



Article Estimation of Blooming Start with the Adaptation of the Unified Model for Three Apricot Cultivars (*Prunus armeniaca* L.) Based on Long-Term Observations in Hungary (1994–2020)

Ildikó Mesterházy¹, Péter Raffai², László Szalay³, László Bozó^{4,5} and Márta Ladányi^{1,*}

- ¹ Department of Applied Statistics, Hungarian University of Agriculture and Life Sciences, Villányi út 29-43, H-1118 Budapest, Hungary; mesterhazy.ildiko@uni-mate.hu
- ² Department of Atomic Physics, Eötvös Loránd University, Pázmány Péter sétány 1/A, H-1117 Budapest, Hungary; peter.raffai@ttk.elte.hu
- ³ Department of Pomology, Hungarian University of Agriculture and Life Sciences, Villányi út 29-43, H-1118 Budapest, Hungary; szalay.laszlo@uni-mate.hu
- ⁴ Institute of Environmental Sciences, Hungarian University of Agriculture and Life Sciences, Villányi út 29-43, H-1118 Budapest, Hungary; bozo.laszlo@uni-mate.hu
- ⁵ Hungarian Meteorological Service, Kitaibel Pál utca 1, H-1024 Budapest, Hungary
- * Correspondence: ladanyi.marta@uni-mate.hu

Abstract: The aim of our research was to adapt Chuine's unified model to estimate the beginning of blooming of three apricot cultivars ('Ceglédi bíborkajszi', 'Gönci magyar kajszi', and 'Rózsakajszi C.1406') in Hungary in the time period 1994–2020. The unified model is based on the collection of chilling and forcing units. The complexity of the model lies in the high number of parameters necessary to run it. Following the work of other researchers, we reduced the number of relevant model parameters (MP) to six. In order to estimate the six MPs, we used a simulated annealing optimization method (known for being effective in avoiding getting stuck in local minima). From the results, we determined the local optimum of six MPs, and the global optimum parameter vector for three apricot cultivars. With these global optimum parameter vectors, the beginning of blooming could be estimated with a root-mean-square error (RMSE) of less than 2.5 days, using the knowledge of the daily mean temperature in the time period 1994–2020.

Keywords: apricot cultivars; blooming start; unified model; simulated annealing; long-term observation; chilling unit; forcing unit; temperature accumulation; endodormancy break; ecodormancy

1. Introduction

The bud burst and the blooming are the most extensively studied phenophases of temperate trees (for more details see [1]). Such studies found that the dominant environmental factor affecting the growth speed of trees is air temperature [2]. In the last few decades, several temperature-based, mechanistic phenology models were produced for simulating the vegetative (e.g., bud burst) or reproductive (e.g., blooming) phenology of temperate and boreal trees (for more details see [1]). These models are based on the response of trees to the chilling requirement (the accumulation of which breaks endodormancy), and also the response of bud growth to forcing heat requirement (which forces the growth during spring after endodormancy break). Phenological models are important tools for planning agricultural practices [3], particularly for the prevention of frost damage in the short term [4,5] and for projecting the impact of climate change in the long term [6–9].

Dormancy is an important phase in the life of temperate zone fruit trees. Regular dormancy is essential for surviving unfavorable temperatures in winter [10]. Sufficient chilling units are needed for the breaking of endodormancy of apricot (*Prunus armeniaca* L.) buds. According to Andreini et al. [11], early cultivars are controlled by minimum temperatures, but intermediate and late cultivars are controlled by mean temperatures.



Citation: Mesterházy, I.; Raffai, P.; Szalay, L.; Bozó, L.; Ladányi, M. Estimation of Blooming Start with the Adaptation of the Unified Model for Three Apricot Cultivars (*Prunus armeniaca* L.) Based on Long-Term Observations in Hungary (1994–2020). Diversity 2022, 14, 560. https://doi.org/10.3390/d14070560

Academic Editors: Michael Wink, Luc Legal, Ben-Erik Van Wyk and Michel Baguette

Received: 8 June 2022 Accepted: 10 July 2022 Published: 12 July 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Blooming time is an important phenological trait of apricot cultivars. It is determined genetically, but modified by environmental factors, mainly by several elements of climate, which is why, for the aspect of blooming time, there are significant differences between cultivars, production sites, and years. Knowledge of blooming time of apricot genotypes is also important for basic research, breeding, and good cultivation practice. It is an important element of the exact description of cultivars [12]. Blooming time is a crucial phenological trait for breeding [13,14]. Apricot is an early blooming species in general, and is endangered by frost damage [15]. Extremely early blooming genotypes frequently suffer under low temperatures [16]. There are self-incompatible cultivars in apricot orchards that need pollinizers cultivars with the same blooming time [17]. Therefore, the knowledge of blooming time of cultivars is essential from a practical aspect as well.

Hungary is situated in the northern zone of apricot production. In Hungary, the first flowers of apricot trees open between the end of February and second half of April, depending on the genotype, the orchard site, and the year [17–21]. In southern countries, and under milder climate conditions, the blooming time of apricot cultivars is earlier, sometimes starting at the end of January [22–24].

Based on the long-term observations in different parts of the world, the blooming time of apricot cultivars changed during the last few decades, similar to other temperate zone deciduous tree species. Most studies show advancing spring phenological phases and gradually earlier blooming time because of global warming [21,25–34]. Only a small number of articles, on a few genotypes and locations, show the opposite, i.e., delayed spring phenological processes and later blooming in response to warming [35–37]. The hypothesis of Guo et al. [38] is the following: the spring phenological processes of temperate zone deciduous plants in locations with cold winters should be determined primarily by temperatures during ecodormancy, when the accumulation of forcing units is occurring, whereas at sites with warm winters, temperatures during the endodormancy (chilling requirement) should play a more important role in the regulation of spring phenological processes. Insufficient chilling may cause not just delayed, but irregular, blooming, as well as a lack of crop [14,39,40]. Temperature has a significant impact on the regulation of phenological processes just before blooming and during blooming time [41,42].

In our study, we focused on the beginning of blooming of three apricot cultivars in Hungary, based on daily mean temperatures. Phenology models are very sensitive to local climatic conditions and plant species. Therefore, they must be adapted to local conditions [43]. We used the unified model of Chuine [43]. This model is based on the accumulation of chilling and forcing units. The unified model provides a statistical framework for standard model identification, comparison, and simplification [43,44]. With the appropriate parameter selection, the unified model approximates the sequential model [2,45–47], the parallel model [2,46–48], and the deepening rest model [49], as well as the four phases model [2,50]. During the dormant period, the biochemical and biophysical processes are not precisely known, therefore, parameter estimation is difficult. There are two methods used to estimate parameters: the response of shoots to temperature is studied under controlled conditions, or statistical models are run on long-term data sets [1]. For the estimation of the unified model parameters, optimization methods such as the simulated annealing method (SAM) are used [1]. The SAM handles the local extrema better than traditional methods, by avoiding getting stuck in them [51–53].

2. Materials and Methods

2.1. Meteorological and Phenological Data

We used the blooming dates of three self-fertilizing apricot cultivars (*Prunus armeniaca* L.; 'Ceglédi bíborkajszi' (cb), 'Gönci magyar kajszi' (gm), and 'Rózsakajszi C.1406' (ro)) recorded by the research team of the Department of Pomology of the predecessor institutes the Hungarian University of Agriculture and Life Sciences in the experimental farm in the time period 1994–2020. The beginning of blooming (blooming start) was the day of the phenological process, when at least 5% of flowers were opened on the trees of the observed

cultivars. In addition, we used the time when the string stage occurred in at least 50% of the trees [34]. Our collection was in Szigetcsép ($47^{\circ}15'10.6''$ N 18°57'26.6" E) until 2007. Three years before the excision of this plantation, we set up a new experimental plantation in 2004 in Soroksár ($47^{\circ}23'51.8''$ N 19°09'03.2" E), where we continued our studies. The environmental conditions of the two production sites are very similar, because they are very close to each other. The examination of the phenological process of apricot cultivars was carried out in parallel at both plantations in 2004, 2005, and 2006. No significant difference was found between the two production sites in these processes [34]. The beginning and end of the blooming of cultivars occurred on the same days at both sites. Data evaluated in this paper are from Szigetcsép between September 1994 and April 2006, and from Soroksár from September 2006 to April 2020. The training system at both plantations is compact vase with 5 × 3 m spacing with *Prunus cerasifera* seedling rootstocks. In the orchard, integrated plant protection was applied. In both plantations, six trees per cultivars were available for testing.

For the model building, we used the daily mean temperatures observed in the synoptic station of Marczell György main observatory of the Hungarian Meteorological Service (47°25′49.2″ N 19°06′43.7″ E) between September 1994 and April 2020. These data were considered to be good estimations of the daily mean temperature in the apricot plantations, taking into account the close distance between the observatory and experimental plantations and the low variance of the temperature layer, as well as the flat terrain of the surrounding area [54].

2.2. The Unified Model

The unified model [43] uses nine parameters (a_c , b_c , c_c , b_f , c_f , w, k, C_{crit} , t_c) to estimate the day of bud burst or the beginning of blooming of woody trees. In what follows, during the description of the unified model (UM), we use the definition of UM in the sense that it estimates the beginning of blooming.

The estimated critical amount of accumulated chilling units (C_{crit}) necessary to break the endodormancy and the total accumulated chilling units (C_{tot}) are defined as follows:

$$\sum_{t_0}^{t_1} \frac{1}{1 + e^{a_c (T - c_c)^2 + b_c (T - c_c)}},$$
(1)

$$C_{tot} = \sum_{t_0}^{t_c} \frac{1}{1 + e^{a_c (T - c_c)^2 + b_c (T - c_c)}},$$
(2)

where a_c and b_c are estimated weight parameters, c_c is the estimated parameter of the maximum point, T is the daily mean temperature, t_0 is a fix date (1st of September), t_1 is the beginning of ecodormancy (beginning of the forcing period), and the estimated parameter t_c is the last day of chilling unit accumulation.

By fixing t_0 to 1st of September, we begin our chilling unit accumulation calculations on this date [43], but this does not constrain the model accuracy, because under Hungarian environmental conditions, chilling unit accumulation starts much later, mainly around the end of October [9,55].

The function of the chilling unit accumulation (1) or (2) is a bell-shape curve (Figure 1a) with its maximum value taken at the temperature that is optimal for the plant for chilling unit accumulation (c_c). This optimal value is usually a positive temperature close to zero.



Figure 1. The schematic diagram of the chilling (upper panel: (**a**)) and forcing (lower panel: (**b**)) unit accumulation depending on the daily mean temperature for 'Ceglédi bíborkajszi', 'Gönci magyar kajszi', and 'Rózsakajszi C.1406'.

The estimated critical amount of forcing units (F_{crit}) necessary to stimulate the bud burst is calculated as follows:

$$F_{tot} = \sum_{t_1}^{t_2} \frac{1}{1 + e^{b_f(T - c_f)}},$$
(3)

$$F_{crit} = w e^{kC_{tot}},\tag{4}$$

where b_f is an estimated weight parameter, c_f is an estimated parameter of the inflexion point of the function, T is the daily mean temperature, t_1 is the beginning of ecodormancy (beginning of the forcing period), t_2 is the day of the beginning of blooming, w > 0 is an estimated weight parameter, and k < 0 is an estimated parameter of the relation of F_{crit} and the total amount of chilling units C_{tot} . The beginning of blooming is set off when $F_{tot} \ge F_{crit}$. Considering Equation (4), it is obvious that F_{crit} and C_{tot} are in a negative relationship [56]. This relationship expresses that a higher amount of chilling units means a lower amount of forcing units is needed to set the beginning of blooming off, which was proven experimentally [57–61].

The function of the forcing unit accumulation (3) is an S-shape curve (Figure 1b), expressing the higher and higher forcing effect of warming temperatures.

We applied two simplifications to Chuine's unified model, because the high number of parameters can complicate the optimization, often impairing the accuracy of the estimate [62–64]. Moreover, there is a high probability that the underlying biological content disappears during optimization [7,65]. The simplifications are as follows:

(1) According to Caffarra and Eccel [7], b_c can be set to 0, so we described the c accumulation in the endodormancy with the following equation:

$$C'_{*}(T) = \sum \frac{2}{1 + e^{a_{c}(T - c_{c})^{2}}}.$$
(5)

(2) It does not strongly constrain the model accuracy if we assume that the chilling unit accumulation ends at the beginning of ecodormancy ($t_c = t_1$), [43]. We defined this day as the one when the string stage occurs [66,67]. The observed string stage data were available from the data base of the examined apricot cultivars in the time period 1994–2020. Assuming $t_c = t_1$, it follows that $C_{crit} = C_{tot}$. In our study, t_2 is the day of the beginning of blooming.

We had six parameters left to estimate (a_c , c_c , b_f , c_f , w, k). Based on the literature, we chose a particularly large parameter space for the first runs [7–9,43,63,64]. The limits of this parameter space are shown in Table 1. Since k is a negative number very close to zero, we performed the optimization for k_{exp} according to the following equation:

$$k = -10^{-k_{exp}}$$
. (6)

| Parameter | Minimum Value | Maximum Value | Step Length |
|----------------|---------------|---------------|-------------|
| ac | 0 | 10 | 0.01 |
| C _C | -50 | 50 | 0.10 |
| C _C | -10 | 0 | 0.01 |
| b _f | -30 | 30 | 0.10 |
| Cf | 0 | 200 | 0.10 |
| w | 2 | 9 | 0.01 |

Table 1. The boundaries of the parameter space and the step length ¹ used for the first estimation.

¹ These are not fixed step lengths: the σ parameter of the Gaussian distribution was used to select the step length.

2.3. Parameter Estimation with the Simulated Annealing Method

We used the simulated annealing method to estimate the parameters [51,52]. During the simulated annealing calculation process, we searched for the optimal six-dimensional parameter vector, which results in the best-fit to the measured blooming data set. The goodness-of-fit was defined as the root-mean-square error (RMSE) between the estimated and observed data. This measure was minimized within the boundaries of the parameter space. To achieve this, we started a random walk process within the chosen allowed parameter space (Table 1). The starting coordinates were randomized according to a uniform distribution defined between the boundaries of the individual parameters.

At the beginning of the random walk, we set a so-called 'temperature' parameter T^* to its starting value T_{start} , defined as the goodness-of-fit at the starting point. In each random walking step, the temperature parameter T^* was lowered ('cooled') by a factor of $1 - T_{step}$, where $T_{step} = 0.001$. The 'cooling' process was performed from T_{start} to $T_{crit} = 0.01 \cdot T_{start}$, so the random walk was finished when $T^* \leq T_{crit}$.

At the beginning of each walk, we randomly chose a parameter to modify (i.e., the axis along which to step with optimization by 'cooling'), and a step length from a Gaussian distribution with zero mean and σ deviation (σ was fixed, Table 1). If a step moved out from the interval of allowed parameters, we stepped towards the opposite direction along

the axis of the same parameter. Note that in some exceptional cases when this opposite step also moved out from the boundaries (i.e., the step length was too large), we terminated the whole fitting process, and sent an error message.

A step is accepted with a probability 1 if the measure of goodness-of-fit is smaller than it was previously, and it is accepted by a probability of $p = e^{-\frac{Diff}{T^*}}$ if the measure is larger than before. Here, Diff is the absolute difference between the old and the new goodness-of-fit measure. One can see that as T^* decreases in every step, the same Diffresults in a decreasing probability of the new position being accepted. This step acceptance algorithm ensured that the optimization is not stuck in local minima [53]. As a result of one optimization run (a 'walk'), we obtain the best-fitting vector of six parameters and the corresponding root-mean-square error (RMSE) value. Altogether, we performed 10,000 simulated annealing walks per cultivar to estimate the parameter vectors of the three apricot cultivars.

We used the MATLAB program system, Microsoft Excel (version: 2015), and Microsoft paint.net 4.2.15 software for our calculations and representations of our results.

3. Results

In reporting our results of 10,000 random walks to estimate the parameters of the three cultivars, we use the following notations for the cultivars: 'Ceglédi bíborkajszi' as 'cb', 'Gönci magyar kajszi' as 'gm', and 'Rózsakajszi' as 'ro'.

In what follows, we lead the reader through the optimizing procedure in eight steps.

1. First, we observe that for each apricot cultivar, the forcing parameters c_f and w are strongly related, although not linearly (see the upper panel in Figure 2). Therefore, these two parameters cannot be optimized independently. Using the empirical relationship between c_f and w obtained from the optimization process, we calculate the optimal values of c_f for all fixed values of w;



Figure 2. The forcing parameter values of c_f and w (upper panel: (a)) and the histogram of the optimal forcing parameter values of w (lower panel: (b)) for 'Ceglédi bíborkajszi', based on 10,000 random walk optimization processes. (We obtained similar diagrams for 'Gönci magyar kajszi' and 'Rózsakajszi C.1406').

- 2. Based on the resulted parameter vectors of all walks, we plot the histogram of the optimal parameter values of w (see the lower panel in Figure 2). We see that the optimal parameter values of w are dense mainly around three or four small to high values; more exactly, around one small, two medium, and one high value for 'Rózsakajszi C.1406', while around one small, one medium, and one high value for the other two cultivars. We immediately exclude the high values, because we obtained C_f values in those cases between -10 °C and -30 °C, which are unlikely during the forcing period in Hungary [9,68];
- 3. The results of most walks are dense around the small value for each apricot cultivar, and we obtained the lowest RMSE values here, too. So, we fix the parameter value w at the median of the preferred range of 'small' optimal parameters w: $w_{cb} = 15.6$, $w_{gm} = 17.9$, $w_{ro} = 19.4$;
- 4. As a next step, we narrow the parameter space according to the biologically possible parameter values for Hungary (Table 2) [7,9,65,69,70]. In the original parameter space, we find several similarly good parameter vectors, that fit statistically very well to the observed blooming dates, but they are biologically impossible.

Table 2. The boundaries of the parameter space and the step length1 for the second estimation.

| Parameter | Minimum Value | Maximum Value | Step Length |
|------------------|---------------|---------------|-------------|
| ac | 0.2 | 1.0 | 0.001 |
| C _C | 1 | 5 | 0.005 |
| b_f | -0.9 | -0.1 | 0.001 |
| c _f | 6 | 14 | 0.010 |
| k _{exp} | 2 | 6 | 0.005 |

With the aim of finding biologically realistic optimal parameter vectors [68], we started another 10,000 walks for each cultivar, applying the fixed parameters w_{cb} , w_{gm} , and w_{ro} . As a result, we obtained 10,000 limit vectors of the six parameters that the optimization converged to. In order to visualize this result, we created fifteen histograms (for five parameters of the three cultivars based on 10,000 limit values, not shown) to find the local optimum parameter values. To detect the significantly more frequent limit values, we divided the histograms into one hundred bins, because it is the square root of the amount of the limit parameter values. Thus, in the random case, an average of one hundred data points falls in each bin ($\mu = 100$). Unsurprisingly, this happened with natural fluctuation following a Poisson distribution. Having such a large number of limit points, the Poisson distribution could be approximated by the Gaussian distribution with standard deviation $\sigma = \sqrt{\mu} = 10$. Focusing on a histogram, we define the limit point frequency in a bin as significantly high if it is above the value $\mu + 3\sigma = 130$. From the optimized 15 parameters, in seven cases, namely for c_f^{cb} , k_{exp}^{cb} , a_c^{gm} , c_g^{gm} , a_c^{gm} , a_c^{ro} , and c_f^{ro} , we obtain one or more significantly frequented bins next to each other. In another six cases, namely for the parameters b_f^{cb} , b_{f}^{gm} , k_{exp}^{gm} , c_{c}^{ro} , b_{f}^{ro} , and k_{exp}^{ro} , there are more non-adjacent significantly frequented bins. In the remaining two cases (a_c^{cb}, c_c^{cb}) , we do not obtain any bin with at least 130 data points, but there are several bins with more than $\mu + 2\sigma = 120$ optimized parameter values. We define the local optima of the parameters as the medians of the significantly frequented bins. In the case of non-adjacent significant bins, we searched for the local optimum of the parameter in the bin with the largest number of optimized values (Table 3).

| | | number of and standa superscrip | optimized li ard deviation ots 'cb', 'gm', | imit values n of the RM , and 'ro' re | (optimum l ISE. The val espectively. | oins), the nu ues belongi | imber of the | e limits in the ultivars 'Ceg | em, the me lédi bíbork | dian and the ajszi', 'Göne | e standard d ci magyar ka | eviation, tog ajszi', and 'R | ether with th ózsakajszi C. | e maximum 1406' are de | , the median noted by the |
|---------------|------------|---------------------------------------|--|---|--|------------------------------|--------------|----------------------------------|---------------------------|-------------------------------|------------------------------|---------------------------------|--------------------------------|---------------------------|------------------------------|
| | a_c^{cb} | c_c^{cb} | b_f^{cb} | c_f^{cb} | k_{exp}^{cb} | a_c^{gm} | c_c^{gm} | b_f^{gm} | c_f^{gm} | k_{exp}^{gm} | a_c^{ro} | C_c^{ro} | b_f^{ro} | c_f^{ro} | k_{exp}^{ro} |
| Minimum | 0.568 | 1.400 | -0.436 | 7.600 | 2.080 | 0.248 | 3.160 | -0.420 | 7.280 | 2.040 | 0.312 | 2.640 | -0.556 | 7.360 | 2.040 |
| Maximum | 0.576 | 1.440 | -0.428 | 9.280 | 2.480 | 0.256 | 3.200 | -0.380 | 9.040 | 2.400 | 0.320 | 2.720 | -0.484 | 8.560 | 2.600 |
| No. of items | 128 | 129 | 156 | 7480 | 1592 | 143 | 138 | 735 | 7950 | 1680 | 132 | 270 | 1318 | 7180 | 2210 |
| Median | 0.572 | 1.420 | -0.432 | 8.210 | 2.260 | 0.252 | 3.180 | -0.400 | 7.880 | 2.220 | 0.316 | 2.680 | -0.520 | 7.710 | 2.310 |
| St. deviation | 0.002 | 0.010 | 0.002 | 0.420 | 0.110 | 0.002 | 0.010 | 0.011 | 0.430 | 0.100 | 0.002 | 0.020 | 0.021 | 0.310 | 0.160 |
| Maximum RMSE | 4.40 | 4.17 | 3.40 | 4.60 | 4.39 | 5.04 | 4.66 | 4.58 | 7.18 | 4.68 | 4.78 | 5.63 | 4.62 | 5.78 | 5.05 |
| Median RMSE | 2.92 | 2.94 | 2.84 | 2.86 | 2.66 | 2.82 | 2.81 | 2.79 | 2.81 | 2.49 | 2.47 | 2.38 | 2.41 | 2.41 | 2.15 |
| St. dev. RMSE | 0.33 | 0.33 | 0.18 | 0.21 | 0.31 | 0.49 | 0.43 | 0.27 | 0.25 | 0.33 | 0.57 | 0.63 | 0.31 | 0.31 | 0.50 |

Table 3. Characterization of the local optimum parameter vectors of the unified model: the minimum and maximum values of the bins with significantly higher ι, e

5. Then, we searched for the global optimum of the parameter space for each apricot cultivar. We define the global optimum parameter vector as the parameter vector with the lowest root-mean-square error (RMSE) among the grid of values of Table 4. It is seen that, in many cases $(a_c^{cb}, c_c^{cb}, b_f^{cb}, a_c^{gm}, c_s^{gm}, b_f^{gm}, a_c^{ro}, c_c^{ro}, b_f^{ro}$, and c_f^{ro}), the global optimal parameter values do not fall in the local optimum bins. This is most surprising for the parameter c_f^{ro} , where more than 70% of the walk limits fall in the local optimal bin, but the global optimum parameter value does not;

| Table 4. The values of the global optimum parameter vectors of the unified model and the corre- |
|--|
| sponding RMSE values for 'Ceglédi bíborkajszi', 'Gönci magyar kajszi', and 'Rózsakajszi C.1406'. |

| Parameter | 'Ceglédi bíborkajszi' | 'Gönci magyar kajszi' | 'Rózsakajszi C.1406' | | |
|----------------------|-----------------------|-----------------------|----------------------|--|--|
| | 0.949 | 0.216 | 0.608 | | |
| C _C | 1.50 | 2.13 | 2.42 | | |
| b _f | -0.626 | -0.443 | -0.365 | | |
| c_f | 8.30 | 9.04 | 8.84 | | |
| w | 15.60 | 17.90 | 19.40 | | |
| $k_{exp}(k)$ | 2.14 (-0.0072) | 2.08 (-0.0083) | 2.07 (-0.0086) | | |
| $t_c = t_1$ | 14th of January | 22nd of January | 30th of January | | |
| t_2 | 27th of March | 29th of March | 1st of April | | |
| $C_{crit} = C_{tot}$ | 12.73 | 29.78 | 19.69 | | |
| F_{crit} | 14.24 | 13.99 | 16.41 | | |
| F_{tot} | 14.57 | 14.31 | 16.82 | | |
| RMSE | 2.37 | 2.10 | 1.49 | | |

- 6. Using the global optimum parameter vector, we estimated the blooming date for each apricot cultivar with an average error less than 2.5 days (RMSE < 2.5). For comparison, if we take the mean blooming data calculated over all the years as a constant [64], the average error of the estimation (i.e., the error of the base model) is as high as 9.7–10.6 days, depending on cultivars;
- 7. Finally, based on the daily average temperature and the global optimal parameter vectors, we calculated the critical amount of chilling and forcing units, and determined the chilling and forcing process for each cultivar in the period 1994–2020 (Figures 1 and 3). We provide the parameter values that are optimized with the simulated annealing method, applying the unified model and the observed string stage and blooming data of years 1994–2000 (Table 4). The temperature that is optimal for the plant for chilling unit accumulation (c_c) is 1.50 °C for 'Ceglédi bíborkajszi', 2.13 °C for 'Gönci magyar kajszi', and 2.42 °C for 'Rózsakajszi C.1406' in the period 1994–2020. According to our calculations, the most chilling units ($C_{crit} = 29.8$ units) are necessary for 'Gönci magyar kajszi', and the least chilling units ($C_{crit} = 12.7$ units) are required by 'Ceglédi bíborkajszi' for breaking the endodormancy (Table 4). The inflection point of the forcing unit accumulation (i.e., c_f) is between 8.30 and 9.04 °C, depending on the cultivars. This curve has no maximum point, but the forcing unit accumulation is close to the maximum (1 unit) at 12–15 $^{\circ}$ C (more than 0.9 units) that could be considered as 'optimal temperature' for the plant in their preparation for blooming. The average accumulated forcing units for the blooming are between 14.0 and 16.4 units for each cultivar in the period 1994-2020 (Table 4). Surprisingly, the absolute value of parameter k of our results is larger than is reported in the publications of other researchers (i.e., in between -10^{-4} and -10^{-8}) [8,9,43,64]. This may lead to a conclusion that, in the case of Hungarian apricots, the chilling unit accumulation has a relatively larger effect on forcing unit accumulation.



Figure 3. The annual chilling (blue curves) and forcing unit (orange curves) accumulation in the time period September 1994–April 2020 (highlighted: September 2014–April 2015 as a 'pattern period': this period has the lowest RMSE compared to the chilling units calculated from the mean daily temperatures of the twenty-six studied periods, i.e., the results of the year that can be considered as the most similar one to the 'average year') for 'Ceglédi bíborkajszi' (**a**), 'Gönci magyar kajszi' (**b**), and 'Rózsakajszi C.1406' (**c**).

Note that though the change in the observed and estimated blooming start is not proven as significant in the past 26 years, the slopes of their trends are all negative, below -0.2 (Table 5). Since the slopes of the parameters F_{crit} , $C_{crit} = C_{tot}$, and F_{tot} are almost equal to zero, i.e., they seem to not be changing with time as the blooming start does, our model can be directly applied in climate change impact studies as well. While the unsatisfactory or slowed down chilling unit accumulation delays the blooming start, the warming temperatures speed up the forcing accumulation. This complex relation with opposite directions can be simulated by our model.

Table 5. The mean, standard deviation (StDev), range, lower and upper 95% confidence limits (LCI, UCI) of the observed and estimated blooming start (BM), and the parameters of the unified model F_{crit} , $C_{crit} = C_{tot}$, and F_{tot} , together with their slope in the measured 26 years (1994–2020) with their corresponding significance levels (*p*)of the varieties 'Ceglédi bíborkajszi', 'Gönci magyar kajszi', and 'Rózsakajszi C.1406'.

| | | Observed BM | Estimated BM | F _{crit} | $C_{crit}=C_{tot}$ | F _{tot} |
|----------|-------|-------------|--------------|-------------------|--------------------|------------------|
| szi | Mean | 207.9 | 208.4 | 14.2 | 12.7 | 14.6 |
| caj | StDev | 10.8 | 12.1 | 0.4 | 3.8 | 0.5 |
| orl | Range | 48.0 | 51.0 | 1.5 | 14.8 | 1.7 |
| bíb | LCI | 203.8 | 203.7 | 14.1 | 11.3 | 14.4 |
| di | UCI | 212.1 | 213.1 | 14.4 | 14.2 | 14.7 |
| glé | Slope | -0.224 | -0.219 | 0.004 | -0.041 | -0.001 |
| Č | р | 0.438 | 0.500 | 0.696 | 0.686 | 0.933 |
| szi | Mean | 210.3 | 210.2 | 14.0 | 29.8 | 14.3 |
| kaj | StDev | 10.6 | 11.2 | 0.8 | 6.5 | 0.8 |
| arl | Range | 46.0 | 47.0 | 2.6 | 22.3 | 2.8 |
| gy | LCI | 206.2 | 205.9 | 13.7 | 27.3 | 14.0 |
| ma | UCI | 214.3 | 214.5 | 14.3 | 32.3 | 14.6 |
| ici j | Slope | -0.283 | -0.213 | 0.001 | -0.005 | -0.003 |
| Gör | p | 0.316 | 0.479 | 0.978 | 0.977 | 0.881 |
| 06 | Mean | 212.9 | 212.8 | 16.4 | 19.7 | 16.8 |
| .14 | StDev | 10.0 | 10.2 | 0.7 | 4.7 | 0.7 |
| <u> </u> | Range | 41.0 | 40.0 | 2.6 | 18.9 | 3.2 |
| jszi | LCI | 209.0 | 208.9 | 16.2 | 17.9 | 16.5 |
| lka | UCI | 216.7 | 216.7 | 16.7 | 21.5 | 17.1 |
| zsa | Slope | -0.305 | -0.257 | -0.001 | 0.012 | 0.003 |
| Ró | p | 0.252 | 0.344 | 0.933 | 0.925 | 0.880 |

4. Discussion and Conclusions

Phenology models play an important role in planning agricultural practice [3–5], and also in research of phenological changes in plants caused by climate change [6–9]. In our work, we fit Chuine's unified model [43] to the blooming data sets of three apricot cultivars ('Ceglédi bíborkajszi', 'Gönci magyar kajszi', and 'Rózsakajszi C.1406') in Hungary in time period 1994–2020. Szalay et al. [34] analyzed the same data sets in the period 1994–2018. They observe a shift in string stage of ca. 0.5 days/year later, and in the beginning of blooming of ca. 0.125 days/year earlier. They explained this change by the warming climate in the recent decades in Hungary [71]. The chilling units accumulate more slowly in mild winters, which delays the phenological phases in dormancy [72,73]. On the other hand, the warmer spring causes an earlier beginning of blooming [31].

Due to the higher winter temperatures, and the inhibitory effect on chilling unit accumulation, the phenology models that consider only forcing unit accumulation are no longer suitable for estimating the beginning of bud burst and blooming [74–77]. That is why we chose the unified model [43], which contains both chilling and forcing unit accumulation. For the estimation of the parameters, we used the simulated annealing method [51,52], which avoids the problem of getting stuck in local minima.

We reduced the nine-parameter model to a six-parameter model with two simplifications [7,43], thus, we could accelerate the parameter estimation [63,64]. We show that there is a strong, non-linear relationship between the parameters c_f and w. After obtaining a great number of parameters from our random walk optimization, using the histograms of the limit parameters, we defined the local optimum parameter values as the median of the bins with a significantly high number of limits that the optimization converged to. Finally, we defined the global optimum parameter vector as the one with the lowest root-mean-square error (RMSE). It is an interesting result that two-thirds of the global optimum parameter values do not fall into the local optimum parameter bins. We estimated the beginning of blooming during the period of 1994–2020, using the global optimum parameter vector with an RMSE of less than 2.5 days, which can be considered as a good estimation compared to the results of several papers (2.6–5.6; [8,9,68,78]).

In our calculations, the maximum of the chilling unit accumulation is between 1.50 and 2.42 °C, depending on the cultivars. The inflection point of the forcing unit accumulation curve is between 8.30 and 9.04 °C, while the forcing unit accumulation is almost maximal (more than 0.9 units) between 12 °C and 15 °C, depending on the cultivars. Other research [68,79,80] determined the maximum of the chilling and forcing unit accumulation for European fruit trees at temperatures that are slightly higher: around 5 °C and around 25 °C, respectively. But there may be differences in response to temperature even within populations of a given species [81]. Thus, it is possible that the results of various studies cover a relatively wide range of chilling and forcing unit requirement values. The maximum of chilling unit accumulation is found between -28 °C and 9 °C for Quercus mongolica [63] and Taxus baccata [43], respectively, and the inflection point of forcing unit accumulation is shown to be between -14.5 °C and 16 °C in the case of Olea europaca [43] and Vitis vinifera L. [7], respectively. In the case of extreme negative values, the limit is probably statistically the best parameter vector, but biologically it may be incorrect or hardly interpretable [68]. In the case of mechanistic phenology models, however, the biological representativeness is essential.

In some cases (when parameter *k* is around -10^{-7} or more), a simplification can be applied with k = 0 and $w = F_{crit}$. But, in view of our research, this simplification is not justified, because the absolute value of parameter *k* is larger (between -0.0072 and -0.0086) than it is in publications of other researchers $(-10^{-8}--10^{-4})$ [8,9,43,64]. It can mean that, in the case of Hungarian apricots, the chilling unit accumulation has a larger effect on forcing unit accumulation.

With our adapted Chuine's unified model, in the future we can provide a more accurate estimation for the blooming time of the apricot varieties in the studied area. Therefore, the preparation for frost-hazardous conditions can become notably more effective. Since the blooming times of apricot varieties in Hungary are quite close to each other [21], and the climatic conditions of apricot growing areas are also very similar [82], our results can easily be adapted to other Hungarian varieties and regions.

Making estimations for the future using climate model data requires other preliminary studies, because the extension of the phenological models for the future may be questionable [7,9,64,68,83,84], though we also can find very promising new results [85,86].

Author Contributions: Conceptualization, M.L. and L.S.; methodology, M.L. and L.S.; software, P.R.; formal analysis, M.L., I.M. and P.R.; investigation, L.S.; resources, L.B. and L.S.; data curation, M.L., I.M. and P.R.; writing—original draft preparation, M.L., I.M., L.S. and P.R.; writing—review and editing, L.B., M.L., I.M., L.S. and P.R.; visualization, I.M. and P.R.; supervision, L.B. and M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Chuine, I.; Kramer, K.; Hänninen, H. Plant development models. In Phenology: An Integrative Environmental Science; Schwartz, M.D., Ed.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2003; pp. 217–235.
- Hänninen, H. Modelling bud dormancy release in trees from cool and temperate regions. *Acta For. Fenn.* 1990, 213, 7660. [CrossRef]
- 3. Williams, D.W.; Andris, H.L.; Beede, R.H.; Luvisi, D.A.; Norton, M.V.K.; Williams, L.E. Validation of a Model for the Growth and Development of the Thompson Seedless Grapevine. II. Phenology. *Am. J. Enol. Vitic.* **1985**, *36*, 283–289.
- Linkosalo, T.; Carter, T.; Häkkinen, R.; Hari, P. Predicting spring phenology and frost damage risk of *Betula* spp. Under climatic warming: A comparison of two models. *Tree Physiol.* 2000, 20, 1175–1182. [CrossRef]

- 5. Eccel, E.; Rea, R.; Caffarra, A.; Crisci, A. Risk of spring frost to apple production under future climate scenarios: The role of phenological acclimation. *Int. J. Biometeorol.* **2009**, *53*, 273–286. [CrossRef]
- 6. Moriondo, M.; Bindi, M. Impact of climate change of typical Mediterranean crops. Ital. J. Agrometorol. 2007, 12, 5–12.
- Caffarra, A.; Eccel, E. Increasing the robustness of phenological models for *Vitis vinifera* cv. Chardonnay. *Int. J. Biometeorol.* 2010, 54, 255–267. [CrossRef] [PubMed]
- 8. Fila, G.; Di Lena, B.; Gardiman, M.; Storchi, P.; Tomasi, D.; Silvestroni, O.; Pitacco, A. Calibration and validation of grapevine budburst models using growth-room experiments as data source. *Agric. For. Meteorol.* **2012**, *160*, 69–79. [CrossRef]
- Hlaszny, E. A Szőlő (Vitis vinifera L.) Korai Fenológiai Válaszadásának Modellezése a Kunsági Borvidéken Növényfelvételezések, Időjárási Megfigyelések és Regionális Klímamodell Alapján. Ph.D. Thesis, Corvinus University of Budapest, Budapest, Hungary, 2012; 163p. (In Hungarian).
- Faust, M.; Erez, A.; Rowland, L.J.; Wang, S.Y.; Norman, H.A. Bud dormancy in perennial fruit trees: Physiological basis for dormancy induction, maintenance, and release. *HortScience* 1997, 32, 623–629. [CrossRef]
- Andreini, L.; García de Cortázar-Atauri, I.; Chuine, I.; Viti, R.; Bartolini, S.; Ruiz, D.; Campoy, J.A.; Legave, J.M.; Audergon Jean-Marc Bertuzzi, P. Understanding dormancy release in apricot flower buds (*Prunuus armeniaca* L.) using several process-based phenological models. *Agric. For. Meteorol.* 2014, 184, 210–219. [CrossRef]
- 12. Bellini, E. *The Fruit Woody Species*; ARSIA: Firenze, Italy, 2007; Volume 1–2, 1069p.
- 13. Ledbetter, C.A. Apricots. In *Temperate Fruit Crop Breeding*; Hancock, J.H., Ed.; Springer Science and Business Media B.V.: Dordrecht, The Nederlands, 2008; pp. 39–82.
- 14. Campoy, J.A.; Ruiz, D.; Egea, J. Dormancy in temperate fruit trees in a global warming context: A review. *Sci. Hortic.* **2011**, 130, 357–372. [CrossRef]
- 15. Soltész, M. Blooming. In *Floral Biology of Temperate Zone Fruit Trees and Small Fruits;* Nyéki, J., Soltész, M., Eds.; Akadémiai Kiadó: Budapest, Hungary, 1996; pp. 80–131.
- 16. Szalay, L. Development and cold hardiness of flower buds of stone fruits. In *Morphology, Biology and Fertility of Flowers in Temperate Zone Fruits;* Nyéki, J., Soltész, M., Szabó, Z., Eds.; Academic Press: Budapest, Hungary, 2008; pp. 63–82.
- 17. Szabó, Z.; Nyéki, J.; Soltész, M. Apricot (*Prunus armeniaca* L.). In *Floral Biology, Pollination and Fertilisation in Temperate Zone Fruit Species and Grape*; Kozma, P., Nyéki, J., Soltész, M., Szabó, Z., Eds.; Akadémiai Kiadó: Budapest, Hungary, 2003; pp. 411–423.
- 18. Szabó, Z.; Nyéki, J. Blossoming, fructification and combination of apricot varieties. Acta Hortic. 1991, 293, 295–302. [CrossRef]
- 19. Pedryc, A. A Kajszibarack Néhány Tulajdonságának Variabilitása a Nemesítés Szemszögéből. Ph.D. Thesis, Hungarian Academy of Sciences, Budapest, Hungary, 1992. (In Hungarian).
- Szalay, L.; Szabó, Z. Blooming time of some apricot varieties of different origin in Hungary. Int. J. Hortic. Sci. 1999, 5, 16–20. [CrossRef]
- Surányi, D. A Sárgabarack (The Apricot). Magyarország Kultúrflórája II; Kötet, 9, Füzet; Szent István Egyetemi Kiadó: Gödöllő, Hungary, 2011; 303p. (In Hungarian)
- 22. Hsiang, T.-F.; Lin, Y.-J.; Yamane, H.; Tao, R. Characterization of Japanese Apricot (Prunus mume) Floral Bud Development Using a Modified BBCH Scale and Analysis of the Relationship between BBCH Stages and Floral Primordium Development and the Dormancy Phase Transition. *Horticulturae* 2021, *7*, 142. [CrossRef]
- 23. Della Strada, G.; Pennone, F.; Fideghelli, C.; Monastra, F.; Cobiancchi, D. *Monografia di Cultivar di Albicocco*; Istituto Sperimentaleper la Frutticoltura: Rome, Italy, 1989; 239p. (In Italian)
- 24. Pirazzini, P. Prove di impollinazione su nueve cultivar di albicocco nell'Imolese. Italus Hortus 1997, 4, 70–71. (In Italian)
- 25. Fitter, A.H.; Fitter, R.S.R. Rapid changes in blooming time in British plants. Science 2002, 296, 1689–1691. [CrossRef]
- Parmesan, C.; Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 2003, 421, 37–42. [CrossRef] [PubMed]
- 27. Chmielewski, F.-M.; Müller, A.; Bruns, E. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agric. For. Meteorol.* 2004, 121, 69–78. [CrossRef]
- Wolfe, D.W.; Schwartz, M.D.; Lakso, A.N.; Otsuki, Y.; Pool, R.M.; Shaulis, N.J. Climate change and shifts in spring phenology of three horticultural woody perennials in north eastern USA. *Int. J. Biometeorol.* 2005, 49, 303–309. [CrossRef] [PubMed]
- 29. Legave, J.M.; Clauzel, G. Long-term evolution of flowering time in apricot cultivars grown in southern France: Which future impacts of global warming? *Acta Hortic.* 2006, 717, 47–50. [CrossRef]
- 30. Parmesan, C. Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Glob. Change Biol.* **2007**, *13*, 1860–1872. [CrossRef]
- Legave, J.M.; Christen, D.; Giovannini, D.; Oger, R. Global warming in Europe and its impact on floral bud phenology in fruit species. Acta Hortic. 2009, 838, 21–26. [CrossRef]
- 32. Grab, S.; Craparo, A. Advance of apple and pear tree full bloom dates in response to climate change in the south western Cape, South Africa: 1973–2009. *Agric. For. Meteorol.* **2011**, 151, 406–413. [CrossRef]
- Cook, B.I.; Wolkovich, E.M.; Parmesan, C. Divergent responses to spring and winter warming drive community level blooming trends. Proc. Natl. Acad. Sci. USA 2012, 109, 9000–9005. [CrossRef] [PubMed]
- Szalay, L.; Froemel-Hajnal, V.; Bakos, J.; Ladányi, M. Changes of the microsporogenesis process and blooming time of three apricot genotypes (*Prunus armeniaca* L.) in Central Hungary based on long-term observation (1994–2018). *Sci. Hortic.* 2019, 246, 279–288. [CrossRef]

- 35. Yu, H.; Luedeling, E.; Xu, J. Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 22151–22156. [CrossRef] [PubMed]
- 36. Bartolini, S.; Massani, R.; Iacona, C.; Guerriero, R.; Viti, R. Forty-year investigations on apricot blooming: Evidences of climate change effects. *Sci. Hortic.* 2019, 244, 399–405. [CrossRef]
- Bartolini, S.; Massai, R.; Viti, R. The influence of autumn-winter temperatures on endodormancy release and blooming performance of apricot (*Prunus armeniaca* L.) in central Italy based on long-term observations. *J. Hortic. Sci. Biotechnol.* 2020, 95, 794–803. [CrossRef]
- 38. Guo, L.; Dai, J.; Wang, M.; Xu, J.; Luedeling, E. Responses of spring phenology in temperate zone trees to climate warming: A case study of apricot blooming in China. *Agric. For. Meteorol.* **2015**, 201, 1–7. [CrossRef]
- 39. Luedeling, E. Climate change impacts on winter chill for temperate fruit and nut production: A review. *Sci. Hortic.* **2012**, 144, 218–229. [CrossRef]
- Campoy, J.A.; Audergon, J.M.; Ruiz, D. Genomic designing for new climate-resilient apricot varieties in a warming context. In *Genomic Designing of Climate-Smart Fruit Crops*; Kole, C., Ed.; Springer Nature: Cham, Switzerland, 2020; pp. 73–90.
- 41. Rodrigo, J.; Herrero, M. Effects of pre-blossom temperatures on flower development and fruit set in apricot. *Sci. Hortic.* 2002, *92*, 125–135. [CrossRef]
- Lakatos, L.; Nyéki, J.; Soltész, M.; Szabó, Z.; Racskó, J. Effect of meteorological variables on the blooming time. In *Morphology, Biology and Fertility of Flowers in Temperate Zone Fruits*; Nyéki, J., Soltész, M., Szabó, Z., Eds.; Akadémiai Kiadó: Budapest, Hungary, 2008; pp. 117–140.
- 43. Chuine, I. A Unified Model for Budburst of Trees. J. Theor. Biol. 2000, 207, 337–347. [CrossRef] [PubMed]
- 44. Fu, Y.H.; Campioli, M.; Demarée, G.; Deckmyn, A.; Hamdi, R.; Janssens, I.A.; Deckmyn, G. Bayesian calibration of the Unified budburst model in six temperate tree species. *Int. J. Biometeorol.* **2012**, *56*, 153–164. [CrossRef] [PubMed]
- 45. Richardson, E.A.; Seeley, S.D.; Walker, D.R. A model for estimating the completion of rest for 'Redhaven' and 'Elberta' peach trees. *HortScience* **1974**, *9*, 331–332.
- 46. Sarvas, R. Investigations on the Annual Cycle of Development of Forest Trees: Autumn Dormancy and Winter Dormancy; Communicationes Instituti Forestalis Fenniae: Vantaa, Finland, 1974; Volume 84, pp. 1–101.
- 47. Hänninen, H. Effects of temperature on dormancy release in woody plants: Implications of prevailing models. *Silva Fenn.* **1987**, 21, 279–299. [CrossRef]
- 48. Landsberg, J.J. Apple fruit bud development and growth; analysis and an empirical model. *Ann. Bot.* **1974**, *38*, 1013–1023. [CrossRef]
- 49. Kobayashi, K.D.; Fuchigami, L.H.; English, M.J. Modelling temperature requirements for rest development in *Cornus sericea*. J. *Am. Soc. Horic. Sci.* **1982**, 107, 914–918.
- 50. Vegis, A. Dormancy in higher plants. Annu. Rev. Plant Physiol. 1964, 15, 185–224. [CrossRef]
- 51. Press, W.H.; Teukoisky, S.A.; Vetterling, W.T.; Flannery, B.P. The Art of Scientific Computing. In *Numerical Recipes*, 3rd ed.; Cambridge University Press: Cambridge, UK, 2007; 1235p.
- 52. Weise, T. *Global Optimization Algorithms–Theory and Application*, 2nd ed.; e-book; Thomas Weise's private publication; 2009; pp. 263–267. Available online: http://www.it-weise.de/projects/book.pdf (accessed on 11 July 2022).
- 53. Chuine, I.; Cour, P.; Rousseau, D.D. Fitting models predicting dates of blooming of temperate-zone trees using simulated annealing. *Plant Cell Environ.* **1998**, *21*, 455–466. [CrossRef]
- 54. WMO. Volume I—Measurement of Meteorological Variables, No. 8. In *Guide to Instruments and Methods of Observation;* World Meteorological Organization: Geneva, Switzerland, 2018; p. 548.
- Legave, J.M.; Blanke, M.; Christen, D.; Giovannini, D.; Mathieu, V.; Oger, R. A comprehensive overview of spatial and temporal variability of apple bud dormancy release and blooming phenology in Western Europe. *Int. J. Biometeorol.* 2013, 57, 317–331. [CrossRef]
- 56. Guo, L.; Dai, J.; Ranjitkar, S.; Yu, H.; Xu, J.; Luedeling, E. Chilling and heat requirements for blooming in temperate fruit trees. *Int. J. Biometeorol.* **2014**, *58*, 1195–1206. [CrossRef]
- 57. Cannell, M.G.R.; Smith, R.I. Thermal Time, chill days and prediction of budburst in *Picea sitchensis*. J. Appl. Ecol. **1983**, 20, 951–963. [CrossRef]
- 58. Murray, M.B.; Cannell, G.R.; Smith, R.I. Date of budburst of fit teen tree species in Britain following climate warming. *J. Appl. Ecol.* **1989**, *26*, 693–700. [CrossRef]
- 59. Heide, O. Dormancy release in beech buds (*Fagus sylvatica*) requires both chilling and long days. *Physiol. Plant* **1993**, *89*, 187–191. [CrossRef]
- 60. Myking, T.; Heide, O.M. Dormancy release and chilling requirement of buds of latitudinal ecotypes of *Betula pendula* and *B. pubescens*. *Tree Physiol*. **1995**, *15*, 697–704. [CrossRef]
- 61. Chuine, I.; Cour, P. Climatic determinants of budburst seasonality of temperate-zone trees. *New Phytol.* **1999**, *143*, 339–349. [CrossRef]
- 62. Janssen, P.H.M.; Heuberger, P.S.C. Calibration of process-oriented models. Ecol. Model. 1995, 83, 55-66. [CrossRef]
- 63. Fan, D.; Zhu, W.; Zheng, Z.; Zhang, D.; Pan, Y.; Jiang, N. Change in the Green-Up Dates for *Quercus mongolica* in Northeast China and Its Climate-Driven Mechanism from 1962 to 2012. *PLoS ONE* **2015**, *10*, e0130516. [CrossRef]

- 64. Dai, W.; Jin, H.; Zhang, Y.; Liu, T.; Zhou, Z. Detecting temporal changes in the temperature sensitivity of spring phenology with global warming: Application of machine learning in phenological model. *Agric. For. Meteorol.* **2019**, *279*, 14. [CrossRef]
- 65. Thornley, J.H.M.; Johnson, R. Plant and Crop Modelling: A Mathematical Approach to Plant and Crop Physiology; Clarendon Press: Oxford, UK, 1990; 684p.
- 66. Németh, S. A Virágrügy- és Gyümölcsfejlődés Fenológiai, Morfológiai és Biokémiai Jellemzése Fontosabb Kajszifajták Esetében. Ph.D. Thesis, Corvinus University of Budapest, Budapest, Hungary, 2012; 146p. (In Hungarian).
- 67. Herrera, S.; Lora, J.; Fadón, E.; Hedhly, A.; Alonso, J.M.; Hormaza, J.I.; Rodrigo, J. Male Meiosis as a Biomarker for Endo- to Ecodormancy Transition in Apricot. *Front. Plant Sci.* **2022**, *13*, 842333. [CrossRef]
- Chuine, I.; Bonhomme, M.; Legave, J.-M.; García de Cortázar-Atauri, I.; Charrier, G.; Lacointe, A.; Améglio, T. 2016: Can phenological models predict tree phenology accurately in the future? The unrevealed hurdle of endodormancy break. *Glob. Change Biol.* 2016, 22, 3444–3460. [CrossRef]
- 69. Campoy, J.A.; Ruiz, D.; Nortes, M.D.; Egea, J. Temperature efficiency for dormancy release in apricot varies when applied at different amounts of chilling accumulation. *Plant Biol.* **2012**, *15*, 28–35. [CrossRef] [PubMed]
- 70. Gao, Z.; Zhuang, W.; Wang, L.; Shao, J.; Luo, X.; Cai, B.; Zhang, Z. Evaluation of Chilling and Heat Requirements in Japanese Apricot with Three Models. *HortScience* **2012**, *47*, 1826–1831. [CrossRef]
- 71. Bartholy, J.; Pongrácz, R. Klímaváltozás; Lecture Notes; Eötvös Loránd University: Budapest, Hungary, 2013; 180p. (In Hungarian)
- 72. Viti, R.; Monteleone, P. Observations on flower bud growth in some low yield varieties of apricot. *Acta Hortic.* **1991**, 293, 319–326. [CrossRef]
- Sunley, R.J.; Atkinson, C.J.; Jones, H.G. Chill unit models and recent changes in the occurrence of winter chill and spring frost in the United Kingdom. *J. Hortic. Sci. Biotechnol.* 2006, *81*, 949–958. [CrossRef]
- 74. Legave, J.; Farrera, I.; Alméras, T.; Calleja, M. Selecting models of apple flowering time and understanding how global warming has had an impact on this trait. *J. Hortic. Sci. Biotechnol.* **2008**, *83*, 76–84. [CrossRef]
- 75. Garcia de Cortazar-Atauri, I.; Brisson, N.; Gaudillere, J. Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.). *Int. J. Biometeorol.* **2009**, *53*, 317–326. [CrossRef]
- 76. Chuine, I. Why does phenology drive species distribution? Philos. Trans. Biol. Sci. 2010, 365, 3149–3160. [CrossRef]
- 77. Vitasse, Y.; Francois, C.; Delpierre, N.; Dufrene, E.; Kremer, A.; Chuine, I.; Delzon, S. Assessing the effects of climate change on the phenology of European temperate trees. *Agric. For. Meteorol.* **2011**, *151*, 969–980. [CrossRef]
- 78. Chmielewski, F.-M.; Blümel, K.; Henniges, Y.; Blanke, M.; Weber, R.W.S.; Zoth, M. Phenological models for the beginning of apple blossom in Germany. *Meteorol. Z.* 2011, 20, 487–496. [CrossRef]
- 79. Pouget, R. Méthode d'appréciation de l'évolution physiologique des bourgeons pendant la phase de pré-débourrement. Application à l'étude comparée du débourrement de la vigne. *Vitis* **1967**, *6*, 294–302. (In French)
- 80. Hauagge, R.; Cummins, J. Pome Fruit Genetic Pool for Production in Warm Climates. In *Temperate Fruit Crops in Warm Climates*; Erez, A., Ed.; Springer: Amsterdam, The Netherlands, 2000; pp. 267–303.
- 81. Vitasse, Y.; Hoch, G.; Randin, C.F.; Lenz, A.; Kollas, C.; Scheepens, J.F.; Körner, C. Elevational adaptation and plasticity in seedling phenology of temperate deciduous tree species. *Oecologia* **2013**, *171*, 663–678. [CrossRef]
- 82. Pór, J. Kajsziültetvények létesítése. In *Kajszi;* Pénzes, B., Szalay, L., Eds.; Mezőgazda Kiadó: Budapest, Hungary, 2003; pp. 186–197. (In Hungarian)
- 83. Hufkens, K.; Basler, D.; Milliman, T.; Melaas, E.K.; Richardson, A.D. An integrated phenology modelling framework in R. *Methods Ecol. Evol.* **2018**, *9*, 1276–1285. [CrossRef]
- 84. Atagul, O.; Calle, A.; Demirel, G.; Lawton, J.N.; Bridges, W.C.; Gasic, K. Estimating Heat Requirement for Flowering in Peach Germplasm. *Agronomy* **2022**, *12*, 1002. [CrossRef]
- 85. Eduardo Fernandez, E.; Krefting, P.; Kunz, A.; Do, H.; Fadón, E.; Luedeling, E. Boosting statistical delineation of chill and heat periods in temperate fruit trees through multi-environment observations. *Agric. For. Meteorol.* **2021**, *310*, 108652. [CrossRef]
- 86. Yang, J.; Huo, Z.; Wang, P.; Wu, D.; Ma, Y.; Yao, S.; Dong, H. Process-based indicators for timely identification of apricot frost disaster on the warm temperate zone, China. *Theor. Appl. Climatol.* **2021**, *146*, 1143–1155. [CrossRef]