Comunicata Scientiae
Horticultural Journal

ORIGINAL ARTICLE
published: 20 September 2023
https://doi.org/10.14295/CS.v14.4054

Phenology and phyllochron of seven strawberry cultivars grown in substrate and greenhouse in the Brazilian subtropics

Yuri dos Santos Deggerone[1], Thomas dos Santos Trentin[1], Sabrina Carla Kujawa[1], Gustavo Eduardo Albrecht[1], Rudinei Fante[1], Ivan Junior Kaspary[1], Michele Fornari[1], José Luís Trevizan Chiomento[1]*

[1]University of Passo Fundo, Passo Fundo, Brazil
*Corresponding author, e-mail: jose-trevizan@hotmail.com

Abstract

Knowing the phenology and phyllochron of strawberry cultivars allows the establishment of phytotechnical managements aimed at enhancing the productive chain of this horticultural crop. Thus, the objective of this work was to investigate whether phenology and phyllochron differ among strawberry cultivars grown in substrate and greenhouse. The treatments were seven strawberry cultivars arranged in a randomized block design, with four replications. Leaf emission rate, occurrence, and duration of phenological stages were evaluated. 'Fronteras' was considered the earliest to start fruiting, as it had the lowest phyllochron value, while 'Albion' was the latest. Through multivariate analysis, the formation of two groups among strawberry cultivars was observed according to their phenological characteristics. Group 1 gathered the five strawberry cultivars classified as having neutral-days in terms of flowering and group 2 was composed of the two short-day cultivars. It is concluded that, under the cultivation conditions of southern Brazil, 'Fronteras' is the earliest to start the fruit harvest, provided it is transplanted in May, and 'Albion' is the latest. Neutral-day cultivars have a shorter transplant cycle until the beginning of harvest, while short-day cultivars require a longer interval for this transition, with a prolonged vegetative period.

Keywords: *Fragaria X ananassa Duch.*, leaf emission rate, multivariate analysis, phenological stages

Introduction

As one of the most economically valuable horticultural crops, strawberry (*Fragaria* X *ananassa* Duch.) is reaching new agricultural frontiers on a global scale (Chiomento et al., 2020). Brazil occupies the 17th position among the largest producers of strawberries, with a cultivated area of 5,200 hectares (ha) and a production of more than 200,000 tons (t), which represents an average productivity of approximately 38.5 t ha^{-1} (Antunes at al., 2021).

In the last decade, new strawberry cultivars are being adapted to soil and climate conditions of the producing regions. Due to the possible environmental impacts caused by climate change (Zhang et al., 2016), the phenology and phyllochron of strawberry cultivars, grown in substrate and greenhouse, are constantly changing and, therefore, are not fully understood. Due to the geoclimatic and ecophysiological interactions that occur in agroecosystems, strawberry development needs to be frequently studied to know the adaptability of cultivars in relation to the cultivation environment.

Phenology studies the main morphological changes that occur in the plant during its development. Knowledge about the phenology of a species or cultivar works as a tool for predicting events and making decisions in relation to crop management (Tomazetti et al., 2015). One way used to calculate the number of leaves, in mathematical models, is through the concept of phyllochron, defined as the time interval between the appearance of two successive leaves on the main crown of the plant (Xue et al., 2004).

Over the years, the development of the strawberry crop has undergone changes in its phenology (Costa et al., 2016). This includes, mainly, the beginning of flowering and fruiting. Temperature and photoperiod are the two main environmental signals that regulate

Received: 03 August 2022
Accepted: 21 March 2023

flowering in strawberry cultivars classified as short-day (SD), neutral-day (ND), and long-day (LD) (Durner, 2016). These processes are directly related to the time of transplanting the daughter plants (Costa et al., 2017).

For the establishment of commercial crops, the daughter plants used by producers in the Brazilian subtropics are mainly developed in Argentine and Chilean Patagonia. This makes it difficult for the daughter plants to be available at the time indicated for the establishment (early autumn) and conditions the time of transplanting to the delivery of the daughter plants. It was observed that, due to this irregularity, changes occur in the crop cycle. These changes may be related to the development of the daughter plant in the nursery, which needs cold hours to accumulate carbon in its crown and, after its transplant, to start the flowering process (Tazzo et al., 2015). However, Chilean and Argentinean nurseries do not provide producers with information regarding the accumulation of cold by daughter plants (Costa et al., 2017).

The literature on the phenology of horticultural crops shows the impact caused by temperature changes on plant growth and development (Wang et al., 2015). Thus, the occurrence and duration of phenophases have interannual variability, mainly at the beginning and end of the growth period (Lovaisa et al., 2015).

Therefore, here we investigated whether phenology and phyllochron differ among strawberry cultivars in substrate and greenhouse in the Brazilian subtropics.

Materials and Methods

The plant material for the experiment corresponded to bare-root strawberry daughter plants, received from the Llahuén/Chilean Patagonia nursery (33° 50' 15.41" S, 70° 40' 03.06" W). The research was conducted in the municipality of Passo Fundo (28° 15' 41" S 52° 24' 45" W), Rio Grande do Sul (RS), Brazil, from May (autumn) to October (spring) 2021 in a 430 m^2 greenhouse, with semicircular roof, installed in the northwest-southeast direction. The galvanized steel structure was covered with a low-density polyethylene film (150 micron thick) with anti-ultraviolet additive.

We studied seven strawberry cultivars ('Albion', 'Aromas', 'Camino Real', 'Fronteras', 'Monterey', 'Portola', and 'San Andreas'), arranged in a randomized block design with four replications. Each plot consisted of six plants.

'Camino Real' and 'Fronteras' cultivars are classified as short-day (SD) and 'Albion', 'Aromas', 'Monterey', 'Portola', and 'San Andreas' cultivars are classified as neutral-day (ND) in relation to flowering.

The strawberry cultivation system used was in substrate. The daughter plants were transplanted from May to July (winter) 2021, as they were received from the Chilean nursery, in containers measuring 1 m long x 0.5 m wide, filled with the Dallemole® substrate. This material is composed of pine bark, rice husk, rice ash, and class A organic compost. The plants were distributed at a spacing of 0.17 m, with one row of plants per container. The physical and chemical characterization of the substrate is shown in (**Table 1**).

Table 1. Physical and chemical properties of the Dallemole® substrate

Physical properties[1]						
D	TP	AE	RAW	BW	RW	
(kg m^{-3})	(m^3 m^{-3})					
212	0.885	0.502	0.144	0.017	0.222	
Chemical properties[2]						
N	P_2O_5	K_2O	OC	pH	EC	C / N
% (m m^{-1})					mS cm^{-1}	ratio
0.82	0.58	<0.25	26.10	7.6	1.05	33.42

[1]D: density; TP = total porosity; AE: aeration space; RAW: easily available water; BW: buffer water; RW: remaining water. [2]N: nitrogen; P_2O_5: phosphorus pentoxide; K_2O: potassium oxide; OC: organic carbon; pH: hydrogen potential; EC: electric conductivity; C/N ratio: relationship between carbon and nitrogen.

We use localized irrigation (drip tapes), in the automated system, with a flow rate of 1.41 L h^{-1} per dripper. The irrigation regimen was activated seven times a day, with total wetness of 14 minutes. The nutrient solutions supplied to the plants, weekly, were made according to (Furlani & Fernandes Júnior, 2004), containing: calcium nitrate, potassium nitrate, monoammonium phosphate, monopotassium phosphate, magnesium sulfate, boric acid, copper sulphate, manganese sulphate, zinc sulfate, sodium molybdate, and iron chelate.

During the execution of the experiment, through a meteorological mini-station, the air temperature (**Figure 1**) and the photoperiod (**Figure 2**) inside the greenhouse were monitored. According to the microclimatic characterization of the cultivation environment, absolute minimum and maximum temperatures of -2.8°C (July 29, 2021) and 39.7°C (September 12, 2021) were recorded, respectively (Figure 1). The general average temperature was 17.4°C (Figure 1). During the experiment, 43 days were recorded with temperatures below 7.0°C (Figure 1). The photoperiod ranged from 10.2 to 12.7 hours of light (Figure 2).

The phyllochron was evaluated by counting the number of leaves, weekly, from the beginning of leaf emission (from the main crown) until the harvest of the first fruit. A new leaf was considered to be emitted when visible, approximately 1 cm long.

The average daily temperature (ADT) was

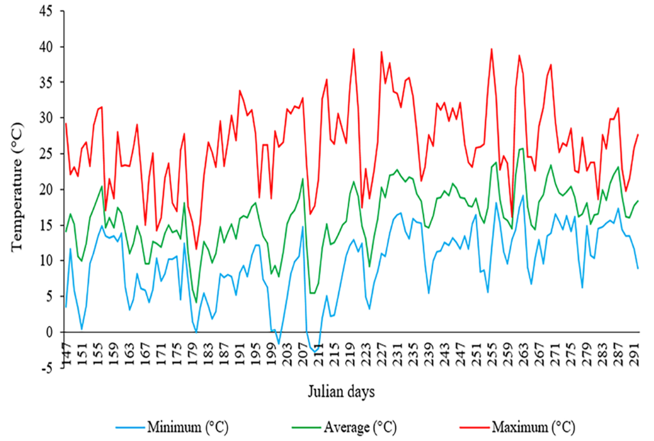

Figure 1. Absolute temperatures recorded in the cultivation environment during the experiment (May to October 2021).

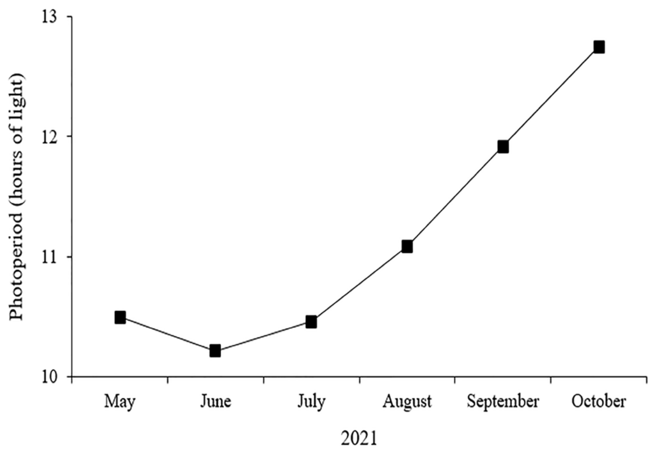

Figure 2. Photoperiod recorded in the cultivation environment during the experiment (May to October 2021).

evaluated by the equation that calculates the arithmetic mean of the temperatures recorded by the meteorological mini-station every hour:

$$ADT\ (°C) = \frac{(t0 + t1 + t2 + \ldots\ldots + t23)}{24} \qquad (1)$$

The daily thermal sum (DTS) was calculated according to (Gilmore Junior & Rogers, 1958) and (Arnold, 1960):

$$DTS\ (°C\ day^{-1}) = ADT - BT \qquad (2)$$

Base temperature (BT) is defined as the minimum temperature below which no leaves appear. The BT for strawberry cultivation was considered as 7.0°C (Antunes et al., 2006). DTS has been accumulated since the transplant of strawberry daughter plants, resulting in the accumulated thermal sum (ATS), that is, ATS (°C day^{-1}) = Σ DTS.

A regression analysis was performed between the number of leaves and the ATS. The angular coefficient of the linear regression is considered the leaf appearance rate (leaves °C day^{-1}) and the phyllochron (°C day leaf^{-1}) was estimated by the inverse of the angular coefficient of the linear regression (Klepper et al., 1982; Kirby, 1995).

Phenological evaluations consisted of weekly observations and notes of five strawberry development stages (**Figure 3**) according to the phenological scale proposed by (Meier et al., 1994) and coding by Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie (BBCH). After the emission of the first inflorescence (stage 55), the primary flower was marked with satin tape to make observations and notes on the later stages (60, 71, and 87).

To estimate the phyllochron, we performed a linear regression between the number of leaves and ATS. The phyllochron was considered as the inverse of the slope of the linear regression. Data referring to phenology were presented in a descriptive way. The date of occurrence of each phenological stage was defined based on the measure of central tendency referring to the mode, which represented the most frequent value in the data set.

Also, the phenological data were submitted to multivariate analysis, with the aid of the Genes® program (Cruz, 2016). To verify the dissimilarity among the cultivars, we used the Mahalanobis distance (D^2) and, through it, we obtained the relative contribution of the phenological stages to the divergence among the seven cultivars, according to (Singh, 1981). The unweighted pair group

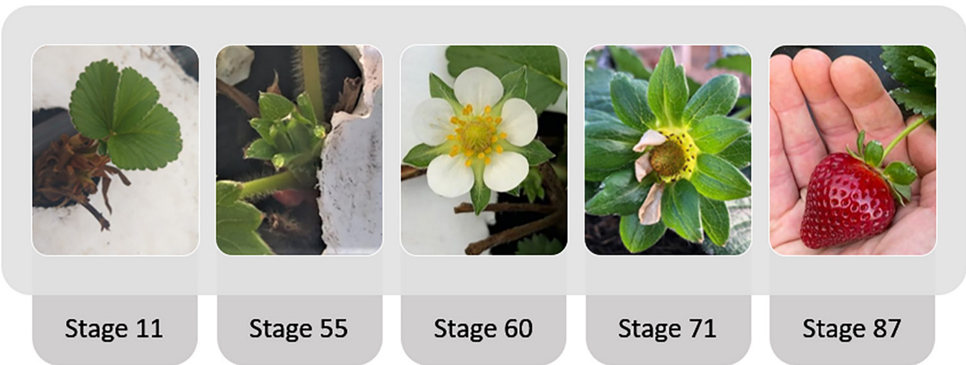

Figure 3. Phenological stages of strawberry considered for evaluation, according to the scale described by Meier et al. (1994). Stage 11: first leaf unfolded; stage 55: first set flowers at the bottom of the rosette; stage 60: first flowers open (primary); stage 71: receptacle protruding from sepal whorl; stage 87: main harvest (more fruits coloured).

method with arithmetic mean (UPGMA) was used for the grouping analysis of cultivars in terms of phenological data, based on the D^2 matrix. After obtaining the dendrogram, it was cut using 85% dissimilarity as a criterion and the grouping was validated using the cophenetic correlation coefficient (CCC).

Results and Discussion

In descending order, the leaf emission rate was 0.0116, 0.0093, 0.0085, 0.0074, 0.0070, 0.0062, and 0.0059 leaves accumulated at each °C day^{-1} for the 'Fronteras', 'Camino Real', 'Monterey', 'Aromas', 'San Andreas', 'Portola', and 'Albion' cultivars, respectively (**Figure 4**), with phyllochron of 86.21, 107.53, 117.65, 135.14, 142.86, 161.29, and 169.49°C day $leaf^{-1}$, in the same order of cultivars, to produce two consecutive leaves (Figure 4). Thus, 'Fronteras' was considered the earliest to start the fruit harvest, as it presented the lowest phyllochron value (86.21°C day $leaf^{-1}$), while 'Albion' was the latest one, as it had the highest phyllochron value (169.49°C day $leaf^{-1}$).

In this study, the interval of days for the emission of a new leaf varied from 9.6 ('Fronteras') to 14.0 ('Albion'). The linear relationships observed in the present study, with determination coefficients (R^2) greater than 0.91 between the number of leaves and ATS (Figure 4), indicated that temperature was one of the decisive factors for the emission of leaves in the analyzed strawberry cultivars.

'Camino Real' and 'Fronteras', both from SD, had a longer duration of stage 11, of 60 and 61 days, respectively, while 'Monterey' remained only at this stage for five days before starting flowering, which occurred 20 days after transplanting the daughter plants (**Table 2**).

The beginning of flowering (stage 55) of 'Albion', 'Monterey', 'Portola', and 'San Andreas' occurred in July and for the other cultivars in August (Table 2). The onset of flowering of the ND cultivars ranged from 20 ('Monterey' and 'Portola') to 42 days ('Albion') after daughter plants transplantation, a process initiated earlier in relation to the SD cultivars that were the first to be transplanted (Table 2).

'Monterey' was the first to open the primary flower of the inflorescence (stage 60) and to start fruiting (stage 71), while 'Camino Real' was the last cultivar to reach both stages (Table 2). The harvest of the first fruit (stage 87) was initiated in 'Fronteras' (Table 2), confirming its precocity indicated by the phyllochron analysis (Figure 4). Despite demanding the longest number of days from transplanting to harvesting, 'Camino Real' and 'Fronteras' presented the shortest time interval from the beginning of flowering to fruit maturation (Table 2).

The ND cultivars had a shorter cycle considering the transplant date until the beginning of the harvest (Table 2). This interval ranged from 69 ('Aromas' and 'Portola') to 92 days ('Albion'). The SD cultivars had a longer cycle (from transplant to harvest), which was 105 days for 'Fronteras' and 107 days for 'Camino Real' (Table 2). Thus, the precocity of these two cultivars in terms of harvesting the first fruit was due to their earlier transplant in relation to the other cultivars.

The thermal sum that was accumulated from transplanting to harvesting the first fruit for each cultivar was 3,083.33°C day^{-1} for 'Albion', 3,245.29°C day^{-1} for 'Aromas', 3,060.70°C day^{-1} for 'Camino Real', 2,825.39°C day^{-1} for 'Fronteras', 2,658.66°C day^{-1} for 'Monterey', 3,166.03°C day^{-1} for 'Portola', and 2,927.14°C day^{-1} for 'San Andreas' (**Figure 5**).

The earliest cultivar regarding the beginning of flowering was 'Monterey', which required 360.82°C day^{-1} to start flowering (Figure 5). The cultivar performed this thermal sum in just 20 days. 'Fronteras' started fruiting by accumulating 744.28°C day^{-1} and, after 14 days, this cultivar reached 911.11°C day^{-1}, when the main fruit was harvested and characterized 'Fronteras' as the earliest cultivar (Table 2, Figure 4, and Figure 5). 'Albion' needed to accumulate 987.85°C day^{-1} to reach harvest and, therefore, it was considered the latest one (Table 2, Figure 4, and Figure 5).

Through multivariate analysis, it was observed that

Table 2. Phenological dates of seven strawberry cultivars grown in substrate and greenhouse

Cultivars	T[1]	Stage 11[2]		Stage 55		Stage 60		Stage 71		Stage 87	TTF	TFH	TTH
		O	D	O	D	O	D	O	D	O			
'Albion'	06.14.21	06.28.21	28	07.26.21	25	08.20.21	3	08.23.21	22	09.14.21	42	50	92
'Aromas'	07.06.21	07.14.21	21	08.04.21	16	08.20.21	5	08.25.21	19	09.13.21	29	40	69
'Camino Real'	05.26.21	06.07.21	60	08.06.21	17	08.23.21	7	08.30.21	11	09.10.21	72	35	107
'Fronteras'	05.26.21	06.02.21	61	08.02.21	16	08.18.21	7	08.25.21	14	09.08.21	68	37	105
'Monterey'	06.24.21	07.09.21	05	07.14.21	16	07.30.21	14	08.13.21	30	09.12.21	20	60	80
'Portola'	07.06.21	07.16.21	10	07.26.21	23	08.18.21	5	08.23.21	21	09.13.21	20	49	69
'San Andreas'	06.24.21	07.09.21	17	07.26.21	14	08.09.21	9	08.18.21	26	09.13.21	32	49	81

[1]T: strawberry daughter plant transplant date; O: date of occurrence of the stage; D: duration, in days, of the stage; TTF: time, in days, from transplanting to beginning of flowering; TFH: time, in days, from beginning of flowering to harvest of first fruit; TTH: time, in days, from transplanting to harvesting the first fruit. [2]Stage 11: first leaf unfolded; stage 55: first set flowers at the bottom of the rosette; stage 60: first flowers open (primary); stage 71: receptacle protruding from sepal whorl; stage 87: main harvest (more fruits coloured).

there was heterogeneity among the seven strawberry cultivars studied. According to their phenological characteristics, two groups of cultivars were generated by the UPGMA method, based on the Mahalanobis distance matrix, and by the Tocher optimization method. Based on the Mahalanobis distance matrix, the dissimilarity was illustrated by a dendrogram generated by the UPGMA method (**Figure 6**), whose adjustment, calculated by the cophenetic correlation coefficient, was 87%, indicating adequacy of the model.

It was observed that the grouping was based on the photoperiod responses of strawberry cultivars in relation to flowering (Figure 6). Group 1 gathered the five cultivars classified as ND (Figure 6). This group showed similar performance in relation to the occurrence of stage 11, the time (in days) between transplanting and the beginning of flowering and the interval of days from transplanting to harvesting the first fruit (Table 2). Group 2 consisted of ‘Camino Real’ and ‘Fronteras’, both from SD (Figure 6). These two cultivars were similar in terms of the occurrence/duration of stage 11, the interval of days from transplanting to the beginning of flowering and the time (in days) between transplanting and harvesting the first fruit (Table 2).

The phenological stage that most contributed to the divergence between the two groups formed (Figure 6) corresponded to the expansion of the first leaf (stage 11), which explained 65.22% of the variability among the cultivars studied (**Table 3**).

Here, we showed that the phyllochron and phenology of strawberry cultivars, in the Brazilian subtropics, are important biotools to determine the precocity of materials to start fruit production.

The literature regarding the strawberry phyllochron is robust, with studies developed evaluating several cultivars and in different producing regions, agroecosystems, and years of cultivation (Rosa et al., 2011; Costa et al., 2019; Chiomento et al., 2020; Costa et al., 2021). Plants with higher phyllochron values have a lower leaf emission rate; thus, they need a higher number of °C day^{-1} for the emergence of two consecutive leaves.

Table 3. Relative contribution (Sj) of phenological stages to dissimilarity among strawberry cultivars

Phenological stages[1]	Sj	Sj (%)
11	13.596.66	65.22
55	2.540.00	12.18
60	2.964.00	14.21
71	1.498.00	7.18
87	248.00	1.18

[1]Stage 11: first leaf unfolded; stage 55: first set flowers at the bottom of the rosette; stage 60: first flowers open (primary); stage 71: receptacle protruding from sepal whorl; stage 87: main harvest (more fruits coloured).

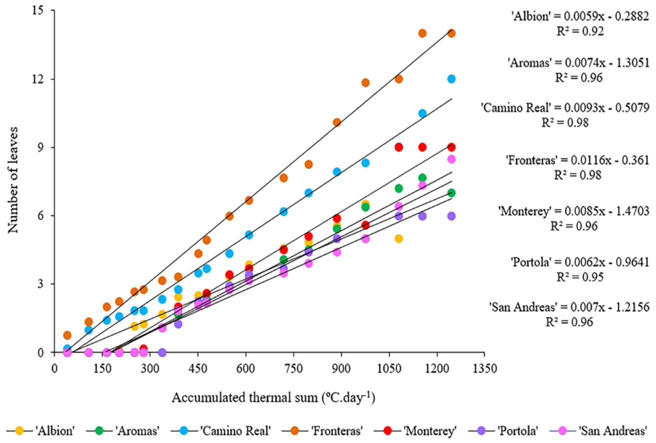

Figure 4. Estimated phyllochron, calculated from the accumulated thermal sum and the number of leaves (of the main crown) of seven strawberry cultivars.

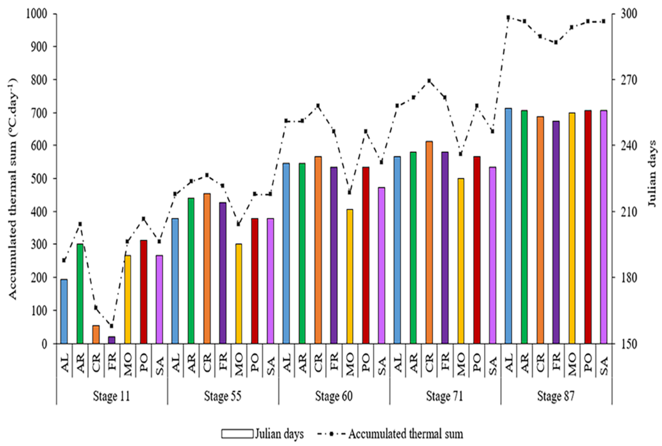

Figure 5. Accumulated thermal sum and Julian days required for each cultivar to reach the main strawberry phenological stages. AL: ‘Albion’; AR: ‘Aromas’; CR: ‘Camino Real’; FR: ‘Fronteras’; MO: ‘Monterey’; PO: ‘Portola’; SA: ‘San Andreas’. Stage 11: first leaf unfolded; stage 55: first set flowers at the bottom of the rosette; stage 60: first flowers open (primary); stage 71: receptacle protruding from sepal whorl; stage 87: main harvest (more fruits coloured).

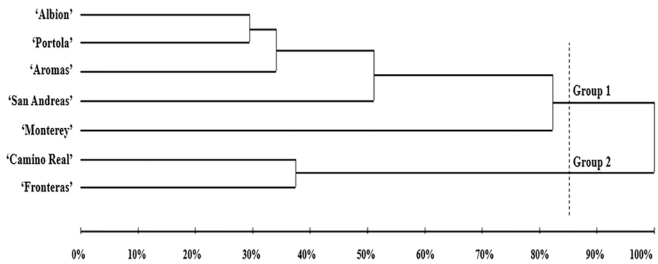

Figure 6. Grouping by the unweighted pair group method with arithmetic mean (UPGMA) of the cultivars in relation to the occurrence (in Julian days) of the main phenological stages of the strawberry.

However, in the vegetative stage, the leaf emission rate must be higher (consequently, the phyllochron is lower) for the plant to produce more leaves before flowering, ensuring a greater number of fruits (Rosa et al., 2011).

It was observed that the time, in days, to issue a new leaf ranged from 9.6 ('Fronteras') to 14.0 ('Albion'). The interval between the emission of two consecutive leaves in the strawberry crop varies from 8 to 12 days and temperature is the main factor that interferes in this phenomenon (Galletta & Himelrick, 1990). When the crop cycle occurs at the recommended time for its cultivation, the response of leaf emission in relation to air temperature is usually linear (Streck et al., 2007), which was confirmed in this work (Figure 4). It is reiterated that 'Fronteras' was considered the earliest to start harvesting fruit (phyllochron of 86.21°C day leaf^{-1}), while 'Albion' was the latest (phyllochron of 169.49°C day leaf^{-1}). Other studies have also reported that SD strawberry cultivars are earlier to start harvesting fruit than those of ND (Costa et al., 2019; Chiomento et al., 2020).

Photoperiod and temperature are the main environmental factors that condition the adaptability of strawberry cultivars to the place of cultivation (Sønsteby & Heide, 2017). Still, both are characterized as extrinsic signals to the plants that regulate the ontogeny of strawberry flowers (Durner, 2016). Among them, the temperature can influence some physiological processes of the culture, such as the need for cold accumulation in plants' crown, the anthesis, and the ripening time of the fruits (Kruger et al., 2012).

The photoassimilates produced in the leaves, which must be stored in the crown of the plants, are crucial for the production of strawberries. These reserves in the form of carbohydrates are associated with the temperatures recorded during the daughter plant development period, still in the nursery (Costa et al., 2017). Thus, the temperature conditions in which the daughter plants are developed must meet the needs of each cultivar (Hidaka et al., 2017) so that, right after the transplant, all the energy is directed to floral induction and, later, to fruiting (Torres-Quezada et al., 2015).

In the strawberry crop, the interaction between photoperiod and temperature can control the flowering of SD cultivars. These cultivars ('Camino Real' and 'Fronteras') are known to flower when submitted to a photoperiod of less than 14 h and under temperatures below 15°C (Hidaka et al., 2017). ND cultivars ('Albion', 'Aromas', 'Monterey', 'Portola', and 'San Andreas') are not photoperiod responsive and thus flower due to temperature (thermoperiodic response to flowering) (Durner, 2016). Therefore, the differentiation of floral buds in this group of ND cultivars occurs via an intrinsic stimulus of the plant (autonomous flowering route) or when several cycles of temperatures below 10°C occur (Heide et al., 2013). Understanding these factors allows producers to determine the time of transplanting, flowering and beginning of harvest (Costa et al., 2021). These ecophysiological contrasts, which group the cultivars in terms of flowering (Figure 6), were evidenced in this study (Figure 1 and Figure 2).

After transplanting the SD cultivars (Table 2) it was verified that the temperature (Figure 1) and photoperiod (Figure 2) were in an optimal range for anthesis to occur. However, this process took place approximately 70 days after transplantation (Table 2). As Chilean nurseries do not provide producers with information related to the cold accumulation in the daughter plants, according to models to estimate the number of hours of cold in the conditions of Chilean Patagonia (Byrne & Bacon, 1992), where the mother plants are multiplied, the temperature may not be sufficient for the accumulation of cold necessary for anthesis to occur (Costa et al., 2017). This suggests that, after transplanting, 'Camino Real' and 'Fronteras' had to fulfill their requirement of accumulating cold hours to later start flowering. This may have contributed to both cultivars demanding a longer time interval, in days, from transplanting to the beginning of harvest (Table 2).

Due to the longer vegetative cycle of SD cultivars, there was a delay in the beginning of their reproductive cycle. This made the cultivation of 'Camino Real' and 'Fronteras' idle, since the plants remained in the field for a long time, requiring intensive management and cultural treatment, in addition to being exposed to certain elements (pests and diseases, for example). Under adequate photoperiod and temperature conditions, it is believed that if the daughter plants of both cultivars had been harvested later in the Chilean nursery, their vegetative cycle, after transplantation in the agroecosystems of southern Brazil, would be shorter and anthesis would occur earlier. However, to prove this hypothesis, other studies need to be conducted considering different harvesting times of daughter plants and their subsequent transplantation in strawberry-producing regions.

In the Brazilian subtropics, the floral induction of strawberry can be delayed for two reasons: 1) reduction of the time of exposition of the plants to the necessary conditions for the formation of quality daughter plants; 2) high temperatures during the formation of daughter plants that are still in the nursery or in the cultivation environment right after transplanting. These factors compromise the storage capacity of photoassimilates in the crown of the plants, determined by the cold hours accumulated in the nursery (Costa et al., 2017).

Even being implanted in June or July, ND cultivars started anthesis 20 to 42 days after transplanting (Table 2). Possibly, due to their greater permanence in the field during daughter plants formation, these cultivars accumulated adequate quantity and quality of cold in the crown and this provided a better quality to the daughter plants. Thus, after its transplant, the reserves accumulated in the crown of the plant were directed to the emission of flowers. The greater the accumulation of cold hours during the daughter plant formation, the shorter the time required to start flowering (Hidaka et al., 2017).

Among the ND cultivars, 'Albion', 'Monterey', and 'San Andreas' were transplanted before (June) the others. However, these three cultivars had an interval (in days) from transplanting to harvesting similar to 'Aromas' and 'Portola'. Therefore, strawberry growers could opt for the cultivation of 'Aromas' and 'Portola' considering their rapid development (short vegetative cycle). Due to the shorter transplant-to-harvest cycle, it is believed that if 'Aromas' and 'Portola' were transplanted in the first half of June, they would start the fruit harvest at the end of August. This would make it possible to deliver fruits in advance to the consumer market in relation to other cultivars. However, further research is needed to validate this hypothesis in order to investigate the morphophenology, morphophysiological and productive performance of these cultivars transplanted at different times.

Our results regarding the phyllochron and phenology of the seven strawberry cultivars contribute to determine the precocity of materials with different photoperiod classifications regarding flowering, when inserted in the Brazilian subtropics (where climatic conditions differ from daughter plants place of origin). The answers obtained with this research can help producers in the choice of cultivars aiming at the staggering of materials to establish their commercial crops. Finally, researchers, horticulturists, and industry should focus on filling the existing gaps related to the morphophenological, morphophysiological, and productive performance of cultivars in other growing regions. This will help to enhance the strawberry production chain on a global scale.

Conclusions

The seven strawberry cultivars, with different photoperiod classifications regarding flowering, differ in relation to phyllochron and phenology. In the cultivation conditions of the Brazilian subtropics, 'Fronteras' is the earliest to start the fruit harvest, as long as it is transplanted in May, and 'Albion' is the latest. The ND cultivars have a shorter transplant cycle until the beginning of the harvest, while the SD cultivars demand a longer interval for this transition, with a prolonged vegetative period. The multivariate analysis groups the cultivars based on the photoperiod responses in relation to flowering and the variability between groups is evidenced mainly by stage 11 (first leaf expansion).

Acknowledgements

To Bioagro Comercial Agropecuária Ltda., for the supply of the strawberry mother plants.

References

Antunes, L.E.C., Reisser Júnior, C., Bonow, S. 2021. Morango: produção aumenta ano a ano. *Campo & Negócio* 1: 87-90.

Antunes, O.T., Calvete, E.O., Rocha, H.C., Nienow, A.A., Mariani, F., Wesp, C.L. 2006. Floração, frutificação e maturação de frutos de morangueiro cultivados em ambiente protegido. *Horticultura Brasileira* 24: 426-430.

Arnold, C.Y. 1960. Maximum-minimum temperature as a basis for computing heat units. *American Society for Horticulture Science* 76: 682-692.

Byrne, D.H., Bacon, T.A. 1992. Chilling estimation: Its importance and estimation. *The Texas Horticulturist* 18: 8-9.

Chiomento, J.L.T., Ferreira, A.F.B., Costa, R.C., Trentin, N.S., Trentin, T.S., Calvete, E.O. 2020. Phyllochron, and root system development of six strawberry cultivars with different photoperiodic flowering responses. *Scientia Agraria Paranaensis* 19: 368-373.

Costa, R.C., Calvete, E.O., Chiomento, J.L.T., Trentin, N.S., De Nardi, F.S. 2017. Vegetative stage of strawberry duration determined by the crop year. *Revista Brasileira de Fruticultura* 39: 831.

Costa, R.C., Calvete, E.O., Mendonça, H.F.C., Campagnolo, A., Chiomento, J.L.T. 2016. Performance of day-neutral strawberry cultivars in soilless culture. *Australian Journal of Crop Science* 10: 94-100.

Costa, R.C., Calvete, E.O., Trentin, N.S., Chiomento, J.L.T., De Nardi, F.S. 2019. Characterization of external morphanatomy of the strawberry identifies new structure. *Scientia Horticulturae* 254: 70-76.

Costa, R.C., Calvete, E.O., Spengler, N.C.L., Chiomento, J.L.T., Trentin, N.S., De Paula, J.E.C. 2021. Morpho-phenological and agronomic performance of strawberry cultivars with different photoperiodic flowering responses. *Acta Scientiarum. Agronomy* 43: 45189.

Cruz, C.D. 2016. Genes software - extended and integrated with the R, Matlab and Selegen. *Acta Scientiarum. Agronomy* 38: 547-552.

Durner, E.F. 2016. Photoperiod and temperature conditioning of 'Sweet Charlie' strawberry (*Fragaria* x *ananassa* Duch.) plugs enhances off-season production. *Scientia Horticulturae* 201: 184-189.

Furlani, P.R., Fernandez Júnior F. 2004. *Cultivo hidropônico de morango em ambiente protegido*. Embrapa Clima Temperado, Curitiba, Brasil. 12 p.

Galletta, G.J., Himelrick, D.G. 1990. *Small fruit crop management*. Englewood Cliffs, New Jersey, EUA. 602 p.

Gilmore Junior, E.C., Rogers, J.S. 1958. Heat units as a method of measuring maturity in corn. *Agronomy Journal* 50: 611-615.

Heide, O.M., Stavang, J.A., Sønsteby, A. 2013. Physiology and genetics of flowering in cultivated and wild strawberries: A review. *The Journal of Horticultural Science and Biotechnology* 88: 1-18.

Hidaka, K., Dan, K., Imamura, H., Takayama, T. 2017. Crown-cooling treatment induces earlier flower bud differentiation of strawberry under high air temperatures. *Environmental Control in Biology* 55: 21-27.

Kirby, E.J.M. 1995. Environmental factors influencing the phyllochron. *Crop Science* 35: 11-19.

Klepper, B., Rickman, R.W., Peterson, C.M. 1982. Quantitative characterization of vegetative development in small cereal grains. *Agronomy Journal* 7: 780-792.

Kruger, E., Josuttis, M., Nestby, R., Toldam-Andersend, T.B., Carlene, C., Mezzetti, B. 2012. Influence of growing conditions at different latitudes of Europe on strawberry growth performance, yield and quality. *Journal of Berry Research* 2: 143-157.

Lovaisa, N.C., Molina, M.F.G., Quintana, P.G.A.D., Salazar, S.M. 2015. Response of strawberry plants inoculated with *Azospirillumand burkholderia* at field conditions. *Revista Agronómica del Noroeste Argentino* 35: 33-36.

Meier, U., Graf, H., Hack, M., Hess, M., Kennel, W., Klose, R., Mappes, D., Seipp, D., Stauss, R., Streif, J., Van Den Boom, T. 1994. Phänologische entwicklungsstadien des kernobstes (*Malus domestica* Borkh. und *Pyrus communis* L.), des steinobstes (Prunus-Arten), der johannisbeere (Ribes-Arten) und der erdbeere (*Fragaria* x *ananassa* Duch.). *Nachrichtenbl Deutchland Pflanzenschutzd* 46: 141-153.

Rosa, H.T., Walter, L.C., Streck, N.A., Andriolo, J.L., Silva, M.R., Langner, J.A. 2011. Base temperature for leaf appearance and phyllochron of selected strawberry cultivars in a subtropical environment. *Bragantia* 70: 939-945.

Singh, D. 1981. The relative importance of characters affecting genetic divergence. *Indian Journal of Genetic and Plant Breeding* 41: 237-245.

Sønsteby, A., Heide, O.M. 2017. Flowering performance and yield of established and recent strawberry cultivars (*Fragaria* x *ananassa*) as affected by raising temperature and photoperiod. *The Journal of Horticultural Science and Biotechnology* 92: 367-375.

Streck, N.A., Rosa, H.T., Walter, L.C., Paula, G.M., Camara, C. 2007. Filocrono de genótipo de arroz irrigado em função de época de semeadura. *Ciência Rural* 37: 323-329.

Tazzo, I.F., Fagherazzi, A.F., Lerin, S.K., Aike, A., Rufato, L. 2015. Exigência térmica de duas seleções e quatro cultivares de morangueiro cultivado no planalto catarinense. *Revista Brasileira de Fruticultura* 37: 550-558.

Tomazetti, T.C., Rossarolla, M.D., Zeist, A.R., Giacobbo, C.L., Welter, L.J., Alberto, C.M. 2015. Fenologia e acúmulo térmico em videiras viníferas na região da Fronteira Oeste do Rio Grande do Sul. *Pesquisa Agropecuária Brasileira* 50: 1033-1041.

Torres-Quezada, E.A., Zotarelli, L., Whitaker, V.M., Santos, B.M., Hernandez-Ochoa, I. 2015. Initial crown diameter of strawberry bare-root transplants affects early and total fruit yield. *HortTechnology* 25: 203-208.

Wang, H., Dai, J., Zheng, J., Ge, Q. 2015. Temperature sensitivity of plant phenology in temperate and subtropical regions of China from 1850 to 2009. *International Journal of Climatology* 35: 913-922.

Xue, Q., Weiss, A., Baenziger, P.S. 2004. Predicting leaf appearance in field-grown winter wheat: Evaluating linear and non-linear models. *Ecological Modelling* 175: 261-270.

Zhang, P., Zhang, J., Chen, M. 2016. Economic impacts of climate change on agriculture: The importance of additional climatic variables other than temperature and precipitation. *Journal of Environmental Economics and Management* 83: 8-31.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.