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Comparison of methodologies for degree-day estimation using numerical methods

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ABSTRACT. The development of projects related to the yield of various crops has been greatly enhanced with the incorporation of mathematical models as well as essential and more consistent equations which enable a prediction and greater approximation to their actual behavior, thus reducing error in estimate. Among the operations requiring further investigation are those related to crop growth, characterized by the ideal temperature for addition of dry matter. Due to the wide use of mathematical methods for representing, analyzing and attaining degree-day estimation as well as the great importance of sugarcane in the Brazilian economy, we carried out an evaluation of the mathematical models and numerical integration methods commonly used for estimating the availability of degrees-day for this crop in the region of Botucatu, in São Paulo State, Brazil. Integration models with discretization every 6 hours have shown satisfactory results in degree-day estimation. Conventional methodologies have shown satisfactory results when the estimation of degrees-day was based on the time-temperature curve for each day and for groups of 3, 7, 15 and 30 days. Through numerical integration method, the region of Botucatu showed a annual thermal availability average from 1,070.6 degrees-day for the sugarcane.

Keywords: vegetative development, heat units, numerical integration methods, sugar cane.

RESUMO. Comparação de metodologias para estimativa de graus-dia usando métodos numéricos. O desenvolvimento de projetos relacionados ao desempenho de diversas culturas tem recebido aperfeiçoamento cada vez maior, incorporado a modelos matemáticos sendo indispensável à utilização de equações cada vez mais consistentes que possibilitem previsão e maior aproximação do comportamento real, diminuindo o erro na obtenção das estimativas. Entre as operações unitárias que demandam maior estudo estão aquelas relacionadas com o crescimento da cultura, caracterizadas pela temperatura ideal para o acréscimo de matéria seca. Pelo amplo uso dos métodos matemáticos na representação, análise e obtenção de estimativas de graus-dia, juntamente com a grande importância que a cultura da cana-de-açúcar tem para a economia brasileira, foi realizada uma avaliação dos modelos matemáticos comumente usados e dos métodos numéricos de integração na estimativa da disponibilidade de graus-dia para essa cultura, na região de Botucatu, Estado de São Paulo. Os modelos de integração, com discretização de 6 em 6 h, apresentaram resultados satisfatórios na estimativa de graus-dia. As metodologias tradicionais apresentaram desempenhos satisfatórios quanto à estimativa de graus-dia com base na curva de temperatura horária para cada dia e para os agrupamentos de três, sete, 15 e 30 dias. Pelo método numérico de integração, a região de Botucatu, Estado de São Paulo, apresentou disponibilidade térmica anual média de 1.070,6 GD para a cultura da cana-de-açúcar.

Palavras-chave: desenvolvimento vegetativo, unidades térmicas, métodos de integração numérica, cana-de-açúcar.

Introduction

The development of projects related to the yield of various crops has been greatly enhanced with the incorporation of mathematical models, as well as more consistent equations, which enable a prediction and greater approximation to their actual behavior, thus reducing the error in model. Among the operations requiring further investigation are those related to crop growth, characterized by the ideal temperature for addition of organic matter. In this scenario, due to the great variation of climatic elements, many problems have arisen and become more complex, particularly those associated with the maturation process. Hence, a study on the variation of temperature in relation to crop yield which enables farmers to program their agricultural activities and no be surprised by meteorological extreme effects.

Managers of farming companies, together with research agencies, must resort to all tools available that can help in decision making. Thus, mathematical modeling can be useful in this area, since it is a technique that integrates knowledge from different disciplines in a common work structure, being able to define clear goals and compare objectives that are often conflictive and enabling to predict a system's behavior, which is particularly important for situations that have not yet been experienced (HANKS; RITCHIE, 1991).

Various studies have been developed with the purpose to estimate the crop productivity, aiming high yield and low cost as well as rationalizing the relationships between the different crop phases, thus searching the maximum performance by means of degree-day models (GALAN et al., 2001; PRELA; RIBEIRO, 2002; SCARPARI; BEAUCLAIR, 2008; SOUZA et al., 2009; VILLA NOVA et al., 1972). However, crop's phenological stages can be predicted based on previous knowledge of the temperature historic series, the location and the caloric sum required by the plant to achieve its maturity point (LITSCHMANN et al., 2008; DAY et al., 2008). During the development of the degree-day approach, estimation processes have incorporated various modeling concepts aiming at enhancing phenomenological representation. Among the models that have been developed, applied and presented, those by Arnold (1959), Villa Nova et al. (1972), Ometto (1981), Snyder (1985) and Scarpari and Beauclair (2004) can be pointed out.

Currently, sugarcane (*Saccharum* spp.) is one of the best options among the springs of renewable energy, presenting big importance in the Brazilian agricultural setting and a promising future in the world setting. Brazil is the greatest and more efficient producer of sugar, alcohol and byproducts of the world. Among the Brazilian States, São Paulo with approximately 66% of area planted in Center-South Brazilian is the main producer followed by the states of Alagoas, Paraná, Minas Gerais, Pernambuco, Mato Grosso, Goiás and Mato Grosso do Sul (VIANA et al., 2008).

The sugarcane Brazilian is cultivated in various soil types under the influence of different climates, resulting in various types of environments for the production, which associated with the management of culture and cultivar chosen interfere in the production and planning of activity sugarcane (FRIZZONE et al., 2001; MAULE et al., 2001; SNYDER et al., 2001; THOMPSON; CKARK, 2005). Decisions based on pre-established criteria, allows the possibility to define risk or economic success of this activity, depending on the decision from the information available, such as the availability of thermal in a given region.

Due to the wide use of mathematical methods for representing, analyzing and calculate degrees-day as well as the great importance of sugarcane crops in the Brazilian economy, we accomplished an evaluation of mathematical models and numerical methods of integration commonly used for estimating the availability of degrees-day for this crop in the region of Botucatu, in São Paulo State, Brazil.

Material and methods

Temperature data from the Meteorological Station at the School of Agronomic Sciences at Botucatu, São Paulo State, Brazil, were used. The Meteorological Station is located at latitude 22° 51' S, longitude at 48° 26' W and at 786 m of altitude. The predominant climatic type based on the Köppen's classification is the Cfa type, hot temperate climate (mesothermal) wet. The average temperature in the coldest month (July) is 17.1°C, and in the hottest month (February), 23.1°C, with an total annual of rainfall and potential evapotranspiration, respectively, of 1,428.4 and 945.2 mm (CUNHA; MARTINS, 2009; ROLIM et al., 2007).

The data were collected from the station at intervals of 1-hour, from 2002 to 2005, between January 1 and December 31 of each year. Thermal availability in day-degrees was estimated by five traditional methodologies used for sugarcane (ARNOLD, 1959; VILLA NOVA et al., 1972; OMETTO, 1981; SNYDER, 1985; SCARPARI and BEAUCLAIR, 2004). Conjointly were studied three numerical integration rules of the quadrature method by Newton-Cotes, which were discretized at different intervals during each observation daily (ARENALES; DAREZZO, 2008), thus enabling twelve different forms of degree-day of estimate by numerical integration. The expressions are listed below.

Conventional methods

- Arnold (1959), apud Souza et al. (2009):

$$GD = \sum_{i=1}^{n} (Ti - Tb) \quad (1)$$

where:

Ti = mean temperature; Tb = basal temperature; n = number of days in the period.

- Villa Nova et al. (1972), apud Lemos Filho et al. (1997):

Situation 1: $Tb \geq Tm$

$$GD = \frac{(TM - Tb)^2}{2.(TM - Tm)} \quad (2)$$

Situation 2: $Tb < Tm$

$$GD = \frac{(Tm - Tb) + (TM - Tm)}{2} \quad (3)$$

Situation 3: $Tb \geq TM$

$GD = 0$

where:

TM = daily maximum temperature, (°C); Tm = daily minimum temperature, (°C); Tb = basal temperature, (°C).

- Scarpare and Beauclair (2004), with adjustament of previous approaches for correction by photoperiod:

Situation 1: $TM > Tb > Tm$

$$GD = \frac{(TM - Tb)^2 + (TM - 25)^2}{2.(TM - Tm)}.f.n \quad (4)$$

Situation 2: $Tb < Tm$

$$GD = Tm - Tb + \left(\left(\frac{TM - Tm}{2}\right) + \frac{(TM - 25)^2}{2.(TM - Tm)}\right).f.n \quad (5)$$

where:

$$f = \left(\frac{N}{24 - N}\right)^2 \quad (6)$$

where:

n = length of day, (hours); TM = daily maximum temperature, (°C); Tm = daily minimum temperature, (°C); Tb = basal temperature, (°C); f = correction in function of the relation to the number of sunshine hours (N) over 24 hours; n = number of days of the month.

- Ometto (1981), apud Souza et al. (2009):

Situation 1: $TB > TM > Tm > Tb$ (corrected)

$$GD = \frac{(TM - Tm)}{2} + (Tm - Tb) \quad (7)$$

Situation 2: $TB > TM > Tb \geq Tm$

$$GD = \frac{(TM - Tb)^2}{2\,(TM - Tm)} \quad (8)$$

Situation 3: $TB > Tb > TM > Tm$

$GD = 0$

Situation 4: $TM > TB > Tm > Tb$

$$GD = \frac{2[(TM - Tm)(Tm - Tb)] + (TM - Tm)^2 - (TM - TB)^2}{2(TM - Tm)} \quad (9)$$

Situation 5: $TM > TB > Tb > Tm$

$$GD = \frac{1}{2}\left(\frac{(TM - Tb)^2 - (TM - TB)^2}{(TM - Tm)}\right) \quad (10)$$

where:

TM = daily maximum temperature, (°C); Tm = daily minimum temperature, (°C); Tb = minimum basal temperature, (°C); TB = maximum basal temperature, (°C).

- Snyder (1985), apud Galán et al. (2001):

Situation 1: $Tb < Tm$

$$GD = \frac{(TM + Tm)}{2} - Tb \quad (11)$$

Situation 2: $Tb > Tm$

$$GD = \frac{\left[(M - Tb)\left(\frac{\pi}{2} - \theta\right) + (W\cos\theta)\right]}{\pi} \quad (12)$$

Situation 3: $Tb < Tm$; $TM > TB$

$$GDb = \frac{(TM + Tm)}{2} - Tb \quad (13)$$

$$GDB = \frac{\left[(M - TB).\left(\frac{\pi}{2} - \varphi\right) + (W.\cos\varphi)\right]}{\pi} \quad (14)$$

$$GD = GDb - GDB \quad (15)$$

Situation 4: $Tb < Tm$; $TM > TB$

$$GDb = \frac{\left[(M - Tb).\left(\frac{\pi}{2} - \theta\right) + (W.\cos\theta)\right]}{\pi} \quad (16)$$

$$GDB = \frac{\left[(M - TB).\left(\frac{\pi}{2} - \varphi\right) + (W.\cos\varphi)\right]}{\pi} \quad (17)$$

$$GD = GDb - GDB \quad (18)$$

where:

$$M = \frac{TM + Tm}{2} \quad (19)$$

$$W = \frac{TM - Tm}{2} \quad (20)$$

$$\theta = arcsen\left(\frac{Tb - M}{W}\right) \quad (21)$$

$$\varphi = arcsen\left(\frac{TB - M}{W}\right) \quad (22)$$

where:

TM = daily maximum temperature, (°C); Tm = daily minimum temperature, (°C); Tb = minimum basal temperature, (°C); TB = maximum basal temperature, (°C).

Numerical Integration Methods

- *Trapeze rule and trapeze rule with steps*

Situation 1: $h = 1/2$

$$GD = \frac{h}{2}.\left[T_0 + 2.T_{12} + T_{24}\right] - Tb \quad (23)$$

Situation 2: $h = 1/4$

$$GD = \frac{h}{2}.\left[T_0 + 2.\left(\sum_{i=6,12,18} T_i\right) + T_{24}\right] - Tb \quad (24)$$

Situation 3: $h = 1/8$

$$GD = \frac{h}{2}.\left[T_0 + 2.\left(\sum_{i=1}^{7} T_{(3\times i)}\right) + T_{24}\right] - Tb \quad (25)$$

Situation 4: $h = 1/24$

$$GD = \frac{h}{2}.\left[T_0 + 2.\left(\sum_{i=1}^{23} T_i\right) + T_{24}\right] - Tb \quad (26)$$

- Simpson's 1/3 numerical integration

Situation 1: $h = 1/2$

$$GD = \frac{h}{3}.\left[T_0 + 4.T_{12} + T_{24}\right] - Tb \quad (27)$$

Situation 2: $h = 1/4$

$$GD = \frac{h}{3}.\left[T_0 + 4.\left(\sum_{i=6,18} T_i\right) + 2.T_{12} + T_{24}\right] - Tb \quad (28)$$

Situation 3: $h = 1/8$

$$GD = \frac{h}{3}.\left[\begin{array}{l} T_0 + 4.\left(\sum_{i=3,9,15,21} T_i\right) \\ + 2.\left(\sum_{i=6,12,18} T_i\right) + T_{24} \end{array}\right] - Tb \quad (29)$$

Situation 4: $h = 1/24$

$$GD = \frac{h}{3}.\left[\begin{array}{l} T_0 + 4.\left(\sum_{i=1}^{12} T_{(2\times i)-1}\right) \\ + 2.\left(\sum_{i=1}^{12} T_{(2\times i)}\right) + T_{24} \end{array}\right] - Tb \quad (30)$$

- Simpson's 3/8 numerical integration

Situation 1: $h = 1/3$

$$GD = \frac{3}{8}.h.\left[T_0 + 3.\sum_{i=8,16} T_i + T_{24}\right] - Tb \quad (31)$$

Situation 2: $h = 1/12$

$$GD = \frac{3}{8}.h.\left[\begin{array}{l} T_0 + 3.\left(\sum_{1}^{4} T_{(6\times i)-4} + \sum_{1}^{4} T_{(6\times i)-2}\right) \\ + 2.\sum_{1}^{3} T_{(6\times i)} \end{array}\right] - Tb \quad (32)$$

Situation 3: $h = 1/24$

$$GD = \frac{3}{8}.h.\left[\begin{matrix} T_0 + 3.\left(\sum_1^8 T_{(3\times i)-2} + \sum_1^8 T_{(3\times i)-1}\right) \\ + 2.\sum_1^7 T_{(3\times i)} \end{matrix}\right] - Tb \qquad (33)$$

where:

h = discretization interval time; Ti = temperature in determined time, with variation between 0 a 24 hour; T_o = temperature in 0 hour; T_{12} = temperature in 12 hours; T_{24} = temperature in 24 hours?; Tb = minimum basal temperature, (°C);

The thermal sum in degrees-day was given by the value of the area between the variation of temperature hourly for each day and the basal temperatures. The minimum and maximum basal temperatures used were of 18 and 38°C, respectively (TERUEL et al., 1997).

Hourly discretizations (h = 1/24) were considered as those presenting the smallest errors, since the greater the discretization interval, the greater the expected error (ARENALES; DAREZZO, 2008). Nevertheless, Simpson's 1/3 numerical integration with hourly discretization was taken as reference based on the analysis of monthly degrees-day by the Scott-Knott test with 1% of probability. The different discretizations in the interval hourly time for possibilities at twelve numerical integration were evaluated by the same statistical test by grouping months from October to April (considered to be hot months) and from May to September (cold months) during the four years of observation. Simple linear regression equations were adjusted between the traditional methodologies and Simpson's 1/3 integration with hourly discretization (h = 1/24). These equations were submitted to an evaluation of the standard error of the estimate (SEE), agreement index (d) and performance index (c), according to the methodology by Barros et al. (2009), in the estimation of degrees-day used by numerical integration adopted as reference.

Results and discussion

When comparing the accumulated values of degrees-day monthly (Table 1) for each of the numerical integration rules used, two groups statistically different were found, because of the difference in temperatures over the seasons of the year. The smallest availability of monthly sums thermal was observed in the period from May to September, with a daily variation of 0.903 to 2.492 DD (degree-day). However, in the spring and summer months we found the greatest daily value for the sugarcane crop (3.17 DD in November to 4.24 DD in March). The rules of numerical integration with hourly discretization did not differ from each other for the hot months either in the monthly estimation of the accumulated degrees-day.

Table 1. Average availability of monthly thermal sums (degrees-day accumulated) in Botucatu, São Paulo State for sugarcane, using methodologies of numerical integration rules with hourly.

Months	Trapeze rule of integration	Simpson's 1/3 rule of integration	Simpson's 3/8 rule of integration
January	117.75 Aa	117.75 Aa	117.75 Aa
February	127.75 Aa	128.00 Aa	128.00 Aa
March	131.25 Aa	131.25 Aa	131.25 Aa
April	117.75 Aa	117.50 Aa	117.50 Aa
Mai	43.25 Ba	43.25 Ba	43.25 Ba
June	41.50 Ba	41.50 Ba	41.50 Ba
July	28.00 Ba	28.00 Ba	28.00 Ba
August	62.50 Ba	62.50 Ba	62.50 Ba
September	74.75 Ba	74.75 Ba	74.75 Ba
October	109.75 Aa	109.25 Aa	109.75 Aa
November	95.00 Aa	94.50 Aa	95.00 Aa
December	123.25 Aa	122.75 Aa	123.00 Aa
Total	1,072.50	1,071.00	1,072.25

*Mean followed by the same uppercase and lowercase letters, column and row respectively, do not differ by Scott Knott test at 1% probability.

The greatest variation was observed for the month of December, but it was not higher than 0.5%. In general, any of these methodologies of hourly integration could be used to establish the comparison with those conventionally used for estimating the accumulated degrees-day. In this study, Simpson's 1/3 integration was used as a basis, it estimates the sum of degrees-day for a time, with at least three points and polynomials, which allows minor errors in the integration (ARENALES; DAREZZO, 2008).

By analyzing only the clustered hot and cold months, we observed that, among the variation possibilities of numerical integration for each method, given by the amplitude of the time discretization interval and its requirements, just in the cold months, the twelve integration methodologies studied did not differ from each other due to the low temperature values observed in these periods (Table 2). On the other hand, in the hot months, the methods trapezoid, Simpson's 1/3 and Simpson's 3/8 with time discretization in 0-24, 0-12-24, 0-8-16-24h differed from the other methodologies, since the greater the discretization interval larger the error found. Consequently, the distribution of the time in interval six hours showed similar results to those from hourly for both the hot and cold months, with variations of 2.87 and 0.06% observed for numerical integration by successive trapezoids and Simpson's 1/3, respectively, in hot months. Hence, it was demonstrated that this time interval can be an interesting possibility for estimating degrees-day when applied in equation 28 (Simpson's 1/3 with discretization every 6 hours), since, in Brazil, records of hourly temperature are not available in most meteorological stations. Also, most of time, long time series of collected data does not exist, which is largely a result from the limitations of instrumentation in rural areas and memory limitations of time storage. It is noteworthy that for moments when the temperature at the time of collection was higher than the maximum basal temperature (38ºC), the temperature value to be considered must be TB itself, since no vegetative development occurs above of the limiting temperature.

Higley et al. (1986) discussed various classes of factors that can influence the capacity of different models to predict accumulated degrees-day and identified that errors associated with the adoption and approximation of the methods used to estimate development rates and basal temperatures, conjointly with the limitation in the evaluation of climatic data, have great impacts on the results found (PRELA et al., 2006). To Camargo et al. (1987), the degree-day method admits a linear relationship between temperature increase and plant development, as each species and/or variety is characterized by a distinct base temperature that can vary according to the plant's age or phenological phase (LITSCHMANN et al., 2008; SOUZA et al., 2009). It is common however, to adopt a single base temperature for the whole plant's cycle, which may lead to errors in predicting of the harvest and yield time of a given variety.

Table 2. Average of the hot months and cold by methodologies of numerical integrations with different time of discretization. Data from 2002 to 2005.

Methodology	Mean of hot months	Mean of cold months
Trapeze		
Hourly	97.92 b	29.02 a
0-24	50.82 c	10.68 a
0-12-24	112.56 a	34.7 a
0-6-12-18-24	100.73 b	28.71 a
0-3-6-9-12-15-18-21-24	101.39 b	30.11 a
1/3 Simpson		
Hourly	96.75 b	28.83 a
0-12-24	135.41 a	45.83 a
0-6-12-18-24	96.81 b	27.09 a
0-3-6-9-12-15-18-21-24	101.64 b	30.61 a
3/8 Simpson		
Hourly	97.49 b	28.9 a
0-8-16-24	110.99 a	32.88 a
0-2-4-6-8-10-12-14-16-18-20-22-24	101.57 b	29.7 a

*Mean followed by the same uppercase letters, column, do not differ by Scott Knott test at 1% probability.

As to this approach, Roltsch et al. (1999) cite that greater reliability on values of degree-day found can be attained with the use of data of hourly temperature, and, consequently, the actual daily and hourly temperature curves are not symmetrical, and their shape may vary considerably due to specific of climatic conditions (atmosphere) and time of the year. When temperature data of daily minimum and maximum (min/max) are used, suppositions of a profile daily temperature are obtained. Such profile is represented by a specific geometric shape (rectangle, triangle, double triangle, single senoidal and double senoidal, among others). However, an alternative is to perform approximations with simple empirical models based on local climatic variations, which can minimize the errors occurring in estimations with geometric shapes pre-defined (RAWORTH, 1994).

Nevertheless, various efforts have been made in the attempt to use correction measures for some methodologies that use such pre-defined geometric shapes based on daily temperature curves utilizing hourly databases, have presented little improvement (ROLTSCH et al., 1999; CESARACCIO et al., 2001; RULM et al., 2010). As example, the method developed by Parton and Logan (1981) can be cited. Their method has shown to be versatile; however, its use requires considerable investment in obtaining parameters for each season of the year and for the behavior of the hourly temperature in at least one year. Additionally, limitations to its use have been identified, since not all day the temperature curves are well represented by the method (ROLTSCH et al., 1999).

It was observed that the methodologies commonly used in Brazil for estimating degrees-day show a tendency to overestimate the monthly accumulated values over the year (Figure 1), except for the method proposed by correction photoperiod, which underestimates in hot months (SD = 9.79) and overestimates in cold months (SD = 8.83), however that variation to the long one of the year favored the obtaining of the most determination coefficient found ($R^2 = 0.9542$). This is explained by the fact that such methodology uses a correction in function of the relation to the number of sunshine hours (N) over 24 hours. The methodologies proposed by Ometto (1981) and Snyder (1985) presented identical results, showing similarity between the geometric figures considered by each estimation method.

When comparing the values degree-day obtained with the numerical integration of data of hourly temperature, in the average the methodologies of Arnold (1959), Villa Nova et al. (1972), Ometto (1981) and Snyder (1985) overestimated the annual availability of degrees-day for the sugarcane crop in 19.90, 17.44, 27.57 and 27.87%, respectively (Table 3), whereas the methodology with correction by photoperiod (Scarpari and Beauclair, 2004) underestimates the monthly availability in to 9.59%. The high standard-deviation values observed in six methodologies resulted from the low temperatures occurring in 2004, which presented an annual average of 19.89ºC whereas, in the other years, the annual temperatures averages were of 21.27, 20.57 and 20.51ºC, respectively for the years 2002, 2003 and 2005. In general, the region of Botucatu, is appropriate for sugarcane, since its annual average temperature is of 20.3ºC, and its annual average hydric deficiency is of 5 mm (CUNHA; MARTINS, 2009).

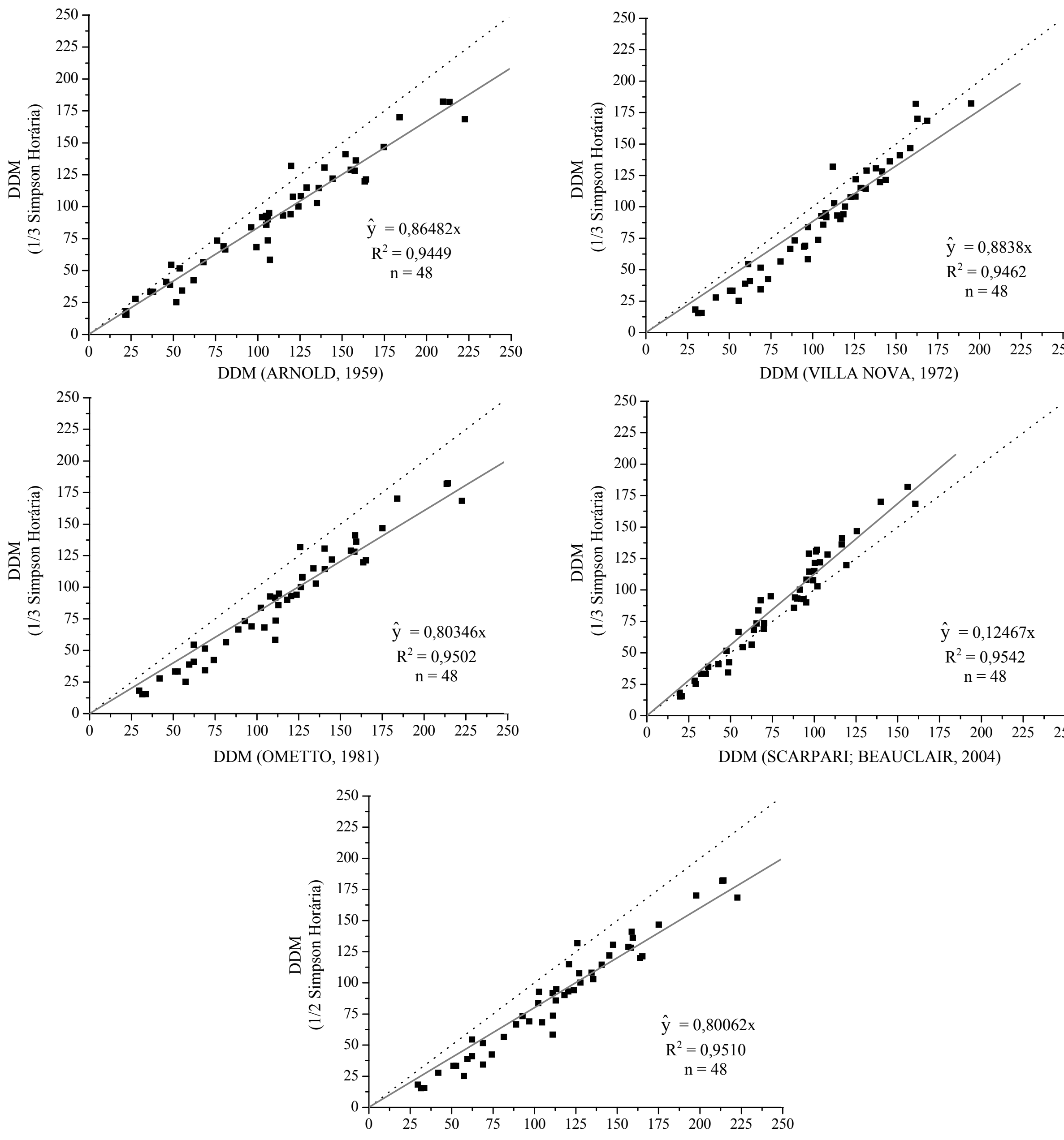

Figure 1. Correlation between monthly degree-day (DDM) by methodologies geometric figure and 1/3 Simpson rule for the numerical integration in hours. Data from 2002 to 2005.

Table 3. Annual availability of degrees-day calculated by six methodologies for the sugarcane crop in Botucatu, São Paulo State. Data from 2002 to 2005.

Year	Methodology					
	Arnold (1959)	Villa Nova et al. (1972)	Ometto (1981)	Snyder (1985)	Scarpari and Beauclair (2004)	1/3 Simpson Hourly
2002	1,656.29	1,477.96	1,703.57	1,704.44	1,178.44	1,324.23
2003	1,252.57	1,263.23	1,354.13	1,368.06	972.16	1,051.70
2004	1,039.43	1,088.67	1,128.48	1,124.25	799.60	873.22
2005	1,185.93	1,199.04	1,276.53	1,278.80	921.40	1,033.10
Mean	1,283.55	1,257.23	1,365.68	1,368.89	967.94	1,070.56
Standard deviation (SD)	263.95	163.86	243.93	245.33	157.90	187.13

The cultivation sugarcane in the Mid-Southern region occurs at two different times, known as "cane cultivation 1-year", performed in October, and "cane cultivation 1-year-and-half", performed in January/February (SCARPARI; BEAUCLAIR, 2004), the thermal sum accumulated during the whole crop cycle and in the different phenophases will depend on the planting type. Cane of 1-year reaches its maximum development from November to April, which then decreases due to adverse climatic conditions, whereas that of cane a-year-and-half is restricted from May to September in function of the climate. The greatest development occurs from October to April, and particularly after December, under favorable of rainfall conditions, which coincides with the variation of degree-day found for this crop in Botucatu, São Paulo State (Table 1).

Scarpari and Beauclair (2008) observed for the cultivars SP 80-3280 and RB 85-5156, in the region of Piracicaba, São Paulo State, using the methodology of the Villa Nova et al. (1972), the thermal sum accumulated by the crop was lower than 1600 DD, with the leaf index showing maximum values between 750 e 1000 DD.

Since the adoption of determination coefficient as the only criterion for defining the quality of a given method is not appropriate due to the fact that it does not establish the type or magnitude of the differences between a standard value and a value predicted for estimation of models or other different measurement mechanisms standard, a study on the performance of the methodologies (Table 4) was conducted according to Barros et al. (2009). It was found that only the methodology proposed by correction by photoperiod showed limitations as regards clusters. For all the methodologies, the greater the data clusters, the better results found in the estimation of degree-day. However, since this concept is widely used, both in crops and in pest management, it is important to evaluate these methods in shorter periods of time.

Table 4. Performance of the methodologies for calculated degrees-day compared with 1/3 Simpson rules for the numerical integration with hourly, in different groupings. Data from 2002 to 2005.

Methodology	a_1	SEE (GD)	R^2	d	C	Classes
15 Days						
Arnold (1959)	0.8533	7.72	0.9112	0.9812	0.94	Excellent
Villa Nova et al. (1972)	0.9233	8.56	0.8780	0.9747	0.91	Excellent
Ometto (1981)	0.8246	8.06	0.9031	0.9776	0.93	Excellent
Scarpari and Beauclair (2004)	0.7579	8.11	0.8988	0.9807	0.93	Excellent
Snyder (1985)	0.8181	7.82	0.9095	0.9795	0.93	Excellent
7 Days						
Arnold (1959)	0.8183	5.00	0.8638	0.9686	0.90	Very Good
Villa Nova et al. (1972)	0.8772	5.67	0.8211	0.9535	0.86	Very Good
Ometto (1981)	0.7942	5.17	0.8524	0.9635	0.89	Very Good
Scarpari and Beauclair (2004)	0.7801	5.40	0.8330	0.9729	0.89	Very Good
Snyder (1985)	0.7914	5.12	0.8555	0.9644	0.89	Very Good
3 Days						
Arnold (1959)	0.9033	2.12	0.8924	0.9370	0.88	Very Good
Villa Nova et al. (1972)	0.9366	2.59	0.8429	0.9504	0.87	Very Good
Ometto (1981)	0.8712	2.26	0.8787	0.9246	0.87	Very Good
Scarpari and Beauclair (2004)	0.8859	1.93	0.8691	0.9336	0.88	Very Good
Snyder (1985)	0.8713	2.24	0.8802	0.9253	0.87	Very Good
1 Day						
Arnold (1959)	0.8826	1.91	0.8133	0.9119	0.80	Good
Villa Nova et al. (1972)	0.9945	1.80	0.7764	0.9437	0.83	Good
Ometto (1981)	0.8713	1.03	0.8168	0.9446	0.85	Good
Scarpari and Beauclair (2004)	1.0803	1.69	0.8443	0,9239	0.83	Good
Snyder (1985)	0.8719	2.02	0.7745	0.9343	0.80	Good

a_1: regression coefficient for the linear regression equation: $DDM_{Integrated} = a_1 (DDM_{Methodologies})$; SEE: standard error of estimative (degrees-day); (R^2): coefficient of determination; (d) índex of agreement; (c) perfomance index.

It was possible to verify that, in general, the methods from Ometto (1981) and Snyder (1985) satisfactorily estimated the degrees-day obtained by the hourly numerical integration, considering the performance rates over 70% for all the clusters analyzed (Table 4). Based on the results from the regression analysis with the data of degree-day clustered in periods of 3, 7 and 15-day, we found an increase in the standard error of the estimation (SEE) in relation to the daily analysis. As the time period examined increases, the accumulated values are higher, therefore, the values of SEE tend to be higher. However, were obtained greater correlation coefficients and, consequently, better performance rates of the analyzed methods.

Conclusion

The numerical integration with discretization every six hours showed satisfactory results in the estimation of degrees-day. Conventional methodologies showed satisfactory performances concerning the estimation of degrees-day based in the hourly temperature curve for each day for the clusters 3, 7, 15 and 30-day. Through numerical integration method, the region of Botucatu, in São Paulo State, Brazil, shows a thermal availability from 1,070.6 degrees-day annual for the sugarcane crop.

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