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ORIGINAL PAPER

Models for the beginning of sour cherry blossom

Philipp Matzneller · Klaus Blümel · Frank-M. Chmielewski

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Abstract Seven different model approaches to calculate the onset of sour cherry blossom for the main growing regions in Rhineland-Palatinate (Germany) were compared. Three of the approaches were pure forcing models (M1, M2, M2DL) and the remaining four models were combined sequential chilling-forcing (CF) models. Model M1 was the commonly used growing degree day (GDD) model in which the starting date of temperature accumulation (t_1), the base temperature (T_{BF}) and the forcing requirement F^* were optimized on the basis of observed data. Because of a relatively late optimal starting date ($t_1 = 1$ March), the model can be applied only to calculate the onset of cherry blossom for present climate conditions. In order to develop forcing models that could possibly be used to estimate possible shifts in the timing of cherry blossom due to climate change, the starting date t_1 of the models was intentionally set to 1 January (M2, M2DL). Unfortunately, model M2 failed in both the optimization and validation period. The introduction of a daylength term (DL) in model M2DL improved model performance. In order to project possible shifts in the timing of plant phenological events, combined CF-models are preferred over pure GDD-models. For this reason four CF-models were developed with (M3DL, M4DL) and without (M3, M4) consideration of daylength in the GDD-approach. The chilling requirement was calculated using chilling hours (M3, M3DL) and chill portions (M4, M4DL). Both models without daylength estimated implausible model parameters and failed model validation. However, models M3DL and M4DL showed meaningful model parameter estimations and the error between modelled and observed data was markedly reduced. Moreover, the models optimized and validated (internal validation) for one sour cherry growing region in Germany, were applied successfully to calculate the beginning of the blossom period in other regions in Europe and even at one station in North America (external validation).

Keywords Growing degree day model · Photoperiod · Model comparison · Beginning of cherry blossom · Phenological modelling · Climate change

Introduction

Specific knowledge and awareness of the influence of climatic conditions on the phenology of temperate fruit trees allows farmers to obtain adequate productivity. Phenological observations help farmers improve their crop management, for example, to correctly time operations such as fertilization, pesticide applications, irrigation and scheduling harvest operations (Chmielewski 2012).

Fruit and forest tree species of temperate zones need a certain amount of cooler temperature in autumn and winter to overcome their endodormancy. Once the chilling requirement has been fulfilled, trees enter into the ecodormancy period, where dormancy is imposed only by unfavorable environmental condition (temperature, daylength, etc.). During ecodormancy, warmer temperature stimuli break winter rest and promote tree development and growth to reach bloom and leafing (Campoy et al. 2011; Kainer et al. 1991; Lang et al. 1987; Perry 1971; Romberger 1963; Samish 1954; Saure 1985; Sarvas 1974). This approach assumes fixed sums of chill and heat requirements that have to be fulfilled successively (sequential approach). Other authors claim that the critical sum of forcing units may be related to the number of chilling units previously accumulated (parallel or alternation models, Cannell and Smith

P. Matzneller (✉) · K. Blümel · F.-M. Chmielewski
Agricultural Climatology, Faculty of Agriculture and Horticulture, Humboldt-University of Berlin, Albrecht-Thaer-Weg 5, 14195 Berlin, Germany
e-mail: philipp.matzneller@agrar.hu-berlin.de

1983; Harrington et al. 2010). However, there is no evidence that one approach is better than the other.

Several models have been suggested to calculate winter chill (Fishman et al. 1987a, b; Gilreath and Buchanan 1981; Linsley-Noakes et al. 1995; Richardson et al. 1974; Shaltout and Unrath 1983; Weinberger 1950). These models have been tested and compared for different climatic conditions and crops, including peach in Israel (Erez 2000; Erez and Lerner 1990; Fishman et al. 1987a, b), South Africa (Allan et al. 1995) and Chile (Perez et al. 2008), almond in Spain (Egea et al. 2003), apricot in Spain (Ruiz et al. 2007), France (Legave et al. 2010) and Italy (Viti et al. 2010) and apple in Italy (Valentini et al. 2001). Within these comparisons, the Dynamic model (Fishman et al. 1987a, b) frequently proved more reliable over a wide range of climatic zones (Campoy et al. 2011).

To calculate phenological phases during ontogenetic development, thermal time models were proposed (Cannell and Smith 1983; Robertson 1968; Sarvas 1974). Growing degree day (GDD) or growing degree hour (GDH) models are adopted widely in horticulture. These models have been used inter alia to predict budburst and full bloom for sour cherries in Hungary (Ladanyi et al. 2009, 2010), leaf emergence and leaf expansion in Michigan and Wisconsin (Eisensmith et al. 1980, 1982), as well as flower bud development stages in Michigan (Anderson et al. 1986; Zavalloni et al. 2006). Different authors estimated bud burst and further phenological stages of forest trees with models that consider a certain chilling accumulation, followed by a period of forcing temperatures (Sarvas 1972, 1974; Cannell and Smith 1983; Chuine et al. 2000; Hänninen and Kramer 2007). However, few combined chilling-forcing models that accurately predict bud burst or flowering stages have been developed for horticultural use (Cesaraccio et al. 2004; Rea and Eccel 2006; Chmielewski et al. 2011).

Therefore, the aim of this study was to develop and test pure forcing and combined chilling-forcing (CF) models that are able to predict the onset of sour cherry blossom. Two different chilling models were selected from the literature, and the original, as well as a modified, GDD-approach recently suggested by Blümel and Chmielewski (2012), were also considered. The newly developed GDD-approach had already been successfully tested by Chmielewski et al. (2012b) in an animal phenological study, and is now compared with the original GDD-model to predict the beginning of cherry blossom. The performance, advantages and disadvantages of these models will be discussed in detail.

Materials and methods

Study sites

The calibration of the models was conducted in two main sour cherry growing regions in Germany. Both are located in the state of Rhineland-Palatinate, which has the highest sour cherry production in Germany. Here, in 2007, 9500 t of sour cherries were produced in a growing area of 853 ha. The main production areas in Rhineland-Palatinate are the greater area of Koblenz (50°21′ N, 7°35′ E) and Mainz (49°59′ N, 8°16′ E), with 164 and 576 ha, respectively. These two areas contributed to 22 % of the German sour cherry production in 2007 (SLRF 2010).

The greater area of Mainz, protected to the north and east by a mountain range, has one of the warmest and driest climates in Germany. Fruit and wine orchards range from 86 m to 240 ma.s.l. The average annual air temperature is 10.2 °C and the mean annual rainfall amounts to 543 mm with drier spells in spring and in late summer. The greater area of Koblenz is also located in a basin with a mild climate which allows fruit cultivation from 70 m to 250 ma.s.l. The mean annual air temperature here is 9.6 °C and the average precipitation reaches about 670 mm. The sour cherry growing regions lie 80 km apart from each other and show similar microclimatic conditions.

Phenological data

Phenological observations for the beginning of sour cherry blossom (*Prunus cerasus*, variety: ‘Schattenmorelle’), obtained from the German Meteorological Service (DWD) for the period 1962 to 2009 were used for calibration of the models. The beginning of blossom was defined as the time in the year when at some places on the plant the first flowers have opened completely (BBCH 60; BAHP 1991). The phenological network of the DWD consists of about 1,500 observers, who make observations on a voluntary basis (Bruns 2001). The phenological observations from the sour cherry growing regions and the surrounding areas were regionalized to a 0.2° grid (14 km×22 km) using second order universal kriging (Blümel and Chmielewski 2011; Wackernagel 1998). This procedure transforms the observed phenological values from each station elevation to the mean altitude of the area contained in the grid cell (drift term depending on altitude). Kriging thereby calculates a weighted mean of different station values. The weights for this mean depend on the distance between the stations, the grid cell center and the variograms (correlations) between stations as well as between stations and the location of the grid center. Figure 1 shows the kriging value for the grid cell 50.0° N/8.2° E (center of the cell) and the original phenological time series (different observation periods), which are all located within the 0.2° grid cell. This figure shows that the kriging method used did not reduce the variance of the station data, which is a precondition for successful model development.

For external validation of the calculated blossoming models, phenological observations of the onset of blossom (BBCH 60) from the standardized Global Phenological

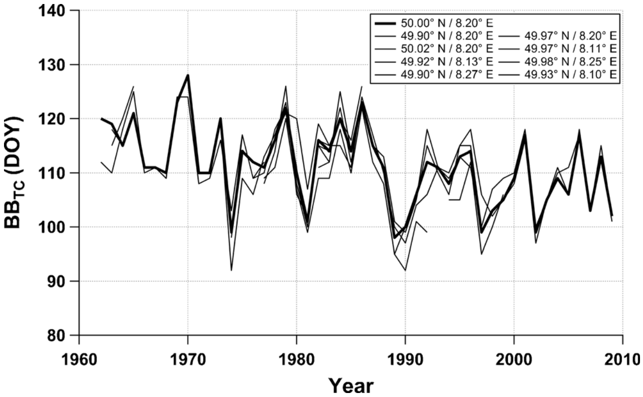


Fig. 1 Dates of onset of sour cherry blossom for the period 1962–2009, observed (*fine lines*) and interpolated by second order universal kriging (*bold line*)

Monitoring Programme (GPM, Chmielewski et al. 2012c) were used. Each station has between 4 and 9 years of observations (see Table 1) and the sour cherry variety that grows in the GPM network is 'Vladimirskaya' (http://gpm.hu-berlin.de).

Meteorological data

Daily air temperature observations from the DWD (mean, minimum and maximum) between 1962 and 2009 were used to optimize the phenological models. Like the phenological observations, the station data of the temperature from the greater area of Mainz and Koblenz were also transformed into gridded data at a resolution of 0.2° using second order universal kriging. In our case, the use of gridded phenological and meteorological station data was absolutely necessary, since we had no long-term time series for air temperature and the beginning of the cherry blossom period from experimental sites. The temperature and the phenological observations were taken at different sites, at different altitudes, and by different observers, etc. Over and above this, the phenological data were available only for different periods between 1962 and 2009 and with some gaps in the time series. The kriging procedure was therefore necessary for the following reasons:

- to fill the observation gaps in the data, in order to create a continuous time series,
- to reduce the subjectivity of phenological observations by the consideration of data from different observers, as already suggested by Schnelle (1961),
- and to have meteorological and phenological data available at the same site (at grid cells).

On the basis of the gridded phenological and temperature data, the two main sour cherry growing regions in Rhineland-Palatinate were represented altogether by four grid cells (Fig. 2). The centers of the pixels for the greater Koblenz area are 50.4° N/7.4° E and 50.4° N/7.6° E, with an average altitude of 193 m and 233 ma.s.l., respectively. The coordinates of the greater Mainz area pixels are 50.0° N/8.0° E and 50.0° N/8.2° E, with an average altitude of 200 m and 150 ma.s.l.

For external validation of the phenological models, temperature data (mean, minimum and maximum) from the GPM were used. These standardized phenological gardens have a weather station in immediate proximity to the observation plot.

In order to use the chilling hour (CH) models, hourly temperatures were generated with the sine-log equations derived by Linvill (1990). These equations are based on the premise that the day-time temperature cycle follows a sine curve from sunrise to sunset, and night-time cooling follows a logarithmic decline:

$$\text{Day}: T_{ih} = (T_{xi} - T_{ni}) \cdot \sin\left(\frac{\pi \cdot t_a}{DL_i + 4}\right) + T_{ni} \quad (1)$$

$$\text{Night}: T_{ih} = T_{ss} - \frac{T_{ss} - T_{ni+1}}{\ln(24 - DL_i)} \cdot \ln(t_b) \quad (2)$$

Table 1 Geographic locations of the stations from the Global Phenological Monitoring Programme (GPM), used for external model validation of the beginning of sour cherry blossom (variety 'Vladimirskaya')

Station	Latitude [°]	Longitude [°]	Altitude [m]	Observation years
Braunschweig (D)	52.28 N	10.45 E	81	2005–2011
Dahlem (D)	52.46 N	13.30 E	51	2007–2011
Geisenheim (D)	49.98 N	7.97 E	118	2004–2010
Offenbach (D)	50.10 N	8.78 E	99	2007, 2009–2011
Schleswig (D)	54.53 N	9.55 E	43	2002–2003, 2005–2010
Tharandt (D)	50.98 N	13.53 E	365	2004–2010
Linden (D)	50.53 N	8.68 E	172	2004–2011
Graupa (D)	51.00 N	13.93 E	180	2005, 2007–2010
Praha (CZ)	50.13 N	14.37 E	284	2006–2011
Banska Bystrica (SK)	48.73 N	19.12 E	427	2003–2010
Milwaukee (WI, US)	43.38 N	88.02 W	265	2002–2010

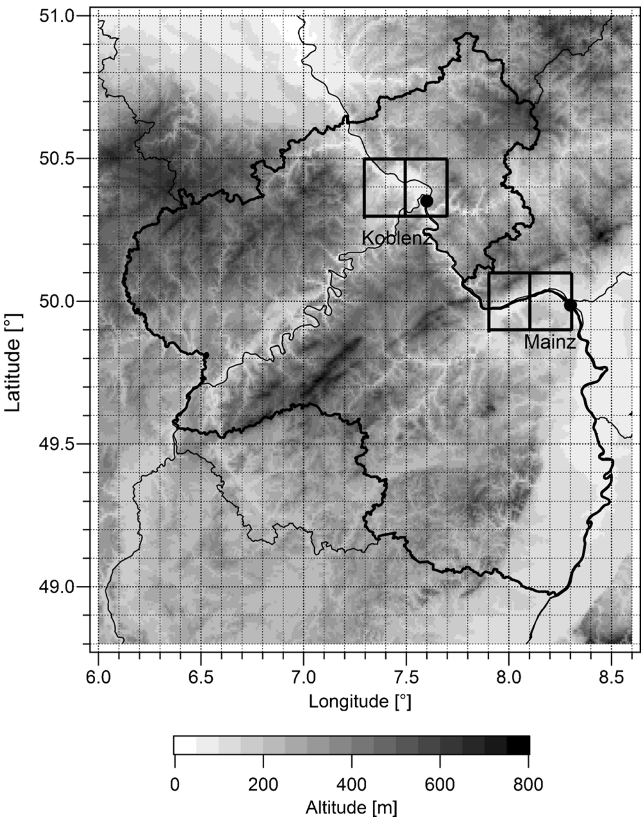


Fig. 2 Location of the sour cherry growing areas in Rhineland-Palatinate and the selected grid cells (*four bold rectangles*)

where T_{ih} is the temperature (°C) at day i and hour h, T_{xi} and T_{ni} is maximum and minimum temperature at day i, DL_{i} the daylength in hours (from sunrise to sunset), t_{a} is the time in hours after sunrise, $T_{\mathrm{ni+1}}$ minimum temperature at day $i+1$, t_{b} is the time in hours after sunset +1 h and T_{ss} the temperature at sunset, obtained from Eq. (1).

Phenological modelling

Chilling models

Fruit trees require a certain period of chilling temperatures to break their dormancy before they can react to higher temperature stimuli, which enable and force bud, leaf and flower development (Chmielewski et al. 2011). The chilling requirement of fruit trees is often given in chilling hours (Ruiz et al. 2007; Alburquerque et al. 2008; Campoy et al. 2012), which differ among fruit crops and cultivars. In this paper, combined CF-models that calculate the onset of sour cherry blossom were developed.

In order to calculate the plant specific chilling requirement (C*), two chilling models were used. First, the very common and relatively simple 32–45 °F model (sometimes referred as the Weinberger-Eggert model, Weinberger 1950), which accumulates hours (chilling hour) with temperatures between 0 °C and 7.2 °C beginning from a fixed starting date. This model can be generally described by Eq. (3).

$$S_c(t) = \sum_{i=t_0}^{t} \sum_{h=1}^{24} R_c(T_{ih}) \tag{3}$$

Here, the state of chilling $S_{\mathrm{c}}(t)$ is the sum of chilling hours (CH) between t_0, the beginning of chilling hour accumulation in autumn and t_1, the date when the dormancy (endodormancy) is released. t_1 is defined as the smallest t with $S_{\mathrm{c}}(t) \geq C^*$. R_{c} is the chilling rate for a single time step (Eq. 4).

$$R_c(T_{ih}) = \begin{cases} 0\,\mathrm{CH} & \text{if} \quad T_{ih} \leq 0°\mathrm{C} \text{ or } T_{ih} \geq 7.2°\mathrm{C} \\ 1\,\mathrm{CH} & \text{if} \quad 0°\mathrm{C} < T_{ih} < 7.2°\mathrm{C} \end{cases} \tag{4}$$

Since the 32–45 °F model is still used widely by growers, we considered this very simple approach for chilling accumulation. It does not consider the sequence of cool and warm temperatures and the chill-enhancing effect of moderate temperatures, which was found to have an important role for chilling accumulation of temperate fruit trees (Erez et al. 1979a, b; Erez and Couvillon 1987).

Therefore a second chilling accumulation approach, the very complex Dynamic model (Darbyshire et al. 2011; Fishman et al. 1987a, b), was considered, which calculates chill portions instead of chilling hours. This model assumes that the degree of dormancy completion depends on the level of certain dormancy-breaking factors, which accumulate in buds in a two-step process (Linsley-Noakes et al. 1994). The first step is assumed to be a reversible process that produces a thermally labile precursor (Eq. 5). Formation of the precursor is promoted by chilling temperatures between 0 and 12 °C with an optimum between 6 and 8 °C, while higher temperatures reverse this process. Temperatures between 13 °C and 16 °C can also enhance the process, if they are cycled with lower temperatures. Once a critical portion of the precursor is accumulated $x(t) \geq 1$, it is transformed irreversibly in the second step, to one portion of a stable dormancy-breaking factor or chill portion (CP) (Eq. 6).

$$x(t) = x_s - (x_s - x(t-1)) \cdot \exp(-k_1) \tag{5}$$

$$\text{If}\,(\mathrm{x(t)} \geq 1), \text{ then} \begin{cases} delt = x(t) \cdot P_t \\ CP = CP + delt \\ x(t) = x(t) - delt \end{cases} \tag{6}$$

The values x_s, k_1, and P_t are functions of the temperature T_{ih} and depend on a further six constants (A_0, A_1, E_0, E_1, c, d). The model starts with $x(t=1)=0$ und $CP=0$. t_1 is defined as the time t when the accumulated chill portions are equal to or greater than C* for the first time. A detailed description of the model is given in, e.g., Erez and Fishman (1998) and a computer programme of this model is provided by Erez et al. (1988) as well as by Fishman et al. (1987b).

In both models, the Dynamic and Weinberger-Eggert model, the beginning of chill portions/chilling hours accumulation was set to 1 September. The Dynamic model selects the starting date automatically [if $x(t) \geq 1$ for the first time], but for internal model calculations 1 September was chosen, which does not affect the results.

Forcing models

One of the most important factors regulating ontogenetic development in fruit trees is air temperature (Chuine et al. 2010). For this reason, different temperature-based models to calculate the plant-specific forcing requirement are suggested in the literature. The two most prominent approaches are the growing degree day (GDD) approach (Robertson 1968; Cannell and Smith 1983) and the logistic-function approach according to Sarvas (1974) and Hänninen (1990).

The forcing requirement (F^*) of a tree can be described generally by Eq. (7), where $S_f(t)$ is the state of forcing, R_f the forcing rate function that describes daily temperature accumulation, and t_2 in our case is the beginning of blossom. The temperature accumulation usually starts after the release of endodormancy (t_1), when temperatures are favorable to promote bud development. This is expressed by a base temperature (T_{BF}) and the daily average temperature (T_i), see Eq. 8.

$$S_f(t) = \sum_{i=t_1}^{t} R_f(T_i) \tag{7}$$

Where t_2 is defined as the smallest t with $S_f(t) \geq F^*$. In this study, the forcing rates were calculated according to the GDD-approach (Eq. 8)

$$R_f(T_i) = \max(0, T_i - T_{BF}) \tag{8}$$

Additionally, we tested the modified GDD-model suggested by Blümel and Chmielewski (2012) (Eq. 9). This approach considers the effect of daylength on plant development, since an increasing number of studies claim that photoperiod plays an important role in driving phenophases (e.g., Caffarra et al. 2011; Körner 2007; Körner and Basler 2010, 2012; Linkosalo et al. 2006). The results of Blümel and Chmielewski (2012) document that this approach has some advantages, particularly if the phenological model is to be used to calculate possible shifts in the timing of phenological events due to climate change.

$$R_f(T_i) = \max(0, T_i - T_{BF}) \cdot \left(\frac{DL}{10h}\right)^{EXPO} \tag{9}$$

In Eq. (9), DL is daylength, which is the time between sunrise and sunset in hours and depends on the geographic position and the day of the year (Julian day). EXPO is an additional model parameter, which weighs the importance of photoperiod on the fruit crop. The constant in the denominator (10 h) is a normalization parameter to make the magnitude of the calculated F^* values comparable to the original GDD-approach. Here the accumulated forcing units are given in so called photo-thermal units (PTU).

The accuracy of the models was evaluated by the root mean square error (RMSE) between predicted and observed dates:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \left(d_{pi} - d_{oi}\right)^2}{N}} \tag{10}$$

Here, d_{pi} is the predicted number of days until beginning of blossom for the year i, d_{oi} is the observed number of days for the year i, and N is the number observation years. Additionally, the RMSE was compared with the RMSE0, which is the RMSE of the"0-model" in which the mean blossoming date was used as prediction. This value is (with the exception of the factor $\sqrt{N/(N-1)}$) identical with the standard deviation (SD) of the observed values:

$$RMSE0 = \sqrt{\frac{\sum_{i=1}^{N} \left(\overline{d_{oi}} - d_{oi}\right)^2}{N}} \tag{11}$$

Here, $\overline{d_{oi}}$ is the mean value of the observed dates of beginning of blossom over the analyzed period. Then $1 - \frac{RMSE^2}{RMSE0^2} = R^2$ is the coefficient of determination (1 = perfect model; less than zero: model is worse than simple mean value).

Model calibration and validation

In order to develop phenological models for the beginning of sour cherry blossom, the temperature and phenological data from 1962–2009 were split into two halves. Even years (24 years) were used to optimize the models and odd years to validate them (internal validation). For each model, the individual parameters were optimized at each of the four grid cells within certain ranges, as listed in Table 2. The base temperature (T_{BF}) was always varied in half degree steps between 0.0 and 5.0 °C and all other model parameters (expect for t_1 for model M1, see below) were optimized by

Table 2 Ranges for optimization of model parameters. *DOY* Day of year, *GDD* growing degree days, *PTU* photo thermal units, *CH* chilling hours, *CP* chill portions, *C** chilling requirement, *F** forcing requirement, T_{BF} base temperature

Model parameter	Unit	Range
t_1 (only M1)	[DOY]	32, 36, 41, 46, 51, 56, 60, 64, 69
T_{BF}	[°C]	0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0
C*	[CH]	400–1,800 (varied in 0.1 steps)
	[CP]	25–100 (varied in 0.1 steps)
F*	[GDD, PTU]	50–1,000 (varied in 0.1 steps)
EXPO[a]	[–]	0.0–5.0 (varied in 0.01 steps)

[a] Model parameter that weighs the importance of photoperiod on the fruit crop

searching for the lowest root mean square error ($\mathrm{RMSE}_{\mathrm{opt}}$) between observed and predicted values for each step of T_{BF}, using 'simulated annealing' (Cerny 1985; Kirkpatrick et al. 1983; Metropolis et al. 1953; Press et al. 1997). Simulated annealing is a method used for global optimization to locate a good approximation to the global optimum of a given function (in our case this function is the RMSE of the phenological model, which depends on the unknown model parameters) in a large search space. For our study, simulated annealing is more efficient than exhaustive enumeration, provided that the aim is merely to find an acceptably good solution in a reasonable amount of time. In our case we had to optimize at most four model parameters. For every model, four optimal parameter sets (one per grid cell) with the lowest $\mathrm{RMSE}_{\mathrm{opt}}$ were determined. Then, we averaged the optimized parameters over all four grid cells, to construct a phenological model for the whole sour cherry growing region. In a final step, the $\mathrm{RMSE}_{\mathrm{opt}}$ was recalculated for every model using the mean parameter values for the growing region.

Thereafter, the accuracy of the models was checked by the $\mathrm{RMSE}_{\mathrm{val}}$ between observed and estimated dates for the validation years (also 24 years). For an external validation of the best blossom models, temperature data and phenological observations from 11 GPM-stations were used (Table 1).

In this study, seven different models to predict the beginning of sour cherry blossom were developed; three were forcing models and the remaining four were combined CF-models.

For the first model the parameters t_1, T_{BF} and F* were fitted (Eqs. 7, 8), so that model (M1) is a simple GDD-approach with optimized starting date. Nine different starting dates (t_1: DOY 31–69) were used for model calibration (Table 2). For the second model (M2DL), which is a GDD-model with daylength-term (Eq. 9), the parameters *EXPO*, T_{BF} and F* were optimized and 1 January was selected as starting date for the GDD accumulation, now weighted by DL. To investigate the effect of photoperiod, the same model (t_1=1 January) but without DL-function was fitted (M2). The other models are sequential CF-models that combine the Weinberger-Eggert (M3DL) and the Dynamic model approach (M4DL) with the modified GDD-approach (Eq. 9). In these two models, the parameters *EXPO*, C*, T_{BF} and F* were optimized. As a starting date for the chilling accumulation, t_0=1 September was chosen and the starting date for the forcing model (t_1) was the predicted date when dormancy was broken for each year. To assess also the performance of the daylength term in the combined CF-models, these two models were optimized without DL-function (M3 and M4).

Results

Observed changes in temperature and sour cherry blossom

The analysis of phenological observations during the period 1962–2009 showed that the average beginning of sour cherry blossom in the growing regions (mean of four grid cells) was 24 April (SD=7.2). The earliest date observed was 9 April 1990 and the latest was 8 May 1970. In these 48 years the beginning of blossom had a significant trend of −2.5 days/decade (P<0.01).

In the study area the average air temperature from September to May was 7.2 °C during the period 1962–2009 (Table 3). These months were considered in the model fitting procedure. In September and October the average minimum temperature was 10.0 °C and 6.4 °C, respectively, and therefore these months already contributed to the chilling accumulation in the models. A much higher chilling accumulation can be expected for November, with a mean air temperature of 5.1 °C and average maximum and minimum values of 7.8 °C and 2.5 °C, respectively.

The mean monthly temperatures from December to March (except February) all had a significant positive trend of more than 0.4 °C/decade in the 48-year period and climate projections indicate a possible increase in temperature in the study area. Regional climate models (RCMs) project mean air temperature changes between +3.2 and +4.1 °C for autumn and between +3.4 °C and +4.2 °C for winter (ranges calculated with 5 RCMs: REMO-UBA, ECHAM5-CLM, HadCM3-CLM, WETTREG-2010-1, WETTREG-2010-2; scenario A1B, 2071–2100 vs 1971–2000; Blümel and Chmielewski 2011).

The expected significant increase in temperature in autumn and winter could cause a shift in the release of dormancy, depending on the chilling requirement of the crop (Chmielewski et al. 2012a) and, as a result, change the onset time of blossom. This suggests that pure forcing models,

Table 3 Monthly mean (T), maximum (T_x) and minimum (T_n) air temperatures, 1962–2009 in the sour cherry growing regions in Rhineland-Palatinate (average of four grid cells, see Fig. 2) and observed trends. *SD* Standard deviation

Month	T [°C]	Trend [K/decade]	T_x [°C]	Trend [K/decade]	T_n [°C]	Trend [K/decade]
September	14.3 (SD=1.4)	0.1	19.6 (SD=1.9)	0.1	10.0 (SD=1.3)	0.2
October	9.8 (SD=1.5)	0.2	14.0 (SD=1.7)	0.2	6.4 (SD=1.5)	0.3
November	5.1 (SD=1.7)	0.4*	7.8 (SD=1.7)	0.4*	2.5 (SD=1.6)	0.4
December	2.1 (SD=1.9)	0.4*	4.4 (SD=1.9)	0.4*	−0.3 (SD=2.0)	0.5*
January	1.3 (SD=2.6)	0.4	3.7 (SD=2.6)	0.6*	−1.2 (SD=2.7)	0.4
February	2.2 (SD=2.6)	0.3	5.4 (SD=2.7)	0.5	−0.8 (SD=2.6)	0.3
March	5.4 (SD=1.8)	0.5**	9.7 (SD=2.1)	0.5*	1.7 (SD=1.7)	0.5**
April	9.2 (SD=1.5)	0.4*	14.2 (SD=2.0)	0.5**	4.5 (SD=1.3)	0.3*
May	13.6 (SD=1.6)	0.5**	18.9 (SD=1.9)	0.6**	8.4 (SD=1.3)	0.5**
Mean	7.2 (SD=0.8)	0.3**	3.7 (SD=0.9)	0.3**	11.0 (SD=0.9)	0.4**

*Trend significant with $P\leq0.05$, ** trend significant with$P\leq0.01$

which start the forcing accumulation in spring, probably do not have sufficient accuracy. For future climate conditions it is therefore necessary to use combined CF-models (see details in Discussion).

Model calibration

All models were optimized at the selected four grid cells using the ranges given in Table 2. The model parameters and the RMSE within the optimization period were calculated as the average of the four grid cells. The results are listed in Table 4.

For M1 the optimal base temperature was 2.0 °C with 1 March (DOY 60) as optimal starting date (see Table 4) and with an $RMSE_{opt}$ of 2.57 days [$RMSE0_{opt}$=7.38 days (mean over the four grid cells); SD=0.43 among the four grid cells]. The results between models with and without the DL-term are substantially different. The optimal base temperature for the models without DL varied between 0 °C for the GDD-model M2 (t_1=1 DOY) and 4.0 °C for the combined CF-model M3. However, all models with DL-function had an identical optimal base temperature at 1.0 °C (M2DL, M3DL, M4DL). In the literature, an optimal base temperature for the original GDD-models that predict the beginning of sour cherry blossom can be found between 2.5 °C and 4.0 °C (Ladanyi et al. 2009; Zavalloni et al. 2006).

The DL-models always had the lowest $RMSE_{opt}$ of all the model approaches. M2DL showed an error of 2.54 days, while the combined CF-models with daylength (M3DL, M4DL) had an $RMSE_{opt}$ of 2.53 and 2.19 days, respectively. Thus the best model in optimization was the combined CF-model, which accumulates chill portions according to the Dynamic model.

The $RMSE_{opt}$ of all models without DL were notable higher within the range of 4.15 (M4)–6.30 (M2) days. The difference in $RMSE_{opt}$ between GDD-models M2 and M2DL was the highest with 3.76 days, followed by the CF-models M3 and M3DL with 2.02 days and the CF-models M4 and M4DL with 1.96 days. Therefore, the introduction of the DL-function reduced the $RMSE_{opt}$ between observed and predicted values of the calibration period by more than half.

Table 4 summarizes the optimal model parameters for each model. The *EXPO* parameter for all DL-models was

Table 4 Optimized model parameters (mean values over the four grid cells) and root mean square error (RSME) for optimization ($RMSE_{opt}$) and internal validation ($RMSE_{val}$) (t_1^{calc} is the calculated date of dormancy release in the chilling models; $RMSE0_{opt}$=7.38 days, $RMSE0_{val}$=7.21 days; numbers in parenthesis are the maximum and minimum values of the four grid cells)

Model	t_0 [DOY]	t_1 [DOY]	T_{BF} [°C]	C* [CH, CP]	F* [GDD, PTU]	EXPO [–]	$RMSE_{opt}$ [days]	$RMSE_{val}$ [days]
M1	–	60	2.0	–	250.7 (243–264)	–	2.57	4.30
M2DL	–	1	1.0	–	592.6 (580–607)	2.1 (1.88–2.26)	2.54	2.39
M2	–	1	0.0	–	534.8 (526–550)	–	6.30	6.35
M3DL	244	t_1^{calc}	1.0	1,071.8 (1,032–1,112)	593.6 (583–616)	2.1 (1.98–2.25)	2.53	2.53
M3	244	t_1^{calc}	4.0	1,548.2 (1,535–1,565)	189.3 (180–200)	–	4.55	4.48
M4DL	244	t_1^{calc}	1.0	74.1 (71.7–75.7)	567.4 (556–589)	2.1 (2.03–2.14)	2.19	2.38
M4	244	t_1^{calc}	2.5	89.1 (87.8–90.0)	262.4 (254–273)	–	4.15	3.76

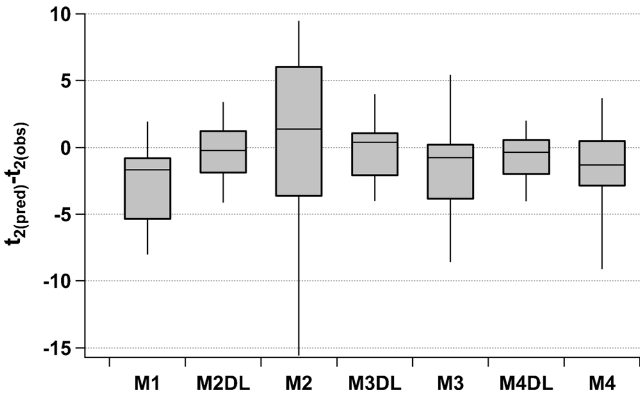


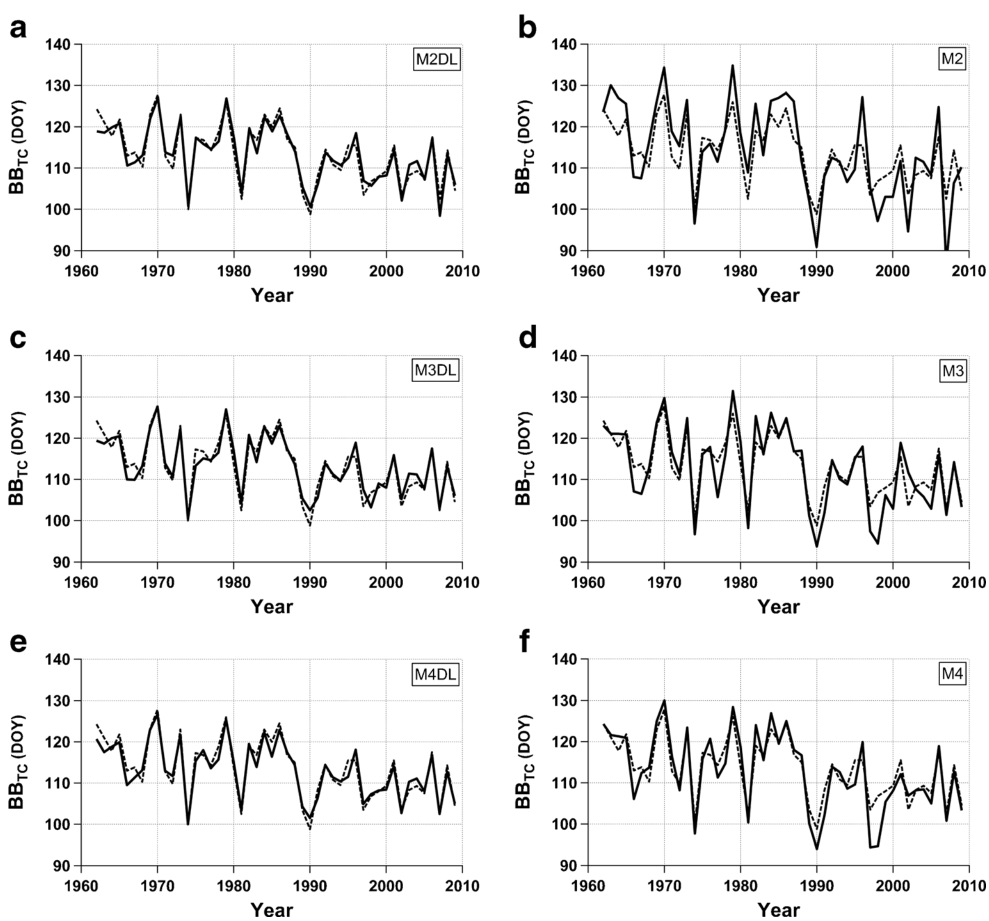
Fig. 3 Boxplot for the residuals in the beginning of cherry blossom [$t_{2(pred)}-t_{2(obs)}$] of the internal validation years (24 years) for the developed models

2.1. The optimal accumulated chilling amounts C* in the models M3 and M4 are 1,572.2 CH and 89.1 CP, respectively. Compared to the literature these values seem too high, despite the paucity of papers documenting the chilling requirement of sour cherries. Anderson et al. (1986) indicate values of 954 chilling units (Utah and Michigan), while Marini (2009) suggests 1,000 CH (Virginia). The introduction of the DL-term in the models led to much more realistic chilling requirements for sour cherries, with 1,071.8 CH for M3DL and 74.1 CP for M4DL. The forcing requirement varied between 567.4 and 593.6 PTU for the models with DL-term and was between 189.3 and 534.8 GDD for the other models. The higher range of *F** of the models without DL is due the different base temperatures of the models.

Model validation

The model performances were evaluated using the second half of the datasets (odd years of 1962–2009). For all DL-models the RMSE for validation was similar to the $RMSE_{opt}$ (Table 4) [$RMSE0_{val}$=7.21 days (mean over the four grid cells); *SD*=0.15 among the four grid cells]. For model M2DL, the error was 2.39 days and thus 0.15 days less than for the calibration period, which is probably accidental. M3DL had the same value compared to the optimization years, while for M4DL the error was slightly higher with 2.38 days. For models M2 and M3 without DL-function the $RMSE_{opt}$ and $RMSE_{val}$ had a similar magnitude with 6.35 and 4.48 days, respectively. For model M4, the $RMSE_{val}$ was 3.76 days and was 0.39 days lower than the $RSME_{opt}$. The highest difference between $RMSE_{opt}$ and $RMSE_{val}$ was found for model M1 with an optimized starting date (DOY = 60),

Fig. 4 Comparison between observed (*dashed line*) and calculated (*solid line*) dates in the beginning of sour cherry blossom (BB_{TC}) in Rhineland-Palatinate between 1962 and 2009 for the models M2DL, M3DL, M4DL (*left*) and M2, M3, M4 (*right*)



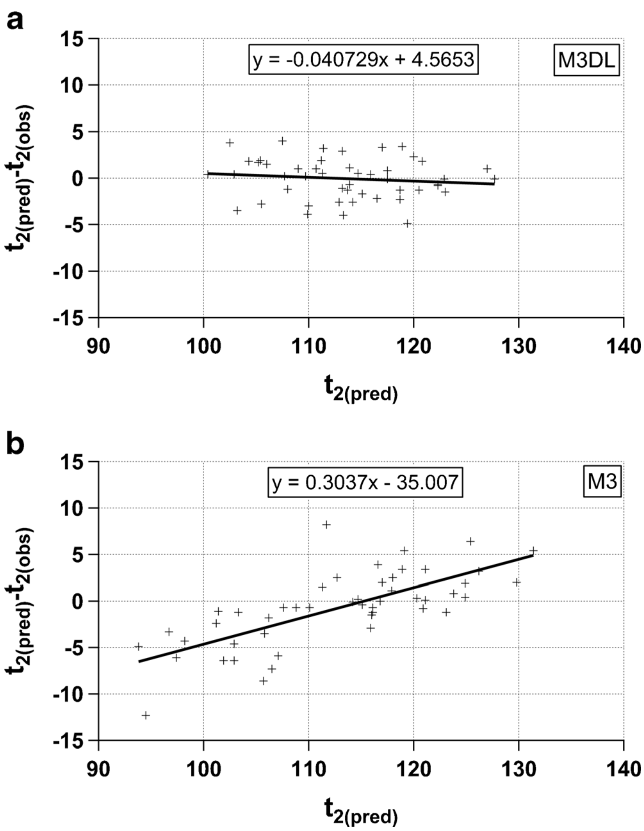


Fig. 5 Scatter plot for the residuals in the beginning of cherry blossom [$t_{2(\text{pred})}$–$t_{2(\text{obs})}$] as function of the predicted t_2-values for the models M3DL (*left*) and M3 (*right*)

where the $RMSE_{val}$ value increased by 1.73 days (from 2.57 to 4.30 days).

A comparison between observed and predicted dates at the beginning of the sour cherry blossom period reflects the difference in the RMSE between the two different approaches (with and without DL) (Fig. 3). The maximum differences between the DL-models are in the range of ±4 days, with the lowest values for model M4DL. Model M2 shows the highest dispersion, with extreme values of more than −15 days and almost +10 days. The dispersion of the 25th and 75th percentile of the differences in the DL-models are lowest, with −1.9 and +1.2 days for model M2DL, −2.1 and +1.1 days for model M3DL and −2.0 and +0.6 days for model M4DL. The 50th percentile in the DL-models differs only slightly from zero, which indicates a low systematic anticipation or delay of the predicted blossom dates. Model M1, except from the 75th to the 100th percentile, presents negative differences and therefore the model predict the blooming dates too early. Figure 4 matches the curves for the DL-models closely, while for models without DL-function the fit is not that close, and especially in some years the differences are relatively high. In 1998, the beginning of blossom is simulated by 12.3 days too early with M3 and by 12.1 days too early with M4, while in 1979 the date is estimated too late (M3: +5.4 days, M2: +8.8 days). The models without DL generally have the tendency to predict the early blooming years too early and the late years too late compared to the observations. In Fig. 5 the errors in t_2 were plotted against the predicted t_2-values. The high slope of the regression line in this scatter plot of the residuals in model M3 (e.g., Wilks 2005, Chap. 6.2.6) indicate a significant systematic error. The slopes in the regression lines were +0.05, +0.44, +0.30 and +0.28 for M1, M2, M3 and M4, while the slopes for DL-models were +0.02, −0.04 and −0.07 for M2DL, M3DL and M4DL, respectively. This result suggests the use of the DL-models to avoid systematic errors in predicting the beginning of blossom. An explanation for the systematic errors of the models without DL-term can be found in Blümel and Chmielewski (2012).

Afterwards, the best performing model approaches (M1, M2DL, M3DL, M4DL) were validated on independent data from the GPM. This dataset contains station data from several locations with different climatic conditions, mainly in Germany and in Europe (one station in North America, Table 1). The results show that the combined CF-models had generally a better performance. Figure 6 shows the differences between the observed and predicted dates of the beginning of sour cherry blossom for all validated stations. The dispersion of the differences is lower in the combined CF-models and amounts −2.0 and −2.1 days at the 25th percentile and 2.3 and 2.0 days at the 75th percentile for model M3DL and M4DL, respectively. As shown for the internal validation model ,M1 predicts the blooming dates too early. The average $RMSE_{val}$ for the CF-models was 3.11 days for the M3DL and 2.95 days for the M4DL (Table 5). Also at the stations Milwaukee (WI, US), Banska Bystrica (SK) and Schleswig (D), the latter being located in northernmost part of Germany, the error was lower than 4 days. Model M1 showed a noticeably higher average RMSE of 4.27 days. In Braunschweig (D), Tharandt (D), Prague (CZ) and Milwaukee (WI, US) the error

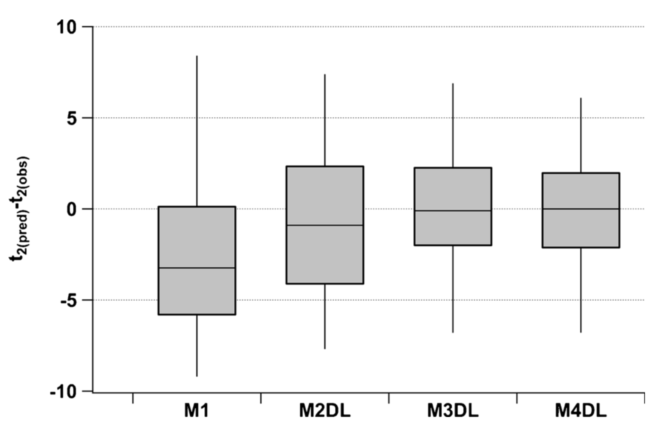


Fig. 6 Boxplot for the residuals in the beginning of cherry blossom [$t_{2(\text{pred})}$–$t_{2(\text{obs})}$] of 11 GPM-stations for the external validation (74 single years) for selected models

Table 5 Root mean square error of external validation ($RMSE_{val}$) for selected models on the observations of the Global Phenological Monitoring Programme (GPM) for the beginning of sour cherry blossom (variety 'Vladimirskaya'). RMSE0 is the root mean square error of the 0-model (see Eq. 11)

Station	M1	M2DL	M3DL	M4DL	RMSE0
Braunschweig (D)	5.25	2.93	2.43	2.68	6.27
Berlin-Dahlem (D)	2.66	3.27	3.07	2.53	4.79
Geisenheim (D)	3.27	3.09	1.12	1.37	4.40
Offenbach (D)	1.21	3.51	3.72	2.43	3.67
Schleswig (D)	4.77	4.15	3.92	3.95	7.57
Tharandt (D)	6.54	4.26	4.23	4.36	5.17
Linden (D)	4.55	3.49	2.87	2.91	5.24
Graupa (D)	4.08	4.25	4.04	3.32	5.35
Praha (CZ)	5.18	3.16	3.13	2.87	6.59
Banska Bystrica (SK)	2.84	2.65	2.64	2.14	3.99
Milwaukee (WI, US)	6.59	3.95	3.02	3.89	5.03
Mean	4.27	3.52	3.11	2.95	5.28

was even greater than 5 days. For this model, in some years the differences between the predicted and observed blossoming dates reached 8 or 10 days. M2DL showed generally less accuracy than the combined CF-models, which indicates that the chilling requirement is an important parameter for modelling the beginning of cherry blossom. The RMSE of this model was never lower (except for model M3DL in Offenbach and model M4DL in Tharandt) than any of the combined CF-models (M3DL, M4DL). If these models are used to project possible changes in the timing of sour cherry blossom for future climate conditions, the use of combined CF-models will be much more desirable.

Discussion and conclusions

In this study, seven models to predict the beginning of sour cherry blossom were developed; in addition to pure forcing models, a sequential approach for combined CF-models was evaluated. Different authors presented combined sequential CF-models, which assume a fixed sum of forcing and chilling units to determine a phenological stage (Cesaraccio et al. 2004; Rea and Eccel 2006; Chmielewski et al. 2011). Other combined CF-models assume that the critical sum of forcing units may be related to the amount of chilling units previously accumulated (Cannell and Smith 1983; Harrington et al. 2010). Both approaches are a simplification of the complex physiology that controls chilling and forcing of trees. Future studies are needed to understand this mechanism more accurately. However, as long as strongly physiologically based models are not available, mechanistic models, in which some parameters have to be optimized, are the only option in phenological modelling. If the models are used for climate impact studies, we strictly recommend careful selection of a phenological model. Not all phenological models such as simple GDD-models are useful for this purpose (Blümel and Chmielewski 2012).

This study has shown that the introduction of a DL-function into a conventional GDD-model to predict the beginning of sour cherry blossom improved model performance in several ways. First, the consideration of daylength allowed the selection of an earlier starting date t_1 of temperature accumulation for the pure GDD-models (M2DL vs M2). This would become relevant if the models were used in climate impact studies to calculate possible shifts in the beginning of sour cherry blossom.

Secondly, the introduction of a DL-function in the combined CF-models (M3DL, M4DL) led to a much more realistic model parameter value for C* compared to models M3 and M4. Also with this point we have to be careful. The chilling requirement, understood as the minimum amount that a specific sour cherry variety has to be exposed to colder temperatures for rest breaking, always remains the same and thus is variety specific. However, the currently available chilling models cannot be applied successfully in all climatic regions (Luedeling et al. 2009). They are only proxies of the result of many different biochemical processes in the flower buds and trees. While the 32–45 °F model can be used in temperate and cold climates, the model fails in warm subtropical climates (Erez 2000). In the latter regions the calculated chilling hours would be incorrect and would not present the chilling requirement of the crop. The same would occur for this model in the case of rising temperatures due to climate change (Chmielewski et al. 2012a). However, the Dynamic model works over a wider climatic range, i.e., in both warm and cold growing regions (Luedeling et al. 2011) and thus is probably more suitable for future projections.

The optimal base temperature for the models with DL-term was constant among all models at 1.0 °C. Since in these models the accumulation of GDD is also influenced by daylength (PTU), the calculated optimal threshold for base temperature in the DL-models is not comparable with the base temperature of the original GDD-approaches. So, it is probably not a contradiction that a slightly higher base temperature for sour cherries is recommended in the literature (Zavalloni et al.

2006; Ladanyi et al. 2009) and even calculated for model M1. Thirdly, the DL-function reduced the RMSE of all models (M2DL, M3DL, M4DL) by more than half compared to the same models without consideration of daylength. We also showed that the much more complicated combined chilling forcing models (M3DL, M4DL) had at least the same accuracy (internal validation) or a better performance (external validation, Table 5) as the pure forcing model M1. The latter model can be used only to calculate the beginning of sour cherry blossom for current climate conditions, since the starting date of temperature accumulation is only 1 March and therefore, for the expected temperature rise, probably too late. Finally, the external validation showed that the combined CF-models that consider the DL-term in the GDD-approach and that were developed for one site in Germany are usable even for different locations in Europe and one site in North America.

Recent studies have shown that pure forcing models, applied on forest tree species in Finland, perform as well as combined CF-models when applied to current climate conditions (Linkosalo et al. 2006, 2008).

Rising temperatures in the future will affect the timing of dormancy release (Chmielewski et al. 2012a) and could alter the performance of pure forcing models (Linkosalo et al. 2008; Thompson and Clark 2008). Therefore, it is necessary to use combined CF-models in order to calculate possible shifts in the blossoming date of fruit trees due to climate change. For fruit trees, a combination of chill portion (Dynamic model) and PTU (Eq. 9) is recommended. The suggested approach led to reliable model parameters, combined with relatively low RMSE values in the case of external model validation. Although the influence of daylength on the timing of phenological events as discussed in the literature is controversial, this study showed that such an influence can exist, at least for sour cherries.

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