959)	0.780 ± 0.036	a	b	0.59	4193.0	8.32
	Ometto(1981)	0.780 ± 0.036	a	b	0.59	4193.0	8.32
	Snyder(1985)	0.780 ± 0.036	a	b	0.59	4193.0	8.32
	Villa *et al.* (1972)	0.836 ± 0.062	a	b	0.35	3178.8	-17.88

SE = standard error; a = t-test with alpha 5% for β_1 values significantly different from zero; b = t-test with alpha 5% for β_1 values significantly different from one.

localities. Under the thermal thresholds evaluated, these three methods were also consistently observed to show no significant differences. The method described by Villa-Nova *et al.* (1972), with negative PB values, was the only one to underestimate the reference method results, ranging between 2.0 and 20.6%.

In the present study, the methods of Arnold (1959), Ometto (1981) and Snyder (1985) showed no descriptive differences by locality regarding the regression coefficient, R^2 or PB values (Tab. 3). Souza *et al.* (2011) also reported that these three methods produce similar results, which is due to the similar geometric forms usedby these methods for estimating the degree-days based on Tb and TB.

According to the above, these methods did not present differences, because most of the minimum temperatures were higher than the Tb in the daily records. However, in a very few cases, the maximum temperatures exceeded the TB. This occurrence causes the methods of Ometto (1981) and Snyder (1985) to consider expressions based only on the Tb, a situation bearing similarity to the arising results with the method of Arnold (1959), which only includes Tb in its mathematical expression. According to Higley *et al.* (1986), even though omitting a maximum development threshold could decrease the precision of the degree-day estimation, the introduced error is low as long as the daily maximum temperatures are generally lower than the maximum threshold temperature for development (TB).

The evaluation criteria did indicate different performance among the localities for themethods of Arnold (1959), Ometto (1981) and Snyder (1985). For example, higher coefficients of determination (R^2) were observed for the localities of El Rosario, El Sauce, Jorge Villamíl, Naranjal and Paraguaicito compared to those on Bertha, Julio Fernández and Pueblo Bello (Tab. 3), this implies a better fit for the first. Carlson and Hancock (1991) and Roltsch *et al.* (1999) highlight the importance of R^2 as an evaluation criterion to determine the degree of fit between methods.

The PB also varied among the localities, although the variation was inconsistent with that described for the adjustment. Comparatively high PB values were obtained for Bertha and El Sauce, where as those for El Rosario, Jorge Villamíland Pueblo Bello were low (Tab. 3). The greater PB for Bertha could be attributed to the lower temperatures recorded in this area (Tab. 1). By contrast, the greater PB for El Sauce could be mostly due to variation in cloudiness and wind speed, which affect the daily temperature fluctuation. Roltsch *et al.* (1999) and Worner (1988) found that when degree-days are estimated by indirect methods, a greater error is found for cold areas or climates in which fast thermal changes occur. Both error and bias are important parameters to consider because the prediction of phenological events is linked to the accumulation of physiological time (Rodríguez *et al.*, 2012).

The accumulated error evaluated by the PB did not exceed 17.1% compared to Arnold (1959), Ometto (1981) or Snyder (1985) methods in any locality (Tab. 3). This error could be considered acceptable for the prediction as regards to the PB found by Rodríguez *et al.* (2012) for Colombia (between 7.13 and 30.57%). The different errors involved may cancel each other to some extent, but the greatest source of error, which is thermal accumulation, results from inaccurate temperature estimation (Pruess, 1983). Those methods with positive PB values overestimated the degree-days relative to the ones calculated by the reference method, which was also reported by Souza *et al.* (2011).

An overestimation can be convenient, considering that an underestimation of accumulated degree-days can lead to erroneous conclusions regarding a phenological event in poikilothermic organisms by inaccurately predicting a later event than actually occurs (Bryant *et al.*, 1998). Plant development may be further affected by not only nutritional status and water stress but also photoperiod in long-day plants and, to a lesser extent, in short-day plants (Bonhomme, 2000). Therefore, any deleterious effects of these factors should be reduced for cash crops, with all required substrates present in amounts adequate to ensure growth (Higley *et al.*, 1986).

The method proposed by Villa-Nova *et al.* (1972) was the only one to present regression coefficients statistically equal to 1 and to underestimate the reference method, contrasting with the results reported by Souza *et al.* (2011).

Conclusion

Considering the PB, the methods proposed by Arnold, Ometto and Snyder tend to overestimate thermal time, whereas the method proposed by Villa-Nova underestimates thermal time, but with a lower performance regarding to the previous ones. However, the performance of each method can vary between zones due to the agri-environmental conditions typical of each locality. Arnold's method can be taken into account when daily temperatures do not exceed the maximum or minimum threshold considered, as in the present study. The use of the different methods depends on the available information and the objective of the thermal time estimation.

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