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Modeling the Budbreak in Peaches: A Basic Approach Using Chill and Heat Accumulation

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Abstract: Phenological shifts in peaches have been observed over the last few years due to the fluctuation of the seasonal climate conditions experienced during dormancy, affecting orchard management practices and influencing production and harvest dates. This study aimed to model the vegetative and floral budbreak of selected peach cultivars. Three peach cultivars, including "Rubyprince", "Harvester", and "Red Globe", were considered in this study based on the representation of the early, early-mid, and mid-seasons. The prediction of the budbreak in peaches was assessed using different models that integrate the combination of chill and heat requirements. Models used include the Weinberger model, the modified Weinberger model, Utah, the dynamic model, and the growing degree model. The accumulation of chill varies according to the season evaluated. A model that considers both chill and heat accumulation is presented for each cultivar. Budbreak as an indicator of dormancy completion was established for each cultivar. The outcome of this study is to determine the amount of chilling accumulation and thermal time required to mark the beginning of the budbreak in selected cultivars with a model that predicts the duration of the dormancy. These results are valuable information that can be used for crop management practices and support the mitigation of cold damage during this critical period of crop development.

Keywords: chilling accumulation models; growing degree-days; chill requirement; heat requirement; phenology; dormancy release

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1. Introduction

Weather and changes in climate influence crop phenology and, consequently, may affect fruit quality and yield. The interrelation of these factors and unanticipated shifts in the climate and weather patterns can influence the phenological process, leading to potential implications in the timing of dormancy release and growth resumption affecting fruit quality [1]. The phenological characterization permits us to relate variations in climate and their impacts on crops [2–4]. A series of phenological events that occur during an annual cycle are essential to ensuring appropriate crop management practices [5]. Deciduous fruit tree orchards can experience unpredictable effects by advancing or delaying phenological stages due to warmer winters [6–8].

A period of rest known as "dormancy" with low-temperature conditions (chilling) is required for peach trees prior to resuming growth under warm temperatures after winter [2,3,9,10].

The Southeastern peach industry faces multiple challenges every year regarding production and demand; climate variability tops the list of challenges, with increased incidences of warm winters in recent years, and one of the major growers' concerns during this stage is the completion of the chill hours requirement for each cultivar.

Three peach cultivars considered in this study were selected according to chilling hours (CH) requirements "Rubyprince" (850 CH), "Red Globe" (850 CH), and "Harvester" (750 CH) [11,12]. These cultivars have also been popular during peak growing season in the Southeast US [13], and they have been studied in quality aspects such as variability in sugars, acids, firmness, color, fruit size, and peach skin properties [14–16].

Some fruit trees survive low temperatures during the winter with dormancy as a physiological response to those challenging conditions [7,17–19]. Temperate tree species use the dormancy process to delay or inhibit floral and vegetative bud growth as a part of their physiological response to low temperatures and short photoperiods [7,20,21]. Chilling refers to the number of low temperatures required by vegetative and floral buds during winter to break dormancy and initiate normal growth and development each growing season. Insufficient chilling symptoms vary with species, and one effect is the delay in anthesis and vegetative budbreak [8,17,18].

The consecutive completion of chilling and heat requirements are decisive in defining the moment of the budbreak in peach [*Prunus persica* (L.) Batsch] [22]. Before the growing season, cultivars need to complete specific chilling requirements as a condition to obtain the heat for floral development [23]. If the required chill is not satisfied, potential consequences in bloom delay, fruit growth, and asynchronous growth could happen, affecting maturity stages and reducing yield [7,24,25]. Although chill accumulation is still happening, heat accumulation can occur at the same time, especially when the plant is in the dormant stage. In peaches, chilling and heat accumulation interact to control the time of bloom [26,27]. Nevertheless, the completion of chilling and heat requirements can be affected by variations in temperatures year by year due to temperatures not being sufficiently low even between nearby places [24,28,29].

The knowledge of the likelihood of chill accumulation reduction could lead to cultivar selection in perennial crops like peaches and orchard management practices [30].

Knowing the moment when the floral bud fulfills the chilling requirement and subsequently begins to accumulate heat is critical to predicting the floral budbreak. Controlled-condition experiments using empirical and statistical methods are one of the most common approaches to determining chilling and heat requirements [24]. The empirical approach focuses on the forced single method, which involves the sequential evaluation of shoots under controlled conditions using growth chambers during the winter season [6]. The same procedure has been used to evaluate the dormancy release in peaches, grapes, apples, almonds, and cherries [22,31,32].

Statistical methods have been applied in the estimation of chilling requirements for different species and varieties using shoots or young potted trees. Phenological records of forcing chill experiments in several climatic conditions have been used, and differences have been found among the same species and varieties in different climatic areas [10,24,33–39].

Chilling can be quantified as chill hours [40] and chill units (that allow for partial chill-hour accumulation and chill negation) [41]. Chill hours refer to the number of hours of low temperature within a specific range that regulates growth in processes such as dormancy. The latter model was adapted according to varying climatic conditions for different locations [42–45].

As an adaptation for cultivars with low chilling requirements, the modified Weinberger model considers temperatures below 11 °C for the accumulation of CH [46,47].

The total accumulation of the difference between the daily mean temperature and the base temperature (Tb) is known as Growing Degree Days (GDD). Tb is defined as the minimum temperature below which significant crop development is not expected. Consecutively, the development of flowering depends on the fulfillment of those thermal requirements as part of plant phenology, which has been defined as a seasonal calendar of biological events [5,48].

Several tools and approaches have been developed to guarantee the feasibility of temperate fruit production. Mathematical models are the most common methods in the quantification of chilling and heat requirements and are broadly applied to numerous species for bloom prediction [6,17,49,50].

The variation in temperature between places and several cultivars makes it difficult to generate a unique model that explains the moment when a floral bud completes the requirements [42]. Peach phenology models used to predict the development stages of typical peach cultivars help growers evaluate the potential response of a peach cultivar in a specific location [2]. This can explain how crops are closely linked to their geographical origin and their adaptability to climatic conditions [3,51].

Numerous models have been developed for the simulation of phenological stages; however, few of them simulate budbreak using an integration of chill and heat requirements. This study aims to model the budbreak in peaches using a basic, simple approach of integrating chill and heat accumulation in the prediction of dormancy release of three commercial peach cultivars in Alabama, USA.

2. Materials and Methods

2.1. Plant Material

Five stem segment samples per cultivar with growing and dormant flower and vegetative buds were collected randomly every week for 23 weeks for two different seasons starting from September 2021 to March 2022 (season 1) and September 2022 to March 2023 (season 2) from the ten-year-old peach orchard of three commercial cultivars, including "Rubyprince", "Harvester", and "Red Globe". Management practices were followed according to commercial recommendations for the area [52]. The orchard was located at the Chilton Regional Research and Extension Center in Clanton, Alabama (32°55′14″ N; 86°40′20″ W).

The shoots selected were positioned from 1.8 to 2.4 m from the ground and oriented at 45° angles vertically from around the canopy [53]. The average length of the shoots ranged between 20 cm and 50 cm. Samples were taken using pruners from either the north or the south-facing side of the tree to minimize the influence of microclimate and sunlight and have a homogeneous sample. Shoots were then wrapped in moistened paper towels, placed into plastic Ziploc bags to avoid desiccation, and transported in a cooler with ice to Auburn, AL. Once in the laboratory, the shoot's base was cut diagonally and submerged in water to keep it moist.

2.2. Assessment of Dormancy Break and Data Acquisition

The dynamic of floral budbreaks was estimated using a biological cutting test performed on about 1570 buds, including both floral and vegetative. These buds were evaluated through daily observations for both seasons [54–57]. Three sections—the apex, midsection, and base—were identified according to the number of nodes and the shoot length. Observations for each section were conducted daily for vegetative and floral budbreaks and recorded in an Excel database. The same method was used for both seasons.

2.3. Controlled Conditions

During season 1 (2021–2022), samples remained in laboratory conditions with a constant temperature of 23 °C. For the 2022–2023 years (season 2), the beakers were placed in growth chambers (Arabidopsis units) to obtain control of relative humidity and photoperiod. Two units (Percival and Conviron), each with two shelves and two light bars, were used for the experiment. Stem segments were evaluated under the same temperature condition (23 °C) [58–60] with relative humidity at 60% and a 12 h/24 h photoperiod under artificial fluorescent lighting.

2.4. Weather Data

Daily weather records were obtained from the nearest weather stations of the Chilton Regional Research and Extension Center and Clanton 2 NE weather station (https://wx.

medius.re). Hourly temperature data were used to calculate heat and chilling requirements for both seasons.

2.5. Heat Requirements

Growing Degree Days were used for heat requirements (HR) calculation in terms of thermal time (TT) and were determined as the accumulation of the difference between the daily average temperature (T_i) above the base temperature (T_b) [41,61] (Equation (1)).

$$TT = \sum_{i=1}^{n} (T_i - T_b) \quad (1)$$

where TT is thermal time, accumulated from the first day (i) of September (2021) until the day when dormancy release occurred (n), Tb of 4.5 °C was used for the calculation of the thermal time [62–64].

2.6. Chill Accumulation

Four different chilling models, the Weinberger model, the modified Weinberger model, the Utah model, and the dynamic model, were used to evaluate the dormancy release (budbreak) in all cultivars assessed for both seasons (2021–2022 and 2022–2023).

2.6.1. Weinberger Model

Is one of the most common and used models due to its simplicity. It determines the accumulation of effective chilling hours at temperatures lower than 7.2 °C. Hours below this temperature account for one chilling hour. In this study, the chilling requirement (CR) was estimated by calculating the sum of chill hours (CHs) using Equation (2) [40,49,65].

$$CH = \Sigma CHs\ (T > 7.2\ ^\circ C,\ CHs = 0; \quad T \leq 7.2\ ^\circ C,\ CHs = 1) \quad (2)$$

where T = temperature; CH = chill hour; °C = degree Celsius. This model has been used widely by several authors and applied to different crops [22,63,66].

2.6.2. Modified Weinberger

This model uses the hourly temperature to calculate the chilling hours. It uses a range of temperatures between 0 °C and 7.2 °C. One hour between those ranges will be equivalent to 1.0 chilling hours (Equation (3)) [67,68].

$$1\ \text{h between}\ 0\ ^\circ C\ \text{and}\ 7.2\ ^\circ C = 1.0\ \text{chill hours} \quad (3)$$

2.6.3. Utah Model

This model considers different chilling efficiencies based on a weight function where the permanence of buds on a range of temperatures between 2.5 and 12.5 °C for 1 h effectively accumulates chill units (CU). One chill unit is accumulated at 6 °C. Relative chilling and negative chilling accumulation are counted in this model. Null chill occurs at temperatures below 0 °C, while negative chill accumulation appears at temperatures above 16 °C [41,44].

2.6.4. Dynamic Model

Based on some principles of the Utah model, the dynamic model calculates chill portions and defines the maximum effectiveness of chilling hours at 6 °C and the null effect when the temperature is equal to −2 °C and 14 °C. The model postulates the accumulation of winter chill in two steps, combining the effects of temperature. First, the cold temperatures lead to the formation of intermediate products. Finally, once the intermediate has accumulated in a certain quantity, it will transform into a chilling portion by a process involving the interaction of relatively warm temperatures. However, high temperatures can negatively affect the chilling accumulation in peach buds. Diurnal modification of low temperatures with temperatures above a certain threshold negates the chilling effect.

Thus, the effect of high temperatures on the chilling accumulation will depend on the level, duration, and cycle length [44,69–72]. An Excel format [73] was used for the calculation of chill portions in this study.

In addition, we used the Weinberger model to accumulate the chilling hours of 24 seasons in Chilton, AL, from 1998 to 2023, to demonstrate the variability in the number of chilling hours during that period.

2.7. Data Analysis and Model Integration

The GLIMMIX SAS procedure (SAS version 9.4; SAS Institute, Cary, NC, USA) was used to compare the budbreak duration in days of the bud position (Base, Medium (Mid), Appex), type of bud (Vegetative and Floral), cultivars ("Harvester", "Red Globe", and "Rubyprince"), and interaction Cultivar Bud type; to compare the factors and interaction, Tukey–Kramer pairwise comparison (Alpha = 0.05) was applied.

To determine the relationship between chilling models and GDD, a Pearson linear correlation was calculated using the CORR SAS procedure. Nonlinear sigmoid models were adjusted to the logistic curve to describe the progress of the number of budbreaks for each cultivar through the NLIN SAS procedure.

To model the budbreak, a multiple linear regression including GDD and Chilling units was estimated (Equation (4)).

$$Y = \beta_0 + \beta_1 \text{Chill} + \beta_2 \text{GDD} \tag{4}$$

where β_0 is the intercept, β_1 is the regression coefficient of chilling units and β_2 is the regression coefficient of the GDD. Evaluation of the adjusted models was performed using the coefficient of determination (R^2), the root means square error (RMSE) [74–77] in Equation (5), and the regression 1:1 of the predicted and the observed values for each cultivar.

$$\text{RSME} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{5}$$

where P_i and O_i are the predicted and observed percentages of the budbreak, I goes from 1 to n dates per year that were measured.

3. Results

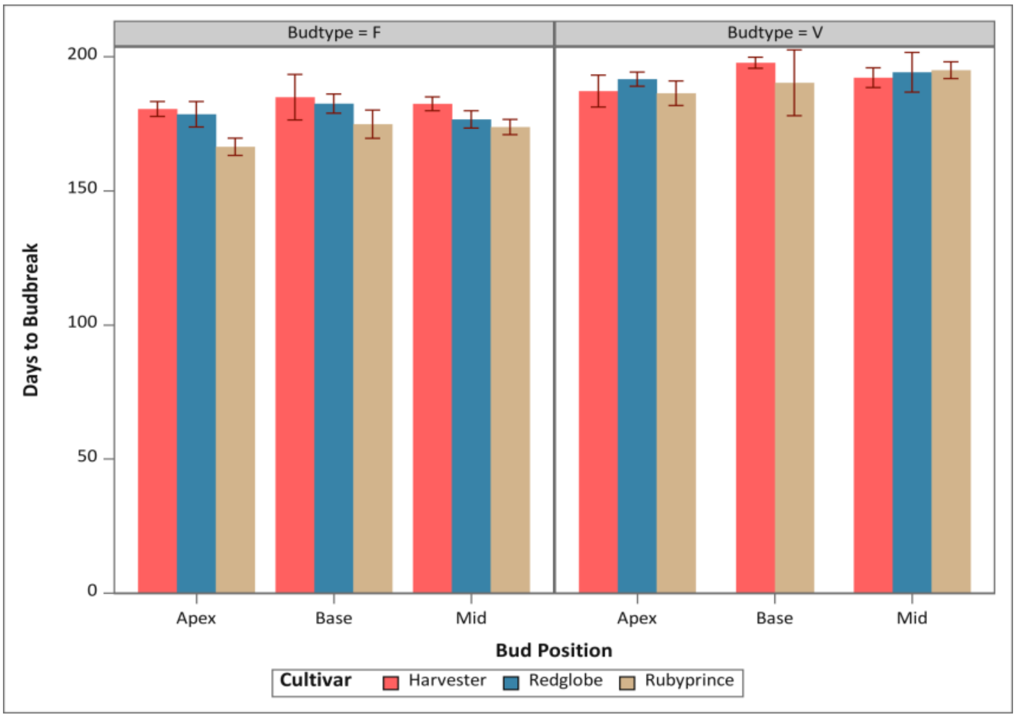
3.1. Assessment of Dormancy Break

The total floral and vegetative budbreak was determined by cultivars as a function of the days to budbreak and shoot position for both seasons (Figure 1). Differences between the days needed for budbreak among the three cultivars were observed for season 1 (2021–2022) (Figure 1A). A total of 268 budbreaks occurred; 95 of the buds recorded were vegetative, and 173 were floral. For season 2 (2022–2023), a total of 878 budbreaks were recorded (580 were floral and 298 were vegetative) (Figure 1B). The total number of buds for both seasons was distributed in all three positions. The highest number of budbreak events were recorded during February and March for all cultivars and seasons 1 (2021–2022) and 2 (2022–2023).

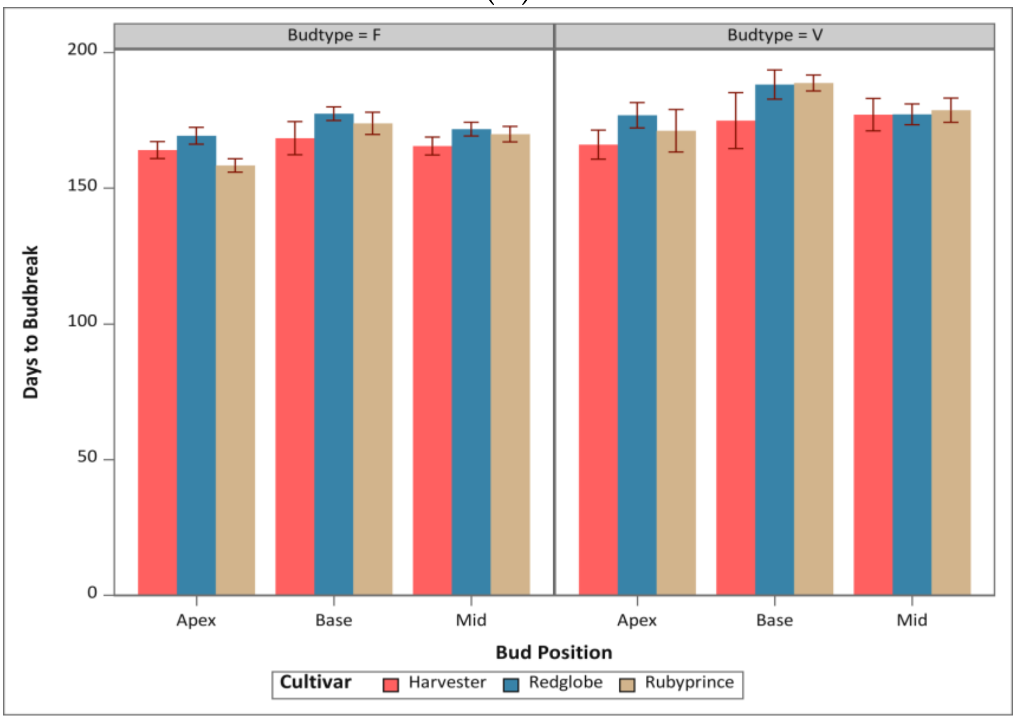
During season 1, significant differences were found for cultivars, bud positions, bud types, and the interaction between cultivar and bud type p-value (<0.0001). For Season 2, there were significant differences among cultivars, bud positions, and bud type p-values (<0.0001), but not for the interaction of cultivar × bud type (Table 1).

Cultivars "Harvester" and "Red Globe" did not show a significant difference between them regarding the number of days to reach dormancy release for season 1. Both cultivars "Harvester" and "Red Globe" were different compared to "Rubyprince" for the number of days of breaking the floral stage; nevertheless, "Harvester" and "Rubyprince" were different from "Red Globe" for season 2. The interaction of cultivar × by bud type was significant for the season 1 p-value (<0.0001) but not for the season 2 p-value (<0.0846) in the number of days for budbreak. For bud type, both seasons showed that vegetative buds took significantly longer than floral buds to break (Table 1).

Regarding the position of the floral buds in the shoot (apex, mid, and base), there were no significant differences between the apex and mid positions, but they were different from the base for season 1. However, all positions showed significant differences for season 2.



(**A**)



(**B**)

Figure 1. Number of days to reach budbreak for floral and vegetative buds by position (Apex, Base, and Mid) for "Harvester", "Red Globe", and "Rubyprince" cultivars. (**A**) Season 1 and (**B**) season 2.

Table 1. Tukey–Kramer Grouping Least Squares Means (Alpha = 0.05). By cultivars, cultivar × bud type, and bud type for both seasons. LS-means (LS-m) with the same letter are not significantly different.

	Cultivar	Estimate	LS-m	Cultivar × Bud Type		Estimate	LS-m	Budtype	Estimate	LS-m
Season 1	Harvester	187.31	A	Harvester	V	191.84	A	V	192.82	A
					F	182.77	B	F	177.70	B
	Red Globe	186.79	A	Red Globe	V	194.58	A			
					F	179.00	B			
	Rubyprince	181.68	B	Rubyprince	V	192.04	A			
					F	171.32	C			
Season 2	Harvester	169.56	B	Harvester	V	172.63	B	V	176.86	A
					F	166.48	C	F	168.63	B
	Red Globe	175.99	A	Red Globe	V	179.33	A			
					F	172.64	B			
	Rubyprince	172.69	B	Rubyprince	V	178.60	B			
					F	166.78	C			

3.2. Onset and Late Release of Dormancy (Budbreak)

The dates and number of days necessary for the earliest and latest floral and vegetative budbreaks for each cultivar were obtained using the chilling hours model as well as the growing degree days model (Table 2). In general, "Rubyprince" was the earliest cultivar to release dormancy for season 1, and "Harvester" was the earliest for season 2. "Rubyprince" was the earliest cultivar in floral budbreak, followed by Red Globe and "Harvester" for season 1, while "Harvester" was the earliest, followed by "Rubyprince" and "Red Globe" for floral budbreak during season 2.

January, February, and March were the months when all the floral and vegetative buds were released from dormancy during both seasons. In general, cultivars needed between 137 and 207 days to reach budbreaks for season 1 and from 123 to 200 for season 2, with September as an initial sampling date. The range of chilling hours accumulated in the earliest and latest budbreaks was between 200 and 985 for season 1 and 232 and 816 for season 2.

Floral and vegetative buds accumulated, in general, a total of 1785.8 to 2577.2 GDD for season 1 and 1744.4 to 2298.5 GDD for season 2 to complete the dormancy release process. The highest value of chill accumulation (802) for floral early budbreak was reported only for "Harvester" during the first season. This might be because samples collected on 2/4/2022. already had accumulated significant amounts of chilling in the field compared to samples that were collected early and fell into the lab. For "Red Globe" and "Ruby Prince", less chill accumulation of 200 and 264 were presented, perhaps due to those buds that burst early accumulating less chilling in the field since they were collected early. In this study, additional chill was not provided to the samples after arriving at the laboratory (Table 2).

Table 2. Dates for onset (E. Date) and latest release of dormancy (budbreaks L. Date), a total of chilling hours (chill), and thermal requirements (GDD) accumulated for "Harvester", "Red Globe", and "Rubyprince" for both seasons in Chilton, AL, USA.

General Budbreak Season 1								
Cultivars	**E. Date**	**DaysBB**	**Chill**	**GDD**	**L. Date**	**DaysBB**	**Chill**	**GDD**
		E Date				L Date		
Harvester	2/16/2022	168	802	1785.8	3/27/2022	207	985	2296.4
Red Globe	2/08/2022	160	200	2439.0	3/27/2022	207	985	2296.4
Rubyprince	1/16/2022	137	264	1894.5	3/27/2022	207	985	2296.4

Table 2. *Cont.*

General Budbreak Season 1								
Cultivars	**E. Date**	**DaysBB**	**Chill**	**GDD**	**L. Date**	**DaysBB**	**Chill**	**GDD**
Floral budbreak								
Harvester	2/16/2022	168	802	1785.8	3/19/2022	199	615	2577.2
Red Globe	2/08/2022	160	200	2439.0	3/19/2022	199	985	2194.4
Rubyprince	1/16/2022	137	264	1894.5	3/10/2022	190	985	1985.9
Vegetative budbreak								
Harvester	3/25/2022	177	615	2171.4	3/27/2022	207	985	2296.4
Red Globe	2/27/2022	179	725	2087.4	3/27/2022	207	985	2296.4
Rubyprince	2/27/2022	179	725	2087.4	3/27/2022	207	985	2296.4
General Budbreak Season 2								
Cultivars	**E. Date**	**DaysBB**	**Chill**	**GDD**	**L. Date**	**DaysBB**	**Chill**	**GDD**
		E Date				L Date		
Harvester	1/02/2023	123	232	1744.4	3/20/2023	200	816	2203.9
Red Globe	1/17/2023	138	371	1794.3	3/19/2023	199	792	2235.0
Rubyprince	1/09/2023	130	232	1837.9	3/19/2023	199	740	2298.5
Floral budbreak								
Harvester	1/2/2023	123	232	1744.4	3/10/2023	190	816	1993.4
Red Globe	1/17/2023	138	371	1794.3	3/16/2023	196	816	2104.4
Rubyprince	1/15/2023	136	371	1757.3	3/06/2023	186	792	1994.5
Vegetative budbreak								
Harvester	1/09/2023	130	232	1837.9	3/20/2023	200	816	2203.9
Red Globe	1/17/2023	138	371	1794.3	3/19/2023	199	792	2235.0
Rubyprince	1/09/2023	130	232	1837.9	3/19/2023	199	740	2298.5

3.3. Modeling the Progression of the Budbreak

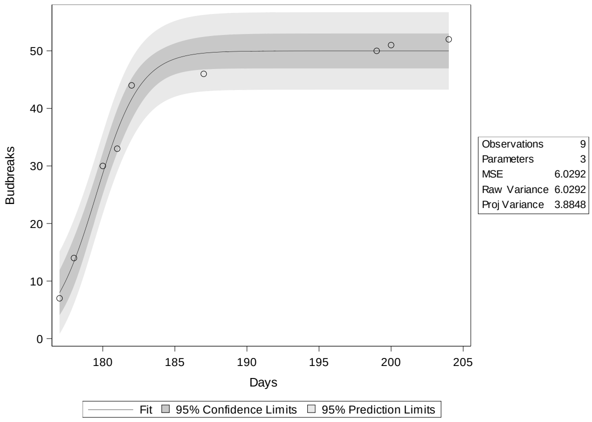
A logistic adjustment was made to fit the sigmoidal trend for the budbreak distribution over time for both floral and vegetative buds. The floral budbreak for season 1 was, in general, delayed compared to season 2. Equations fit statistics, and the curves of the adjustments are presented (Figure 2). Season 1 presented in general less budbreak than Season 2. The environmental factors before the arrival of the samples to the laboratory for both seasons could affect the accumulation of chill in the field since this was a progressive sampling over the season and each year was different. Another possible aspect that could contribute to the lower budbreak was the laboratory conditions. During the first season, mortality of the buds was observed due to the location of the experiment, compared to the second season, where we have more control over the growing chambers.

3.4. Heat and Chilling Requirements

A significant high correlation among all the models for chill accumulation was found for both seasons; GDD was negatively correlated with each of the chill accumulation models in season 1 (Table 3). The high correlation among the chill accumulation models suggests that any of the models can be used for chill accumulation combined with GDD. Similar results for season 2 were obtained (Table 3).

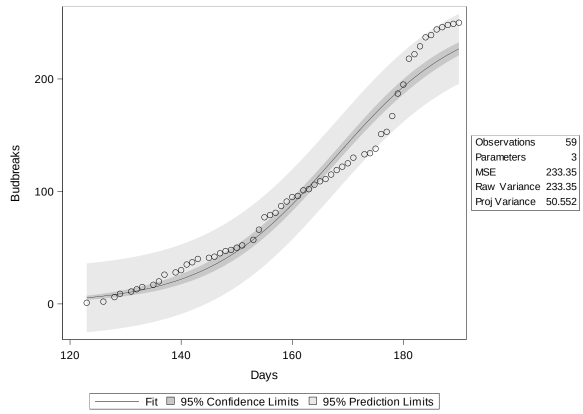
Chilling accumulation for 24 seasons was quantified starting from September to April from 1998 to 2023 to indicate the effect of climate variability using the chill requirements referenced [12] ranging from 750 to 850 (horizontal lines) for the cultivars evaluated (Figure 3). We observed that every year the chill requirements were fulfilled, even though there were some early (January) or late (February) completions. In the same way, the GDD accumulation was conducted for 24 seasons from 1998 to 2023, starting from September to April (Figure 4), to display the effect of warm temperatures accumulated during the same period.

(**A**) Harvester



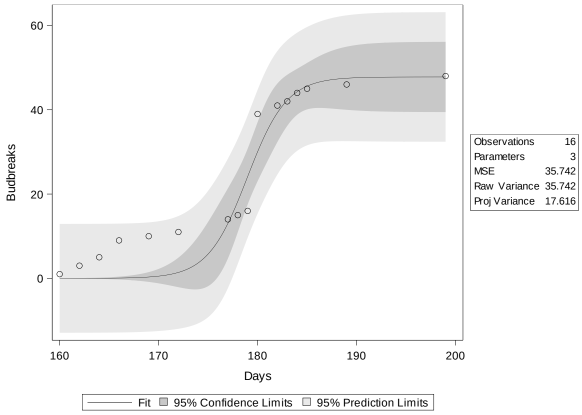
Y = 49.98/(1 + exp(−0.653 × (Days − 179.5)))

(**B**) Harvester



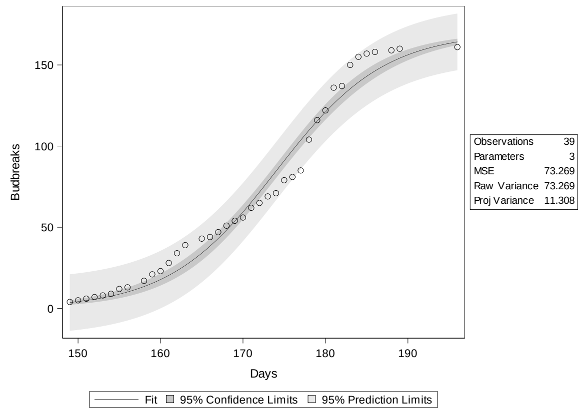
Y = 260/(1 + exp(−0.0861 × (Days − 167.7)))

(**C**) Red Globe



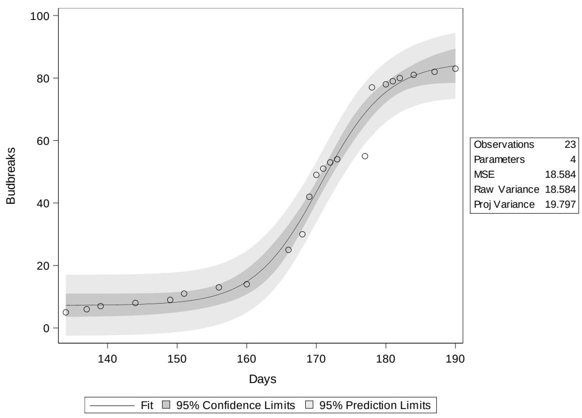
Y = 47.7844/(1 + exp(−0.5023 × (Days − 179.0)))

(**D**) Red Globe



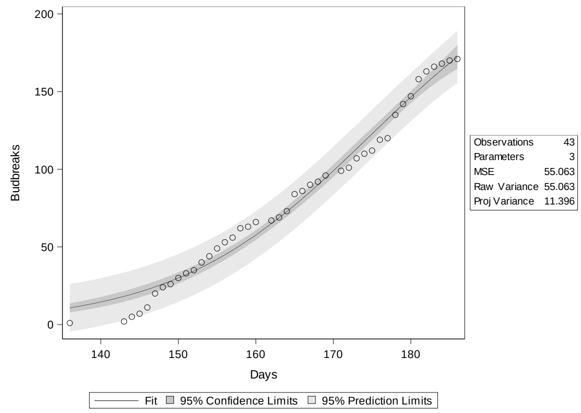
Y = 170/(1 + exp(−0.1525 × (Days − 174.1)))

(**E**) Rubyprince



Y = 7.2417 + (85.2953–7.2417)/(1 + exp(−0.2083 × (days − 170.7)))

(**F**) Rubyprince



Y = 242.3/(1 + exp(−0.0794 × (daysbb − 174.7)))

Figure 2. Logistic adjustment for floral budbreaks for all cultivars and seasons evaluated. Season 1 left panel Season 2 right panel.

Table 3. Pearson correlation coefficients among chilling and GDD models for seasons 1 and 2.

	Chilling Hours	M45	Utah	Dynamic	GDD
Season 1					
Weinberger	1	0.99895 <0.0001	0.99651 <0.0001	0.99603 <0.0001	−0.89997 <0.0001
Modified Weinberger	0.99895 <0.0001	1	0.9917 <0.0001	0.99795 <0.0001	−0.88884 <0.0001
Utah	0.99651 <0.0001	0.9917 <0.0001	1	0.9865 <0.0001	−0.91403 <0.0001
Dynamic	0.99603 <0.0001	0.99795 <0.0001	0.9865 <0.0001	1	−0.88856 <0.0001
GDD	−0.89997 <0.0001	−0.88884 <0.0001	−0.91403 <0.0001	−0.88856 <0.0001	1
Season 2					
Weinberger	1	0.99571 <0.0001	0.93185 <0.0001	0.99379 <0.0001	−0.24014 0.0001
Modified Weinberger	0.99571 <0.0001	1	0.94573 <0.0001	0.99825 <0.0001	−0.22346 0.0004
Utah	0.93185 <0.0001	0.94573 <0.0001	1	0.95211 <0.0001	−0.13096 0.0389
Dynamic	0.99379 <0.0001	0.99825 <0.0001	0.95211 <0.0001	1	−0.20826 0.0009
GDD	−0.24014 0.0001	−0.22346 0.0004	−0.13096 0.0389	−0.20826 0.0009	1

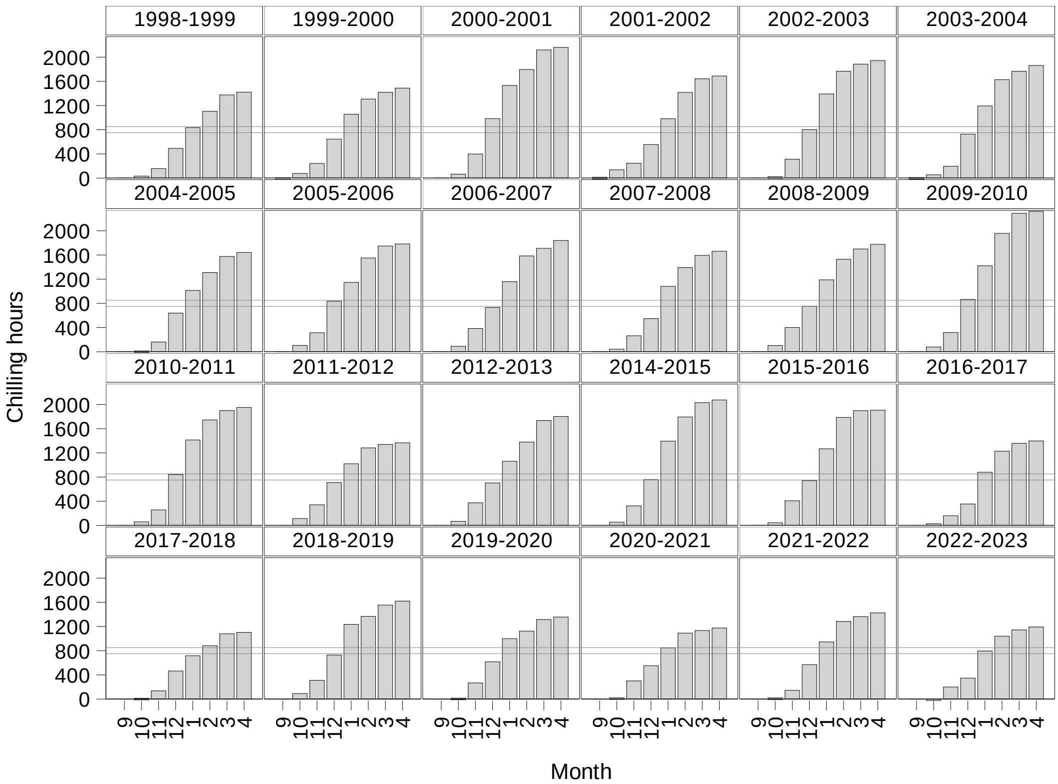


Figure 3. Chill accumulation using the Weinberger model for 24 seasons starting in 1998–2023. The line indicates the range of chill hours accumulated from 750 to 850.

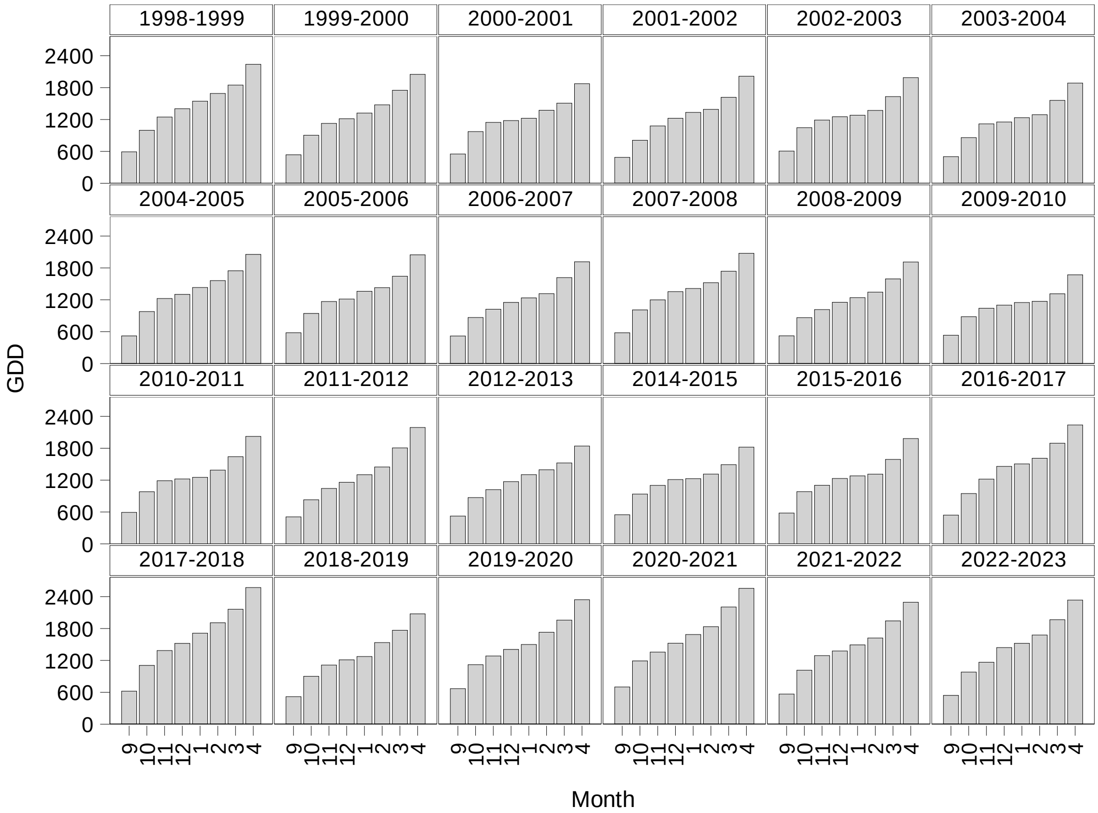


Figure 4. GDD accumulation for 24 seasons starting in 1998–2023.

3.5. Model Integration for Chill and Heat Requirements

The integration of chill and heat requirements and the distribution of budbreaks were obtained for both vegetative and floral buds. All models for the accumulation of chill requirements (chilling hours, M45, Utah, and dynamic model) were used individually in combination with the GDD using 3D graphs to analyze the distribution of chilling hours (x-axis), the GDD (y-axis), and the percentage of the budbreaks (z-axis). An example of the Weinberger model application in a 3D graph displays the relationship between chill (x-axes), heat requirements (y-axes), and the percentage of budbreak (z-axes), indicating that as chill requirements are fulfilled, the GDD requirements would be less. The 3D graphs support the negative correlation between chilling and heat models described before in the correlation matrix. High values of budbreak percentage were obtained with high chill accumulation and low heat accumulation. This tendency was observed for both seasons and bud types (Figure 5).

3.6. Prediction Model

The adjusted models were evaluated by the coefficient of determination (R^2), the root mean square error (RSME), and the line 1:1 for observed vs. predicted values for each cultivar and both seasons for floral and vegetative budbreak. As an example, the Weinberger model adequately fitted the prediction; R-square was above 98% for all the seasons, types of budbreak, and cultivars evaluated. The root means square error (RMSE) varied between 0.34 and 1.02 days for floral budbreak for season 1 and 0.91- and 1.51 days for season 2. For vegetative, the RMSR varied from 0.25 to 0.49 days for season 1 and 0.76 to 1.01 days for season 2.

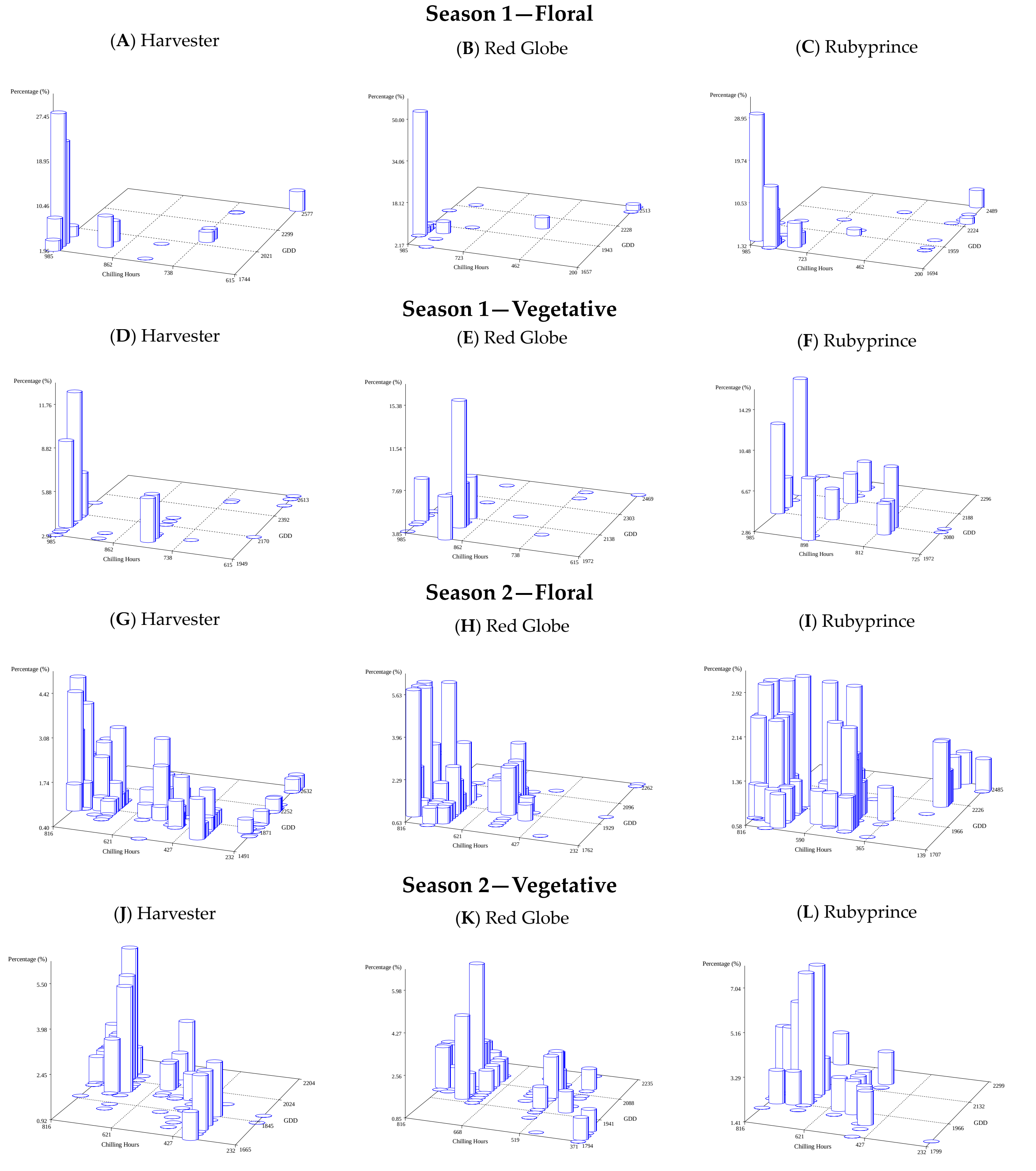


Figure 5. Floral and vegetative budbreak 3D graphs for seasons 1 and 2 using the Weinberger model and its integration with the GDD model for the percentage of budbreak.

The statistics applied Indicated a good fit between the models obtained and confirmed that the simulated values are within an acceptable range of the observed data (Figure 6). These results were similar for all the chilling accumulation models in combination with the

GDD model for all seasons, cultivars, and types of buds because of the high correlation among chilling models.

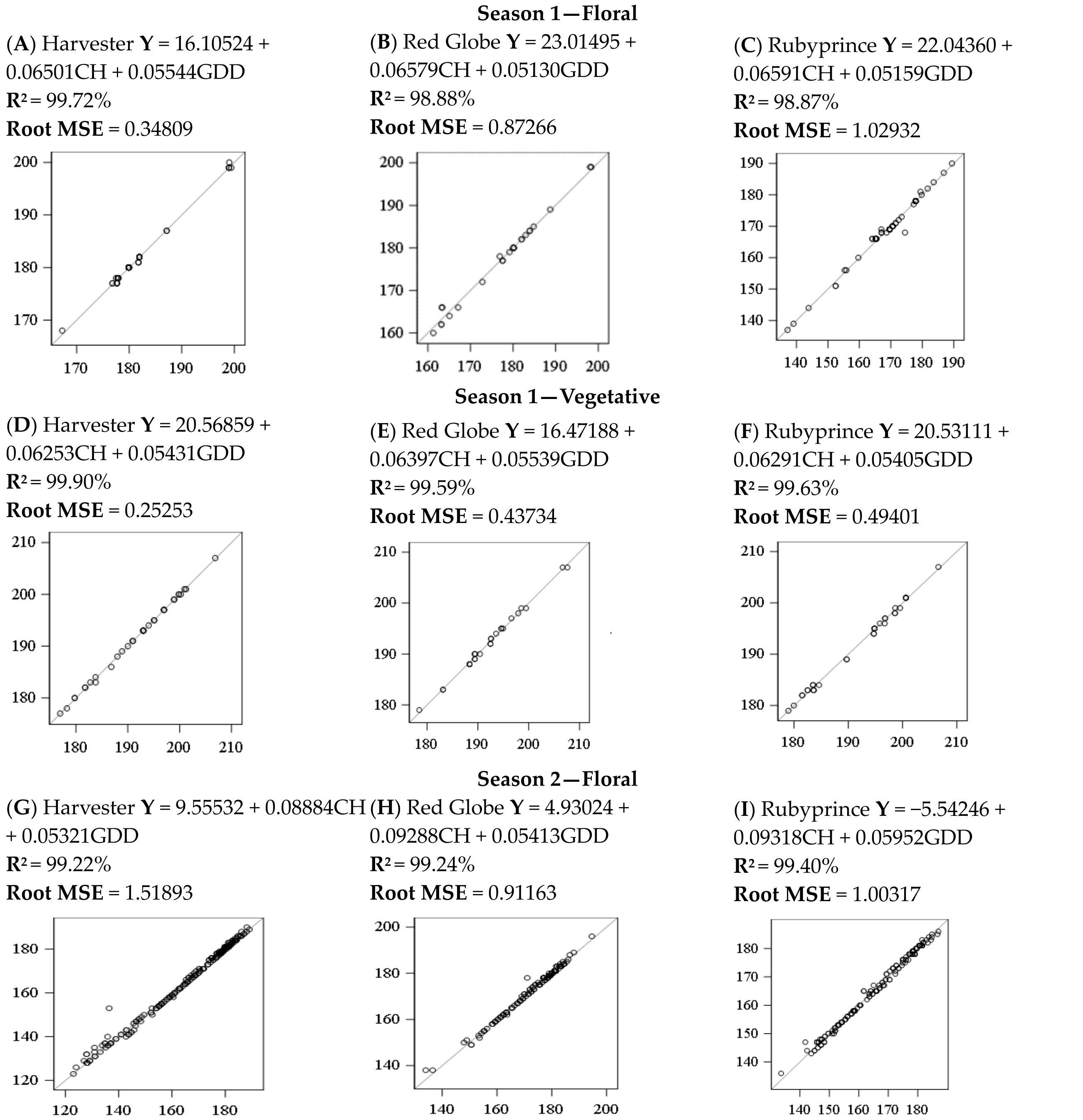


Figure 6. *Cont.*

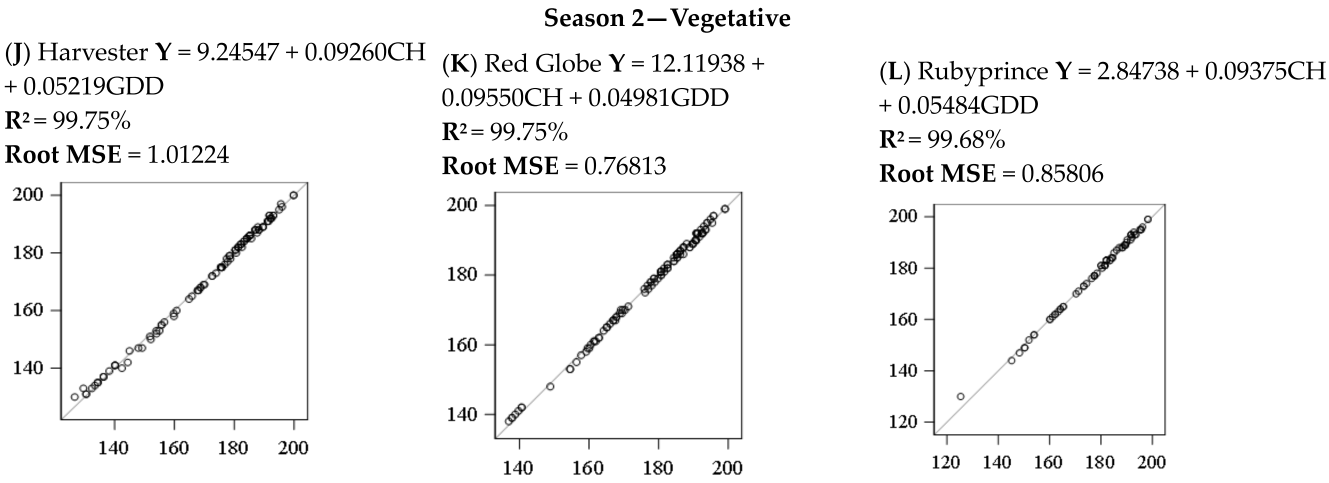


Figure 6. Regression one-to-one for the predicted days for floral and vegetative budbreaks in peach cultivars for both seasons using the Weinberger model.

4. Discussion

Studies have indicated that extreme weather events around the world are happening more often. Variations in temperature from extreme low to extreme high are occurring, affecting the development of any crop. Integration of many aspects, such as proper fertilization with mineral nutrients like iron, nitrogen, potassium, magnesium, and phosphorus, has a relevant impact on fruit load and quality [25,78], soil quality, water availability, pest management, viruses, and bacteria are determined with economic importance on the reduction of physical peach characteristics and production, crop genetics using potential genes in peaches to enhance the fruit characteristics and production [79], among others, play vital roles in fruit quality and yield [25,78–80].

The phenology response to climate change on peaches has been evaluated to show the effect of warming conditions on early blossom dates and late fall events extending the growing season for the past decades [81]. It is important to analyze the temperature variation under laboratory conditions due to the actual temperature fluctuation in the field and the ongoing climate variability. Our results show that given the possibility of warm winters when the number of required chilling hours is not completed, the accumulation of growing degree days would be relevant for the floral and vegetative budbreak. The difference in the number of days to release dormancy in both seasons can be explained since the amount of chill accumulated in both years affected the GGD accumulation differently and consequently the budbreak. Furthermore, the previously presented results would be explained by the effects of the controlled conditions. Although this is one of the most common and used methodologies, shoots are susceptible to drying out; thus, they have to be constantly trimmed to reach greater contact with the water and reduce this possibility. Hypothetically, it is mentioned that controlled conditions may encourage more rapid development [82].

The impact of climate change on the probability of low chill accumulation during winter has increased, showing a lack of chill accumulation for commonly grown peach cultivars in the southeastern United States [30]. Uneven or delayed budbreak occurs in the absence of chill exposure during the fall and early winter. Likewise, the evaluation of floral bud chilling requirements related to the dormancy release process in different fruits has been studied, i.e., in grapevines, to obtain a better understanding of temperature variation. [83,84]. In species like cherries (*Prunus avium* L.), the increase in chilling hours using trees under controlled conditions showed a relationship with the intensification of budbreaks influencing the flower size and fruit set [85].

Chilling is needed to induce the floral and vegetative budbreak under controlled conditions for peaches and nectarines were similar [86]. However, the duration of budbreak for dormant buds for peaches ranged from 20 to 40 days [32,86]. In our case, buds came from the field with a different accumulation of chilling in a progressive sampling from fall until late winter. The average duration for early budbreak varied according to the cultivar from 137 to 197 days in season 1 and from 123 to 138 days to budbreak for season 2.

In this study, we found that peach floral and vegetative buds differ in heat requirements for budbreak. Similar results were obtained in an experiment with different peach cultivars using artificially chilled excised shoots and potted trees, where flower and vegetative buds have different heat requirements during ecodormancy [62].

We applied existing well-referenced models for chilling accumulation ([40,41,65,70,71], among other authors) using a combination of those models with the GDD concept in a very simple approach to developing and evaluating a model for the prediction of floral and vegetative budbreaks in three different peach cultivars, characterized by the different requirements on chill accumulation using a multiple regression model.

This approach is unique and has not been reported before for the peach cultivars evaluated. The data collection was progressive over time, obtaining shoots with different accumulation values for heat and chill requirements. We found a high correlation among all chilling accumulation models for both seasons, a highly negatively correlated GDD with each of the models for season 1, and a low negative correlation for season 2. This agrees with previous results obtained for ornamental peaches, where a significant negative correlation is demonstrated between the models to calculate the chilling and heat requirements in the dormancy release process [87]. In apricots, a negative correlation was found in the interaction between chilling requirements and heat requirements in the transition between budbreak and full bloom stage [39].

The model efficiently estimates the number of budbreaks for two types of buds: floral and vegetative. In this study, the highest correlations were found among the chill accumulation models integrated with Growing Degree Days. Several authors have made applications of models for chilling accumulation and heat accumulation to predict peach phenology ([2,22,71,88], among others), but an integration of both models for the prediction of floral and vegetative budbreak has not been extensively reported.

Our model presents a very simple and flexible approach to be used for predicting the budbreak of floral and vegetative buds across cultivars in different locations and for different years since the conditions of the experiment were controlled in a laboratory. Other models are complex and include a great number of parameters. However, validation with a different set of data is desirable to extend the robustness of the model.

5. Conclusions

This study provides a consistent statistical model built for the estimation of budbreak for three peach cultivars from the beginning of fall until the end of spring. Considering the simplicity of the model, it can be a useful tool to assess the budbreak during the critical months for planning crop management practices. The results of this study contribute to an understanding of the chill accumulation and heat requirements for the floral and vegetative budbreak of three peach cultivars with different requirements.

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