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Predictive thermal sum models suitable for pecan budding and flowering in Brazil

Modelos preditivos de soma térmica adequados para brotação e floração de nogueira-pecã no Brasil

Modelos predictivos de acumulación térmica adecuados para la brotación y floración del Pecán en Brasil

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ABSTRACT
This study aimed at evaluating the characterization of budding and flowering phases of pecan cultivars by means of different thermal sum models. Phenological phases of budding and flowering of cultivars Barton, Chickasaw, Desirable, Elliot, Farley, Jackson, Mohawk, Shawnee, Shoshoni and Success were monitored during three harvests from 2018 to 2021. Five phenological phases were established: beginning of budding, emergence of staminate flowers, emergence of pistillate flowers, beginning of pollen release and beginning of stigma receptivity. In addition to the number of days, five thermal sum models were used: DD base 4.5 °C; DD base 10 °C; DD base 15 °C; DD (Anderson) base 4.0 and DD (Anderson) base 10.0. Thermal requirement of the beginning of budding, emergence of staminate flowers, emergence of pistillate flowers, beginning of pollen release and beginning of stigma receptivity by the DD 4.5 model was around 350 DD°, 670 DD°, 590 DD°, 800 DD° and 760 DD°, respectively. The cultivar Chickasaw has lower thermal requirements in the following phases: budding, emergence of pistillate flowers and stigma receptivity when the DD 4.5 model is used. As the result of its thermal requirement, the cultivar Barton is more easily pollinated by cultivars Farley and Barton itself. The DD 4.5 model was the most suitable one for estimating thermal requirements of pecan budding and flowering.

Keywords: *Carya illinoinensis*, Degree Days, Phenology, Receptivity.

RESUMO
Este estudo teve como objetivo avaliar a caracterização das fases de brotação e floração de cultivares de noz-pecã por meio de diferentes modelos de soma térmica. As fases fenológicas de brotação e floração das cultivares Barton, Chickasaw, Desirable, Elliot, Farley, Jackson, Mohawk, Shawnee, Shoshoni e Success foram monitoradas durante três as safras de 2018 a 2021. Para o estudo foram estabelecidas cinco fases fenológicas: início da brotação, emergência das flores estaminadas, emergência das flores pistiladas, início da liberação de pólen e início da receptividade do estigma. Além do número de dias, foram utilizados cinco modelos de soma térmica: GD base 4,5 °C; GD base 10°C; GD base 15°C; GD (Anderson) base 4.0 e GD (Anderson) base 10.0. O modelo GD 4,5. O modelo GD 4,5 foi o mais adequado para estimar as exigências térmicas da brotação e floração da noz-pecã. A exigência térmica do início da brotação, emergência de flores estaminadas, emergência de flores pistiladas, início da liberação de pólen e início da receptividade do estigma pelo modelo GD 4.5 foi em torno de 350 GD°, 670 GD°, 590 GD°, 800 GD° e 760 GD°, respectivamente. A cultivar Chickasaw apresenta menores exigências térmicas nas seguintes fases: brotação, emergência de flores pistiladas e receptividade do estigma quando utilizado o modelo GD 4,5. Como resultado de sua

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exigência térmica, a cultivar Barton é mais facilmente polinizada pela cultivare Farley e pela própria Barton.

Palavras-chave: *Carya illinoinensis*, Graus-Dias, Fenologia, Receptividade.

RESUMEN
Este estudio tuvo como objetivo evaluar la caracterización de las fases de brotación y floración de cultivares de pecán a través de diferentes modelos de acumulación térmica. Se monitorearon las fases fenológicas de brotación y floración de los cultivares Barton, Chickasaw, Desirable, Elliot, Farley, Jackson, Mohawk, Shawnee, Shoshoni y Success durante tres cosechas del 2018 al 2021. Para el estudio se establecieron cinco fases fenológicas: inicio de brotación, aparición de flores estaminadas, aparición de flores pistiladas, inicio de liberación de polen y inicio de receptividad del estigma. Además del número de días, se utilizaron cinco modelos de acumulación térmica: GD base 4,5 °C; base GD 10°C; base GD 15°C; GD (Anderson) base 4.0 y GD (Anderson) base 10.0. El modelo GD 4.5. El modelo GD 4.5 fue el más adecuado para estimar los requerimientos térmicos de la brotación y floración del pecán. El requerimiento térmico del inicio de la brotación, aparición de flores estaminadas, aparición de flores pistiladas, inicio de liberación de polen e inicio de receptividad del estigma por el modelo GD 4.5 fue de alrededor de 350 GD°, 670 GD°, 590 GD°, 800 GD°. y 760 GD°, respectivamente. El cultivar Chickasaw presenta menores requerimientos térmicos en las siguientes fases: brotación, aparición de flores pistiladas y receptividad del estigma cuando se utiliza el modelo GD 4.5. Como resultado de su requerimiento térmico, el cultivar Barton es polinizado más fácilmente por el cultivar Farley y el propio Barton.

Palabras clave: *Carya illinoinensis*, Grados-Día, Fenología, Receptividad.

1 INTRODUCTION

Pecan (*Carya ilinoinensis*) is a temperate fruit tree whose growing areas have been expanding in Brazil (Fronza *et al*., 2018; Crosa *et al*., 2020; Martins, *et al*., 2023). The estimate is that about 10 thousand ha is used for growing pecan trees in the country. As a result, several questions about their edafoclimatic requirements have been brought up lately (Martins *et al*., 2018).

Southern Brazil is the largest pecan producing region since its growing areas have been expanding (Rolim *et al*., 2022). The Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA) has registered 33 pecan cultivars so far (MAPA, 2024). It triggers the need to determine phenological characteristics of cultivars, mainly in budding

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and flowering phases, and of meteorological variables, because environmental conditions interfere with plant phenology (Tomazetti *et al*., 2015).

Considering the diversity of pecan cultivars, phenological characterization and quantification of the thermal sum or degree days (DD) must be carried out in agreement with genotypes and data on climate in every area (Anzanello *et al*., 2010). Several climate factors must be considered to analyze adaptability and development of species far from their origins (Gray and Brady, 2016). Introduction of the concept of degree days (DD) to describe parameters associated with certain management practices is a viable strategy that enebales better control over the efficient use of resources (Martins *et al*., 2019).

The budding phase, which is the beginning of a new cycle of pecan vegetative growth, is important because it leads to the introduction of products and other cultural treatments (De Marco *et al*., 2021). Flowering is also extremely important due to biological characteristics since pecan is a monoecious plant, i. e., it exhibits separate staminate (aments) and pistillate (bundles) inflorescences but in the same plant (De Marco *et al*., 2021).

Thermal availability exerts direct influence on plant growth and development, i. e., high temperatures accelerate plant metabolism while low ones decrease growth and extend plant cycles (Anzanello and Christo, 2019).

When pecan trees are grown in areas where chill requirements are not thoroughly met, they may exhibit several abnormalities, such as long and poor budding and flowering (Wells, 2017).

To complete their phenological cycles, plants need a certain amount of thermal energy (Borges *et al*., 2014), which is expressed as DD, the difference between the mean room temperature and the base temperature, which is the lowest temperature to develop the vegetatitve cycle (Sato *et al*., 2008).

Thermal sum models have been used for predicting phenological occurrences and for helping to plan orchard management (Bonora *et al*., 2014). Specific thermal sum models have become farmers' allies since they are based on temperatures that occur in production cycles and are quite precise regarding their phenological trends (Drepper *et al*., 2020).

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Therefore, this study aimed at evaluating heat accumulation calculated by different thermal sum models to characterize budding and flowering phases of pecan cultivars grown in the south of Rio Grande do Sul (RS) state, Brazil.

2 MATERIAL AND METHODS

The experiment was carried out in a commercial pecan orchard in Canguçu (31° 28' 31" S; 52° 56' 24" W; altitude 440 m), RS, Brazil for three production cycles: 2018-19, 2019-20 and 2020-21. In the Köppen-Geiger classification, the climate in the area is humid subtropical (Cfa), seasons are well-defined, mean temperature of the coldest month is <22°C and mean annual rainfall is 1476 mm (Dubreuil *et al*, 2013). The soil in the orchard is classified into neossolo (Santos *et al*., 2013). Data on temperature were provided by the CPTEC-INPE automatic station located in Canguçu (31° 24' 21" S; 52° 42' 4" W), RS.

Phenological phases of budding and flowering of the following pecan cultivars were evaluated: Barton, Chickasaw, Desirable, Elliot, Farley, Jackson, Mohawk, Shawnee, Shoshoni and Success. They have been grown since 2010 with no irrigation, 9 x 7 m spacing and density of 158 trees/ha. The experiment had a thoroughly randomized design with ten cultivars and ten replicates. Every replicate consisted of a plant, totalling 100 plots. All plants were subject to the same cultural treatments, such as fertilization, pruning, phytosanitary measures and weed control, which were conducted in the orchard as suggested by the farmer.

To follow the phenology, four branches per plant were marked, i. e., every quadrant (north, south, east and west) got a mark. Evaluations were carried out once a week throughout the vegetative development of plants. In the flowering period, evaluations were conducted every two days. The Biologische Bundesanstalt, Bundessortenamt and CHemical Industry (BBCH) scale, adapted from De Marco *et al* (2021), was used for monitoring pecan phenological phases.

The main phenological phases were classified into five stages. The beginning of budding (BBCH 07) characterized the beginning of the period of vegetative growth.

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Regarding flowering, phenological stages depended on the types of flowers: staminate flower - emergence of male inflorescence (BBCH 54E) and beginning of pollen release (BBCH 65E); pistillate flower - emergence of female flowers (BBCH 54P) and beginning of stigma receptivity (BBCH 65P).

Five models were used for calculating thermal sum values. 1) Degree-days (DD) base 4.5 °C: nothing is added to every hour when temperature is below 4.5 °C while, above it, 4.5 is subtracted from the value of the temperature and, above 25°C, the value to be considered is 25; thus, the maximum that may be accumulated is 20.5 (Richardson *et al*., 1975). 2) DD base 10 °C: nothing is added to every hour when temperature is below 10 °C while, above it, 10 is subtracted from its value and, above 25 °C, the value to be considered is 25; thus, the maximum that may be accumulated is 15.0 (adapted from Richardson *et al*., 1975). 3) DD base 15 °C: nothing is added to every hour when temperature is below 15 °C while, above it, 15 is subtracted from its value and, above 25 °C, the value to be considered is 25; thus, the maximum that may be accumulated is 10 (adapted from Richardson *et al*., 1975). 4) DD (Anderson) base 4: it resulted from the equation [(Tc-Tb)/2]*{1+COS[π/2+π/2*(Th-Tb)/(Tc-Tb)]}, where Tc is the critical temperature (25 °C); Tb is the base temperature (4 °C); Th is the hourly temperature adapted from Anderson *et al*. (1986). 5) DD (Anderson) base 10: it resulted from the equation [(Tc-Tb)/2]*{1+ COS[π/2+π /2*(Th-Tb)/(Tc-Tb)]}, where Tc is the critical temperature (25 °C); Tb is the base temperature (10 °C); Th is the hourly temperature adapted from Anderson *et al* (1986). The number of days was also quantified (McIntyre *et al*., 1982).

The thermal sum was carried out from August 15th on, the day before the period of swollen buds, which shows the movement of buds that precede budding, as proposed by Crosa *et al* (2023).

Model efficiency was analyzed by the coefficient of variation (CV): [(standard deviation/mean) x 100]. CVs were classified into low (below 10%), medium (from 10% to 19.99%), high (from 20% to 29.99%) and very high (above 30%), as proposed by Pimentel-Gomes (1990) and Marques (2021). Data were subject to the analysis of variance by the F-Test. Significant variables ($p<0.05$) had their means compared by the

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Tukey's test. These procedures were carried out by the R program.

3 RESULTS AND DISCUSSION

Results of thermal accumulation in all cultivars show that the predictive models correspond to the phenological development of pecans. In the phase of the beginning of budding, the DD 4.5 model stands out from the other models because it exhibits the lowest CVs in the cases of all cultivars under evaluation (Table 1). Thus, thermal requirement of cultivars in the phases under analysis was evaluated by this model.

Accumulation of DD of cultivars to reach the beginning of budding ranged from 310 DD° to 400 DDº. It should be highlighted that 'Chickasaw' exhibited the lowest thermal requirement to sprout while 'Farley'showed the highest one (Table 1). Regarding their cycles, cultivars may be classified into precocious for the phase of the beginning of budding; this group is composed of Chickasaw, Desirable, Jackson, Elliot and Shoshoni. The median ones are Barton, Shawnee and Success while the late ones are Farley and Mohawk (Table 1).

According to Grajeda *et al* (2020), pecan budding may be more regulated by heat requirements than necessarily by chill hours. Heat units in spring were found to exert more influence on pecan development than chill units in winter. Thus, it implies that high temperatures at the end of August and the beginning of September may favor better budding and crop development (Crosa *et al*., 2023).

According to Putti *et al* (2006), every cultivar has a specific accumulation of thermal sum which is closely related to its chill requirements, i. e., variation in CVs is explained by edafoclimatic requirements of every cultivar. Besides, low temperatures may lead to efficiency in budding, depending on edafoclimatic requirements of every cultivar (Anzanello *et al*., 2010).

Responses to thermal sum models show that, even though the CV is higher in the phase of the beginning of budding, they are in low and medium limits, thus, showing good efficiency and adequate thermal accumulation of pecan trees (Rojo *et al*., 2020).

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Table 1. Accmulation of heat units required by pecan cultivars 'Barton', 'Chickasaw', 'Desirable', 'Elliot', 'Farley', 'Jackson', 'Mohawk', 'Shawnee', 'Shoshoni' and 'Success' to reach the phase of the beginning of budding calculated by five predictive thermal sum models

Cultivars	Models					
	DD* base 4,5 °C	DD base 10 °C	DD base 15 °C	DD (Anderson) base 4,0	DD (Anderson) base 10,0	Number of days
Barton	386,67*	170,39	48,07	389,88	166,27	44,55
CV%	7,98	9,55	11,05	8,45	8,76	5,96
Chickasaw	311,01	130,11	34,45	308,98	129,59	38,11
CV%	12,81	16,09	16,94	13,98	14,40	9,07
Desirable	318,58	133,73	35,08	317,01	132,55	38,83
CV%	7,19	9,59	11,15	8,20	8,55	5,46
Elliot	320,28	140,80	37,68	330,14	139,28	39,66
CV%	13,49	10,82	18,27	14,65	15,31	9,62
Farley	415,29	185,58	53,07	420,50	179,94	47,11
CV%	2,38	3,05	4,08	2,56	2,94	1,67
Jackson	318,58	133,74	35,07	311,01	132,55	38,83
CV%	7,69	9,59	11,15	8,26	8,55	5,46
Mohawk	402,66	178,75	51,05	406,80	173,83	45,94
CV%	8,53	10,30	9,85	9,23	9,49	6,30
Shawnee	346,58	148,33	41,59	346,05	146,38	41,27
CV%	6,77	8,11	5,99	7,37	7,05	5,04
Shoshoni	313,16	130,93	34,29	311,20	129,96	38,33
CV%	4,17	5,00	5,89	4,45	4,68	3,27
Success	346,72	148,73	39,63	347,61	146,17	41,22
CV%	8,07	10,46	13,43	8,80	9,84	5,51

* Accumulation of heat units calculated through each model in the period from August 15 until the beginning of the budding cultivar. DD - Degree days. CV% - Coefficient of variation
Source: Authors

In the phase of emergence of staminate (male) flowers, there is decrease in the CV, which is classified into low in all models under evaluation (Table 2). This result shows the efficiency of the models, but, in the general mean, the pattern of the best response to the thermal sum of the DD 4.5 model is kept. It was also found by the DD 4.5 model in the emergence of pistillate (female) flowers, the lowest CV among all cultivars under investigation (Table 3).

The cultivar that exhibited the lowest thermal sum calculated by the model in the phase of emergence of staminate flowers was 'Desirable' (543.32 DD°) while the one with the highest thermal requirement was 'Mohawk' (631.39 DD°) (Table 2). Concerning phenological cycles, 'Chickasaw' and 'Desirable' are classified into precocious while 'Barton', 'Elliot', 'Jackson', 'Shawnee', 'Shoshoni' and 'Success' are median, and

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'Farley' and 'Mohawk' are late ones (Table 2).

Table 2. Accumulation of heat units required by pecan cultivars 'Barton', 'Chickasaw', 'Desirable', 'Elliot', 'Farley', 'Jackson', 'Mohawk', 'Shawnee', 'Shoshoni' and 'Success' to reach the phase of emergence of staminate flowers calculated by five predictive thermal sum models

Cultivars	Models					
	DD* base 4,5 °C	DD base 10 °C	DD base 15 °C	DD (Anderson) base 4,0	DD (Anderson) base 10,0	Number of days
Barton	611,94*	287,75	89,98	630,09	276,67	64,44
CV%	6,23	6,65	7,32	6,38	6,49	5,54
Chickasaw	546,16	255,48	80,51	560,27	247,47	58,27
CV%	4,02	4,30	4,66	4,11	4,13	3,57
Desirable	543,32	254,05	79,89	577,38	246,07	58,00
CV%	1,39	1,49	1,13	1,47	1,36	1,22
Elliot	586,18	274,86	87,79	602,62	264,59	62,05
CV%	7,12	8,06	10,05	7,36	8,01	5,90
Farley	627,32	29,71	93,91	646,83	285,69	65,66
CV%	3,35	4,30	6,06	3,62	4,55	2,29
Jackson	598,12	281,03	87,81	615,57	270,43	63,11
CV%	3,94	4,31	5,01	4,05	4,24	3,46
Mohawk	631,39	298,71	94,65	650,87	287,34	66,04
CV%	4,32	5,72	7,14	4,55	5,33	3,24
Shawnee	607,42	286,74	92,52	626,08	276,53	63,77
CV%	2,69	3,26	4,80	2,82	3,47	2,19
Shoshoni	599,02	282,00	88,56	616,78	271,70	63,11
CV%	3,62	4,49	6,19	3,87	4,73	2,69
Success	581,87	273,44	85,92	598,42	263,08	61,55
CV%	7,49	7,76	8,34	7,61	7,41	6,78

* Accumulation of heat units calculated through each model in the period from August 15 until the beginning of the emergence of staminate flowers cultivar. DD - Degree days. CV% - Coefficient of variation.
Source: Authors

In the phase of emergence of pistillate flowers, the cultivar with the lowest thermal requirement was 'Chickasaw', whose value of thermal sum was 594.55 DD°, while the one with the highest thermal requirement was Farley, whose value was 781.55 DD° (Table 3). Regarding phenological cycles, precocious cultivars were Chickasaw, Desirable, Jackson and Shawnee, the median ones were Eliott, Shoshoni and Success and the late ones were Barton, Farley and Mohawk (Table 3).

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Table 3. Accumulation of heat units required by pecan cultivars 'Barton', 'Chickasaw', 'Desirable', 'Elliot', 'Farley', 'Jackson', 'Mohawk', 'Shawnee', 'Shoshoni' and 'Success' to reach the phase of emergence of pistillate flowers, calculated by five predictive thermal sum models

Cultivars	Models					
	DD* base 4,5 °C	DD base 10 °C	DD base 15 °C	DD (Anderson) base 4,0	DD (Anderson) base 10,0	Number of days
Barton	755,33*	368,88	121,11	788,27	356,21	75,83
CV%	2,42	2,85	3,67	2,55	2,96	1,88
Chickasaw	594,55	279,12	87,01	611,70	268,57	62,83
CV%	6,88	7,49	8,39	7,12	7,36	5,96
Desirable	608,22	287,75	91,40	626,95	277,66	63,77
CV%	6,22	7,11	8,42	6,52	7,11	5,11
Elliot	678,29	324,52	104,37	702,35	312,51	69,88
CV%	5,02	6,33	8,47	5,42	6,61	3,53
Farley	781,55	382,60	125,63	816,50	369,03	78,11
CV%	3,77	4,40	4,61	4,09	4,52	2,94
Jackson	608,68	286,88	90,31	626,83	276,41	64,05
CV%	2,82	3,25	4,25	2,99	3,38	2,34
Mohawk	767,73	374,57	122,52	801,09	361,00	77,05
CV%	6,28	7,32	7,86	6,76	7,46	4,90
Shawnee	601,19	281,65	82,69	621,04	265,08	62,88
CV%	2,18	2,72	3,85	2,37	2,95	1,61
Shoshoni	601,19	281,69	82,65	621,04	265,08	66,88
CV%	2,18	2,72	3,85	2,37	2,95	1,61
Success	717,14	345,68	111,13	744,31	331,68	73,22
CV%	3,04	3,60	4,35	3,25	3,70	2,33

* Accumulation of heat units calculated through each model in the period from August 15 until the beginning of the emergence of pistillate flowers cultivar. DD - Degree days. CV% - Coefficient of variation

Source: Authors

According to Guo *et al* (2013), a study carried out in China with Chinese chestnuts (*Castanea mollissima* Blume) and red dates (*Zizyphus jujube* Mill.) showed that the beginning of flowering was more dependent on heat accumulation that on chill accumulation. This result was also found by Alonso *et al*. (2005) who showed that heat requirements of peach (*Prunus persica* (L.) Batsch.) were more important to regulate flowering than chill requirements in the cold weather in Saragoça, northeastern Spain. Sparks (1993) reported that pecan budding may occur even with no chill accumulation since heat requirements are satisfied.

In the phase of the beginning of pollen release, there is a pattern which is similar to the one observed in the phase of emergence of staminate flowers, i. e., decrease in mean CV%, with the use of the DD 4.5 model which exhibited the lowest CV among thermal

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sum models (Table 4). Regarding the phase of stigma receptivity, the DD 4.5 model exhibited the lowest mean CV for the cultivars (Table 5).

Table 4. Accumulation of heat units required by pecan cultivars 'Barton', 'Chickasaw', 'Desirable', 'Elliot', 'Farley', 'Jackson', 'Mohawk', 'Shawnee', 'Shoshoni' and 'Success' to reach the phase of the beginning of pollen release by five predictive thermal sum models

Cultivars	Models					
	DD* base 4,5 °C	DD base 10 °C	DD base 15 °C	DD (Anderson) base 4,0	DD (Anderson) base 10,0	Number of days
Barton	837,81*	415,62	137,95	880,04	401,83	82,33
CV%	3,87	4,35	4,64	4,07	4,34	3,17
Chickasaw	779,22	382,08	125,77	814,62	368,96	77,77
CV%	3,68	4,42	5,17	3,97	4,58	2,76
Desirable	776,60	380,38	125,19	811,33	367,11	77,61
CV%	2,01	2,38	2,83	2,15	2,46	1,55
Elliot	788,93	387,51	127,80	825,17	374,15	78,55
CV%	2,84	3,23	3,47	3,01	3,24	2,31
Farley	838,96	415,00	136,93	880,58	400,50	82,66
CV%	1,48	1,75	2,19	1,56	1,82	1,17
Jackson	797,72	392,94	130,13	835,23	379,83	79,16
CV%	4,10	4,77	5,23	4,41	4,92	3,20
Mohawk	854,21	423,60	140,28	897,31	408,96	83,88
CV%	2,35	2,89	3,64	2,53	2,99	1,78
Shawnee	779,83	382,38	126,08	815,00	369,17	77,83
CV%	3,42	3,96	4,19	3,68	4,03	2,71
Shoshoni	755,83	368,47	120,61	788,42	355,54	76,00
CV%	3,58	4,45	4,81	4,09	4,50	2,99
Success	853,55	423,81	140,71	896,57	409,53	83,72
CV%	3,71	4,39	5,31	3,95	4,56	2,87

*Accumulation of heat units calculated through each model in the period from August 15 until the start of beginning of pollen cultivar. DD - Degree days. CV% - Coefficient of variation
Source: Authors

Table 5. Accumulation of heat units required by pecan cultivars 'Barton', 'Chickasaw', 'Desirable', 'Elliot', 'Farley', 'Jackson', 'Mohawk', 'Shawnee', 'Shoshoni' and 'Success' to reach the phase of the beginning of stigma receptivity by five predictive thermal sum models

Cultivars	Models					
	DD* base 4,5 °C	DD base 10 °C	DD base 15 °C	DD (Anderson) base 4,0	DD (Anderson) base 10,0	Number of days
Barton	837,37*	415,79	138,48	879,79	402,44	82,22
CV%	3,51	4,01	4,43	3,70	4,05	2,81
Chickasaw	668,87	318,76	102,20	691,27	306,49	69,22
CV%	1,01	1,32	2,05	1,08	1,40	0,68
Desirable	729,65	354,19	115,69	759,62	341,77	73,83
CV%	2,78	3,20	3,51	2,96	3,25	2,23
Elliot	776,23	380,01	124,65	811,17	366,76	77,61
CV%	5,51	6,30	6,73	5,83	6,27	4,41

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Farley	851,92	421,91	139,20	894,73	407,07	83,77
CV%	1,43	1,75	2,26	1,52	1,84	1,04
Jackson	678,17	324,40	104,51	701,91	312,28	69,88
CV%	2,45	3,02	3,84	2,64	3,10	1,78
Mohawk	862,60	428,53	142,66	906,88	414,50	84,44
CV%	3,00	3,58	4,29	3,19	3,68	2,27
Shawnee	693,82	333,34	108,33	718,82	321,06	71,11
CV%	3,33	3,90	4,87	3,50	3,95	2,60
Shoshoni	755,26	367,90	120,33	787,54	354,75	76,00
CV%	3,22	3,72	3,92	3,44	3,75	2,54
Success	792,00	387,64	126,91	827,57	373,49	79,11
CV%	2,80	3,19	3,08	3,02	3,19	7,26

*Accumulation of heat units calculated through each model in the period from August 15 until the start of beginning of stigma receptivity cultivar. DD - Degree-days. CV% - Coefficient of variation
Source: Authors

Flowering periods also exhibit variable accumulation, a fact that may be caused by requirements of every cultivar. However, thermal sums which result mainly from the phases of stigma receptivity and pollen release show that similarity in thermal requirement may define higher synchronization efficiency of phenological phases of flowering. The thermal sum aims at predicting phenological phases and showing the most adapted cultivars to edafoclimatic conditions in a certain region (Verdugo-Vásquez *et al.*, 2017).

Molitor *et al* (2014) evaluated different temperatures of thermal sums in grapevines and observed that they responded to low temperatures around 3°C, which is below the base temperature used for this crop (10°C). Grapevine budding and flowering also gave significant responses to temperatures above the base temperature.

In the pollination phase, the cultivar with the lowest requirement to reach the phase of pollen release was ‘Shoshoni’ (755.83 DD°) while the one with the highest requirement was ‘Mohawk’ (854.21 DD°) (Table 4). ‘Shoshoni’ was classified into precocious while ‘Barton’, ‘Chickasaw’, ‘Desirable’, ‘Elliot’, ‘Farley’, ‘Jackson’ and ‘Shawnee’ were median and ‘Mohawk’ and ‘Success’ were late (Table 4).

At the beginning of receptivity, the cultivar with the lowest thermal requirement was ‘Chickasaw’ (668.87 DD°) (Table 5) and the one with the highest thermal requirement in this phase was ‘Mohawk’ (862.60 DD°). Cultivars were classified into precocious (‘Chickasaw’ and ‘Jackson’), median (‘Barton’, ‘Desirable’, ‘Elliot’, ‘Farley’,

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'Shoshoni' and 'Success') and late ('Mohawk') (Table 4).

The analysis of thermal requirement in the phase of the beginning of stigma receptivity of the cultivar Barton (Table 4), which is the main cultivar in the orchards, shows that its requirement is 837.37 DD. Cultivars with similar requirements of thermal sums in the period of pollen release (Table 5) are 'Farley' (838.96 DD) and 'Barton' itself (837.81 DD). Both have the highest potential to pollinate female flowers of 'Barton'.

This factor is quite important. According to De marco *et al* (2023), in an experiment of cross-pollination with pecan cultivars, 'Barton' showed that pollination of a plant by pollen of the same cultivar tends to decrease fruit size.

The DD 4.5 model may have had high correlation with the number of days because it encompasses a large range of temperature and improves its response to the ones of specific temperature. This fact induces higher efficiency to models that do not consider temperatures above or below critical temperatures (Fiorentin *et al*., 2015).

Therefore, knowledge of thermal requirements of pecan crops helps farmers to plan orchards and implant new ones mainly in terms of synchronization of periods of pecan flowering.

4 CONCLUSIONS

The DD 4.5 model reached the lowest values of CVs in the five phenological phases under evaluation and proved to be the most applicable one to predict thermal sums in the pecan culture.

The cultivar Chickasaw exhibited the lowest values of thermal sums in the phases of beginning of budding, emergence of pistillate flower and stigma receptivity calculated by the most significant model, i. e., DD 4.5. In the phases of emergence of staminate flowers and beginning of pollen release, they were 'Desirable' and 'Shoshoni', respectively, by the DD 4.5 model.

Cultivars with thermal requirements to release pollen, which coincide with thermal requirements for the beginning of receptivity in 'Barton', were 'Farley' and 'Barton' itself.

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