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ORIGINAL PAPER

Climate change and spring frost damages for sweet cherries in Germany

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Abstract Spring frost can be a limiting factor in sweet cherry (*Prunus avium* L.) production. Rising temperatures in spring force the development of buds, whereby their vulnerability to freezing temperatures continuously increases. With the beginning of blossom, flowers can resist only light frosts without any significant damage. In this study, we investigated the risk of spring frost damages during cherry blossom for historical and future climate conditions at two different sites in NE (Berlin) and SW Germany (Geisenheim). Two phenological models, developed on the basis of phenological observations at the experimental sweet cherry orchard in Berlin-Dahlem and validated for endodormancy release and for warmer climate conditions (already published), were used to calculate the beginning of cherry blossom in Geisenheim, 1951–2015 (external model validation). Afterwards, on the basis of a statistical regionalisation model WETTREG (RCP 8.5), the frequency of frost during cherry blossom was calculated at both sites for historical (1971–2000) and future climate conditions (2011–2100). From these data, we derived the final flower damage, defined as the percentage of frozen flowers due to single or multiple frost events during blossom. The results showed that rising temperatures in this century can premature the beginning of cherry blossom up to 17 days at both sites, independent of the used phenological model. The frequency and strength of frost was characterised by a high temporal and local variability. For both sites, no significant increase in frost frequency and frost damage during blossom was found. In Geisenheim, frost damages significantly decreased from the middle of the twenty-first century. This study additionally emphasises the importance of reliable phenological models which not only work for current but also for changed climate conditions and at different sites. The date of endodormancy release should always be a known parameter in chilling/forcing models.

Keywords Late frost · Flower damage · *Prunus avium* L. · Phenological models · Climate scenarios

Introduction

Next to apples, sweet cherry is the second important fruit tree in Germany, cultivated on 5182 ha (Federal Office of Statistics 2015) and are economically very important for the German fruit market. Sweet cherries, which start to flower early in spring, are usually frost-threatened, although generally early flushing trees are among the most freezing-resistant species during this phase (Vitasse et al. 2014).

Spring frost, mainly during tree blossoming, is one of the mostly feared weather hazards in orchards. It accounts for greater losses in fruit production than any other low temperature stresses (Rieger 1989; White and Haas 1975; Winkler

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et al. 2013). Just a single frost event can lead to yield losses up to 90% in stone-fruit production (Proebsting 1982). During the period of endo- and ecodormancy, biochemical constituents—such as sugars (Chmielewski et al. 2017), amino acids and proteins—may promote the frost hardiness of buds (Lasheen and Chaplin 1971). During this time, the water content in the buds is constant at a low level (53% in 'Summit' cherry buds; Götz et al. 2014). With rising temperatures in spring, which induce the beginning of ontogenetic development, water content in the buds increases and first visible changes on the buds occur, starting with bud swelling (Chmielewski and Götz 2017). During this time, cold resistance of the buds continuously decreases (Longstroth and Perry 1996; Dennis and Howell 1974; Proebsting and Mills 1978; Miranda et al. 2005). Between bud swelling and beginning of cherry blossom, temperature for a 10% damage reduces from $LT_{10} = -8.3$ to $LT_{10} = -2.2$ °C (Ballard et al. 1997). A sure sign of damaged flower is its blackened pistil (Rodrigo 2000; Salazar-Gutiérrez et al. 2014; Matzneller et al. 2016). In order to prevent strong yield losses, sweet cherries naturally build huge flower clusters with more than 20 flowers per cluster (Hue et al. 2016). If nearly 50% of these flowers are damaged, the tree could be able to generate nearly a full crop yield because in years without killing frosts during blossom, 'Summit' develops only 22% of the flowers per cluster to ripe fruits (Hue et al. 2016). Despite this observation, Kappel (2010) found a positive linear correlation ($r^2 = 0.55$) between sweet cherry yield and the number of survived buds after spring frost events. It should be considered that a reduced fruit set due to killing frost can result in a slightly larger fruit size (Whiting and Lang 2004), so that the final yield value is not affected, as large cherries are always attractive for the fruit market.

Rising air temperature due to climate change usually reduces the total number of frost days per year and lengthens the frost-free season (Robeson 2002; Fernández-Long et al. 2013; Yu et al. 2014). Wypych et al. (2016) found a decrease in the number of spring frosts up to 4 days per decade in Western Europe (1951–2010) that was related to rising spring temperature in this region. However, frost risk is not only related to mean temperature but also to the daily temperature variance (Rigby and Porporato 2008). If temperature increases, the timing of phenological phases as well as the timing, frequency and severity of frost events can be altered. While some authors found that last dates of spring frost have occurred earlier, synchronously with plant development (Scheifinger et al. 2003; Eccel et al. 2009), other authors identified that the risk of frost damage has increased with rising temperatures (Rochette et al. 2004; Kaukoranta et al. 2010, Augspurger 2013). Pulatov et al. (2015) investigated the planting and emergency dates of potatoes in Europe and found that a warmer climate can reduce the risk in areas which are most prone to frost damage today. Schwartz et al. (2006) concluded that in the northern hemisphere a complex spatial relationship between the onset of plant growth and subsequent last spring freeze exists, so that it is difficult to detect any general tendency of increasing or decreasing frost risks. Thus, considerable uncertainties to future frost damages of perennial crops exist.

In this study, we used two already published phenological models (Chmielewski and Götz 2016), which were now validated on long-term observations of cherry blossom at a different site (Geisenheim) and following used to investigate the frequency of frost events and the resulting total flower damage during cherry blossom for two sites in Germany on the basis of local climate scenarios.

Materials and methods

Climate data

For this study, we used observed daily data of air temperature (T daily mean, and T_n daily minimum temperature) between 1951 and 2015 from two weather stations, in Berlin-Dahlem (52.47°N, 13.30°E, h = 51 m a.s.l.) and Geisenheim (49.99°N, 7.95°E, h = 110 m a.s.l.), the latter located in Hessen (SW Germany). As climate projection, we used the results of the statistical regionalisation model WETTREG (Kreienkamp et al. 2013, version 2017) which bases on the results of the circulation model MPI-ESM-LR (RCP 8.5, run1; Jacob et al. 2013). WETTREG (weather situation-based regionalisation method) is a statistical regionalisation model which uses large-scale information from the driving climate model (circulation pattern) and corresponding information from the local weather station. If the frequency of a certain weather pattern changes in the future, the weather at the station also changes. In order to represent the variability of climate more realistic, 10 individual realisations (time series of run 0–9) were stochastically generated for the historical (1971–2000) and scenario run (2001–2100). From the scenario run, we used three time-slices: 2011–2040, 2041–2070 and 2071–2100. Data which are given in Tables 5, 6, 7, 8 and 9 are mean values of all 10 WETTREG realisations. The extreme values (Tables 7, 8 and 9) refer to individual runs (0–9) of WETTREG. The Representative Concentration Pathways (RCP 8.5) corresponds to the pathway with the highest greenhouse gas emissions. The greenhouse gas emissions and concentrations in this scenario lead to a radiative forcing of 8.5 W m^{-2} at the end of the century. It is the baseline scenario that does not include any specific climate mitigation target (Moss et al. 2010; Riahi et al. 2011) and shows the strongest possible impact due to climate change.

Phenological observations

Observations of beginning of blossom (BF, BBCH 60) in the experimental sweet cherry orchard in Berlin-Dahlem were available between 2001 and 2015. These data were used to optimise and verify the phenological models. In Berlin-Dahlem, the cultivar ‘Summit’ is grown, which is a medium-late blossoming variety. For Geisenheim, we had long-term observations for the beginning of cherry blossom from the German Weather Service between 1951 and 2015. In this 65-year period, three different cultivars were observed (‘Kassins Frühe’ 1951–1971, ‘Souvenir des Charmes’ 1972–1988, ‘Bigarreau Burlat’ 1989–2015). ‘Kassins Frühe’ is a medium-early blossoming variety and ‘Souvenir des Charmes’ and ‘Bigarreau Burlat’ are early blossoming varieties. On average, the medium-early blossoming varieties bloom 2 days and the early varieties 5 days earlier than ‘Summit’ (M. Balmer, personal communication).

Phenological models

In order to calculate the beginning of cherry blossom, we used two phenological models which were optimised and validated on precise phenological observations of the cultivar ‘Summit’ at the experimental sweet cherry orchard in Berlin-Dahlem (Chmielewski and Götz 2016). Model M20b (subsequently called M20) was a pure forcing (F) model with an optimised starting date (t_1 = 34 DOY) for the accumulation of photo-thermal units (F^* = 212.6 PTU, EXPO = 0.907) above a base temperature of T_{BF} = 3.99 °C. Model M30b (subsequently called M30) was a sequential chilling/forcing (CF) model which bases on a chilling requirement (C*) of 39 chill portions (CP) for dormancy release, and the accumulation of 365.6 PTU (EXPO = 2.555) above T_{BF} = 3.67 °C until BF. Endodormancy release (t_1) and chilling requirement were validated with climate chamber experiments on cherry twigs for four seasons (2011/2012–2014/2015; Chmielewski and Götz 2016).

Both models consider a day length term in the forcing approach which was represented by the EXPO coefficient. The models showed excellent results for the optimisation (2001–2010, $RMSE_O$ of M20 = 1.36 days, M30 = 1.77 days) and validation period (2011–2015, $RMSE_V$ of M20 = 1.18 days, M30 = 1.41 days) and the lowest deviations from the observed blossoming date in our climate change experiment in Berlin-Dahlem (M20, − 3 days; M30, +1 days; Chmielewski and Götz 2016). Thus, we were interested to see how these different model types (F/CF model) will calculate the blossoming dates for long-term historical and changed climate conditions at Geisenheim. Since varieties in Geisenheim are other than those cultivated in Berlin, we had to introduce a cultivar correction. Cultivar-adjusted models for Geisenheim have been named M20* and M30*.

Methodology

At first, we calculated BF from 1951 to 2015 on the basis of M20 and M30 for Berlin-Dahlem and Geisenheim. After cultivar correction, we were able to evaluate the performance of the models for Geisenheim (external model validation). In this study, we assumed that the blossoming period constantly lasts 14 days after BF. This period corresponds to the average duration of cherry blossom at both sites (x = 14.3 days, s = 4.3 days). Afterwards, we used the observed BF data for Geisenheim (1951–2015) to count the number of frost events during cherry blossom (BF until BF +14 days). Since only phenological observations from 2001 to 2015 were available for Berlin-Dahlem, for this site we supplemented the missing data from 1951 to 2000 with M20. Frost events during blossom were classified into light ($-2\ °C \le T_n < 0\ °C$), medium ($-4\ °C \le T_n < -2\ °C$) and strong frosts ($T_n < -4\ °C$). Compared to strong and medium frosts, light frosts cause only low damages to the flowers. The frost damage of an individual frost event was calculated according to experimental findings by Matzneller et al. (2016), Eq. 1. In this experiment, we chose a total exposure time of 2 h, from which the first hour was necessary to reach the desired target temperature, so that we can assume for this study a standard exposure time to frost events of 1 h.

$$FD = 0.94 + \frac{-0.957}{1+\exp\left(\frac{-3.2-T_n}{0.8}\right)} \tag{1}$$

$$\mathrm{FD} = 0: \text{no damage}, \mathrm{FD} = 1: \text{all flowers are killed}$$

In case of multiple frost events on several individual or consecutive days during cherry blossom, subsequent damages must be calculated according to Eq. 2. They only can harm the remaining undamaged flowers after previous frost events. Thus, the total frost damage (FD_{tot}) during a blossoming period calculates as follows (n = number of frost events):

$$\begin{aligned} FD_{tot} &= 1-[1-FD(n-1)]\cdot[1-FD(n)];\ \ n\in\{1,2,3,\ldots\} \\ FD(0) &= 0 \end{aligned} \tag{2}$$

In order to investigate how the frequency of frost during blossom will change until 2100, we used the WETTREG data to calculate the mean absolute frequency of frost events and mean FD_{tot} for all 10 realisations of the historical run (1971–2000) and the three scenario time-slices (2011–2100) of WETTREG. For this, BF were calculated for Berlin-Dahlem with M20 and M30 and for Geisenheim with M20* and M30*. The latter calculations include a correction for the up-to-date cultivar ‘Burlat’ by − 5 days.

Significant changes in air temperature and BF between the historical run and the three time-slices were tested with the

Tukey-HSD test, using the 10 realisations of WETTREG as repetitions. Since the frequency of frost events and frost damages are not normally distributed, we used the Kruskal–Wallis test to detect significant changes of these parameters between the historical run and the three time-slices. The statistical test does not assume normality in the data and is much less sensitive to outliers.

Results

Observed and calculated dates for the beginning of cherry blossom

On average, BF in Berlin-Dahlem starts on 17 April (107 DOY, s = 7.1 days, 2001–2015, Table 1). The earliest date in this period was observed in 2014 (95 DOY), the latest one in 2001 (119 DOY). For the whole period 1951–2015 (data 1951–2000 were calculated with M20), the mean blossoming date is 22 April (112 DOY, s = 9.2 days). Mean cherry blossom in Geisenheim (1951–2015) starts 11 days earlier (101 DOY, s = 9.7 days). The earlier timing of BF in Geisenheim is related to 1 °C higher air temperatures at this site between February and April (Table 2) and reflects additionally the cultivation of early blossoming varieties under milder climate conditions in Geisenheim ($\Delta T(7/1)$ = 17.4 K, Table 2).

Figure 1b shows a very good consistency between modelled and observed data for the beginning of cherry blossom in Geisenheim, after cultivar adjustment. The RMSE between observed and calculated BF dates (1951–2015) is ranging between 3.28 (M20) and 4.04 (M30) days. As expected, the phenological models in Berlin-Dahlem fitted the relatively short observations very well (Fig. 1a).

Frost damage for current climate conditions in Berlin-Dahlem and Geisenheim

Between 1951 and 2015, the calculated number of light frosts during cherry blossom in Berlin-Dahlem and Geisenheim were 21 and 27, respectively (Table 3). These events occurred in 15 years in Berlin-Dahlem and in 13 years in Geisenheim. This means, on average, frost during blossom was observed in nearly all 4–5 years at both sites. The maximum number of light frost during cherry blossom within a year was 3 for Berlin-Dahlem in 1990 and 6 for Geisenheim in 1977. However, light frosts cause only small damages to the flowers up to a maximum damage of 16% (Eq. 2). Medium and strong frosts in the blooming period are relatively rare (Table 3). While in Berlin-Dahlem five events with medium frost were counted, spread over 3 years, in Geisenheim only two medium frost events were observed in 1 year. The only strong frost of − 4.6 °C was observed on 31 March 1977 in Geisenheim.

The mean total frost damage (1951–2015) for Berlin-Dahlem and Geisenheim was in the same magnitude with 3.1 and 3.3%, respectively (Table 4); however, the occurrence and strength of frost damages showed a very high temporal and local variability (Fig. 2). At Berlin-Dahlem in the 1970s, 1980s and in the beginning of the 1990s, frost damages were frequently observed. The very strong frost damage of 88.0% at Berlin-Dahlem in 1991 was the result of four consecutive frost events (one light and three medium frosts) between 20 and 23 April, 8 days after BF on 12 April 1991. In Geisenheim, the highest frequency of frost events was observed in the 1970s and 2000s. The maximum frost damage of 84.7% at Geisenheim in 1977 was the result of seven late frost events during blossom (one strong frost, six light frosts). The strong frost alone caused already a damage of 79.8%.

Possible changes in air temperature and shifts in the beginning of cherry blossom

The historical run of WETTREG (1971–2000) almost reflects the climatic differences between both sites (Table 5). Projected temperatures in Geisenheim are slightly higher (+ 0.5 °C) than observed (Table 2), while air temperature at Berlin-Dahlem is well represented. According to RCP 8.5, mean annual air

Table 1 Beginning of sweet cherry blossom (BF) in Berlin-Dahlem and Geisenheim

Site (period, data)	BF (DOY)	s (days)	Min (DOY)	Max (DOY)	Trend (days/decade)
Berlin-Dahlem					
2001–2015 (OBS)	107	7.1	95	119	–
1951–2015 (M20, OBS)	112	9.2	86	129	− 1.8
Geisenheim					
1951–2015 (OBS)	101	9.7	81	119	− 2.3
1951–2015 (M20*/M30*)	105/105	9.3/7.8	85/89	123/122	–

BF mean, *s* standard deviation, *Min* earliest blossoming date, *Max* latest blossoming date, *OBS* observed data, calculated data with models M20 and M30, for Geisenheim with cultivar adjustment (M20*, M30*), *DOY* day of year

Table 2 Mean annual air temperature (T), mean air temperature between February and April $T(24)$, mean annual minimum temperature (T_n) and mean minimum temperature in April $T_n(4)$, difference between July and January temperature ($\Delta T(7/1)$) in Berlin-Dahlem and Geisenheim, 1971–2000

Site	T, s (°C)	$T(24)$, s (°C)	T_n, s (°C)	$T_n(4)$, s (°C)	$\Delta T(7/1)$ (K)
Berlin-Dahlem	9.6, 0.82	5.1, 1.47	6.0, 0.75	4.5, 1.16	18.1
Geisenheim	10.2, 0.69	6.1, 1.18	6.3, 0.66	4.9, 1.10	17.4

s standard deviation

temperature rises in Geisenheim and Berlin-Dahlem by 3.2 and 3.4 °C, respectively (2071–2100 vs. 1971–2000). Mean annual minimum temperature would increase by nearly 3 °C and mean minimum temperature in April, the current month of BF, by about 2 °C at both sites. Compared to the period 1971–2000, the temperature rise in all time-slices was significant (Table 5).

Calculated mean dates in BF (1971–2000) were comparable with the observations. The mean difference in BF between Geisenheim and Berlin was similar to the observations (M20, −14 days; M30, −12 days; Table 6).

Due to rising air temperatures, BF occurred significantly earlier until 2100 by about 17 days (Table 6). At both sites, a nearly linear advancement of blossom was visible from 2020. In Geisenheim, BF after 2060 occurred nearly in all years in the end of March (Fig. 3). In Berlin-Dahlem, BF advanced from mid-April (2011–2040, 106 DOY) to the beginning of April (2071–2100, 94 DOY). Both phenological models showed very consistent results.

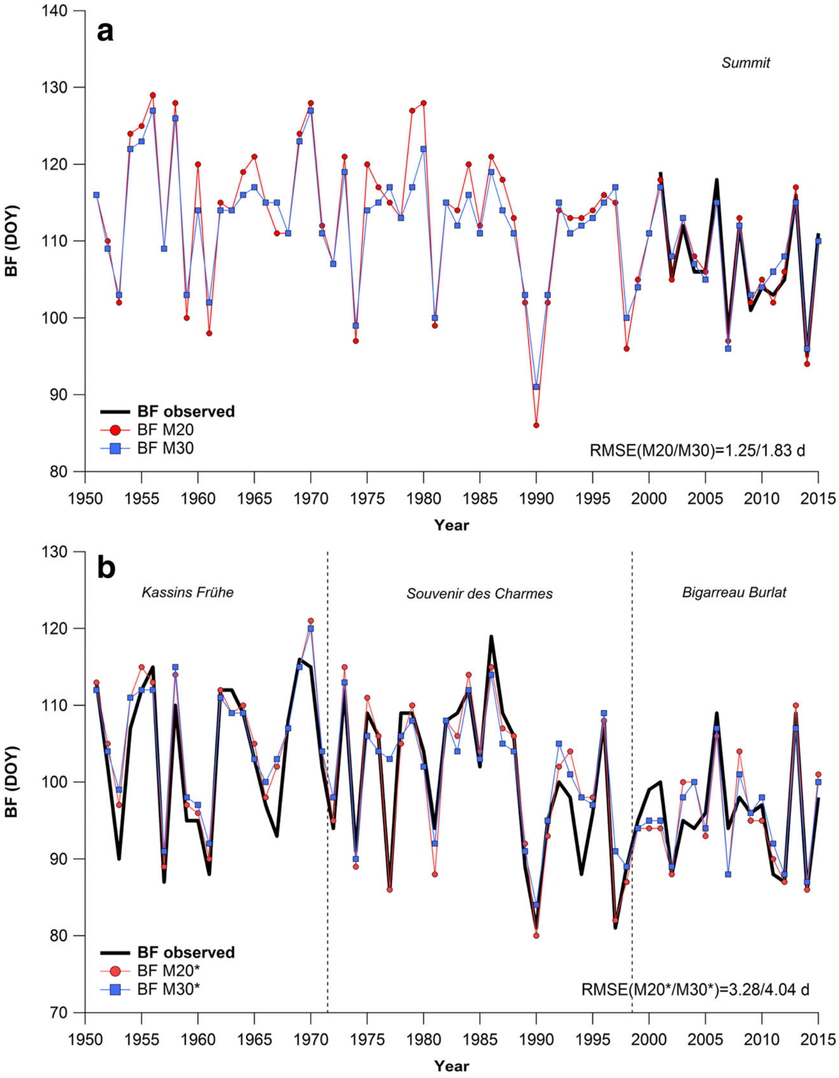

Fig. 1 Observed and calculated beginning of sweet cherry blossom (BF) for Berlin-Dahlem (**a**) and Geisenheim (**b**), 1951–2015. The calculated dates for Geisenheim with M20 and M30 were cultivar adjusted (M20*, M30*). DOY, day of year

Table 3 Mean absolute frequency (AF) of light, medium and strong frost during cherry blossom in Berlin-Dahlem and Geisenheim 1951–2015 (Berlin-Dahlem—supplemented data with M20 between 1951 and 2000)

Frost strength	AF (days)	s (days)	Years with frost during BF
Berlin-Dahlem			
Light frosts	21	0.66	15
Medium frosts	5	0.41	3
Strong frosts	0	0.00	0
Geisenheim			
Light frosts	27	1.07	13
Medium frosts	2	0.25	1
Strong frosts	1	0.12	1

s standard deviation

Frost damages for future climate conditions at Berlin-Dahlem and Geisenheim

The mean absolute frequency of light, medium and strong frosts for current climate conditions in the WETTREG realisations was comparable between both sites (Tables 7 and 8). Similarly to the observations, most frequent were light frosts with a mean frequency between 7.2 days (Berlin-Dahlem, M30) and 9.5 days (Geisenheim, M20*). At both sites, medium frosts were distinctly lower with about 2 days and strong frosts very rare. The comparison of the temporal development of light and medium frosts during blossom until 2100 showed nearly unchanged conditions for Berlin-Dahlem, however a slow decrease of frost events in Geisenheim. The calculated frost damages (Table 9) reflects these results. While the mean FD_{tot} for Berlin-Dahlem stays constant until 2100, it significantly decreases in Geisenheim. The calculations additionally showed that at both sites, frost damages in individual years can be very high until 2070. For instance, in Berlin-Dahlem, eight consecutive frost events in a WETTREG realisation of the period 2041–2070 (run 8—one strong, three medium and four light frosts) led to a total frost damage of 96.6%. In Geisenheim, seven consecutive frost events in a realisation of the period 2011–2040 (run 8—three strong, four medium frosts) killed all flowers. Only in the last time-slice the magnitude of the absolutely highest frost damages clearly decreased.

Table 4 Mean total frost damage (FD_{tot}) and absolutely highest FD_{tot} during cherry blossom in Berlin-Dahlem and Geisenheim 1951–2015

Site	FD_{tot} (%)	s (%)	Highest FD_{tot} (%) / year
Berlin-Dahlem	3.1	12.1	88.0/1991
Geisenheim	3.3	14.4	84.7/1977

s standard deviation

Discussion

Validation of phenological models and shifts in the beginning of blossom

In order to calculate the frost risk for changed climate conditions, phenological models must be tested for their credibility (Cittadini et al. 2006; Eccel et al. 2009; Richardson et al. 2013; Chuine et al. 2016; Darbyshire et al. 2016) because an unrealistic modelled advancement in blossoming time would strongly increase the frost damage. This includes (a) the reliability of the model parameters, (b) the model stability across different sites/climates and (c) the model performance for current and future climate conditions. In this study, we tried to consider all these aspects to a certain extent.

(a) The consideration of a day length (DL) term in M30 led to much more realistic model parameter estimations than conventional CF models (Chmielewski and Götz 2016), which uses the thermal-time approach to accumulate growing degree days (GDD) or growing degree hours (GDH). The chilling requirement of M30 (optimised—$C^* = 39$ CP) was very close to the experimentally found value for 'Summit' in 6 years ($C^* = 40.9 \pm 2.9$ CP; Chmielewski and Götz 2017).

Investigations by Measham et al. (2014) showed that experimentally derived chilling requirements can vary, depending on climatic location and the used experimental design. Thus, the authors concluded that C* cannot be seen as a fixed value. We can imagine that plants in different environments show phenotypic plasticity in its chilling and forcing requirement. However, our investigations for the climate conditions in Northeast Germany showed a relatively stable chilling requirement for 'Summit' among 6 years (experimentally derived), which were additionally confirmed by selected metabolites such as abscisic acid and sugars (Chmielewski et al. 2017).

Since for current climate conditions (1971–2000) endodormancy was released at both study sites in the end of November (Table 6), leading to a relatively short endodormancy phase, the period of ecodormancy lasted much longer. For 'Summit', Chmielewski and Götz (2017) found that ecodormancy lasts 3.5 times longer than endodormancy phase. This is usually a challenge for thermal-time approaches, which start to accumulate GDD or GDH directly after endodormancy release, if temperatures exceed the base temperature (T_{BF}). As a result, GDD/GDH are accumulated too fast in warm climates (blossom is predicted too early) and too slow in cold climates (blossom is predicted too late). For this reason, Darbyshire et al. (2016) concluded that the sequential model is not appropriate for climate projection studies. This conclusion we can confirm since in our climate change experiment, the conventional sequential approach predicted the cherry blossom 22 days earlier than observed (Chmielewski and Götz 2016). However, in the modified approach M30, the DL term did successfully regulate the

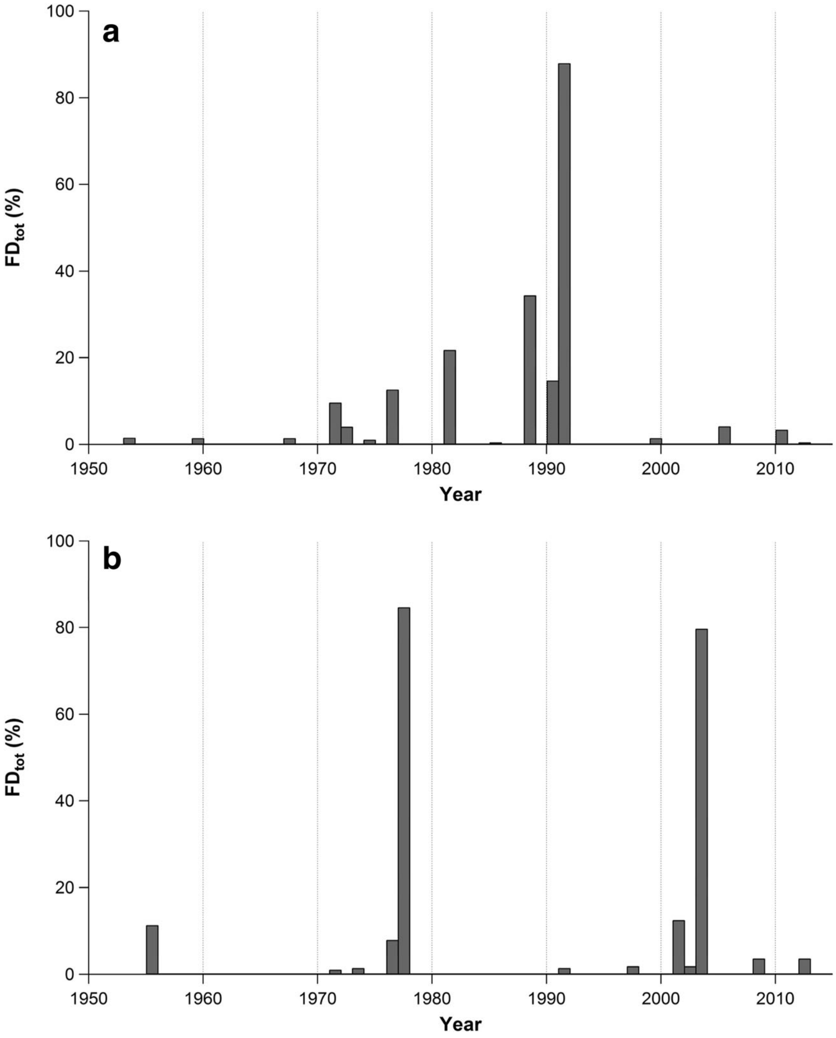

Fig. 2 Occurrence of frost damages during cherry blossom (FD$_{tot}$) in Berlin-Dahlem (**a**) and in Geisenheim (**b**), 1951–2015

Table 5 Mean annual air temperature (T), mean air temperature between February and April $T(24)$, mean annual minimum temperature (T_n), mean minimum temperature in April $T_n(4)$ in Berlin-Dahlem and Geisenheim in the historical WETTREG run (1971–2000) and in the 3 time-slices of the scenarios run (RCP 8.5)

Site (period)	T, s (°C)	$T(24)$, s (°C)	T_n, s (°C)	$T_n(4)$, s (°C)
Berlin-Dahlem				
1971–2000	9.7, 0.84a	5.3, 0.82a	5.8, 0.75a	4.4, 0.63a
2011–2040	10.7, 0.81b	6.0, 0.82b	6.6, 0.69b	5.0, 0.66b
2041–2070	11.9, 0.70c	7.0, 0.56c	7.6, 0.61c	5.8, 0.46c
2071–2100	13.1, 0.66d	8.0, 0.49d	8.8, 0.58d	6.5, 0.51d
Geisenheim				
1971–2000	10.7, 0.79a	6.6, 0.84a	6.9, 0.71a	5.5, 0.76a
2011–2040	11.6, 0.78b	7.3, 0.78b	7.6, 0.66b	6.1, 0.77b
2041–2070	12.7, 0.65c	8.2, 0.48c	8.6, 0.55c	6.9, 0.43c
2071–2100	13.9, 0.62d	9.2, 0.49d	9.7, 0.55d	7.7, 0.59d

Different letters indicate significant differences of means, Tukey-HSD test, $\alpha \leq 0.01$

s standard deviation

accumulation of forcing units (PTU) during the relatively long period of ecodormancy.

We believe that sequential CF models are physiologically justified, if the ecodormancy phase is considered realistic in the forcing approach, because after endodormancy release in the orchard all sampled 'Summit' twigs were able to bloom under controlled forcing conditions. However, the cherry buds in the orchard remained in winter rest. Short warm spells during winter, even if they exceeded T_{BF}, did not change the water content, fresh/dry weight or N/C content in the buds. The first measurable sign of biological activity towards the end of ecodormancy was a continuous increase of the bud's water content, which was related to continuously rising air temperatures for at least 3 weeks in the beginning of spring. This happened for 'Summit' on average 26 days (range 14–35 days, depending on annual temperature course) before bud swelling in the orchard was observed (Chmielewski and Götz 2017).

Parallel models include a lowering of the forcing requirement based on chill accumulation (Chuine et al. 2013). Chill overlap models (Pope et al. 2014; Darbyshire et al. 2016)

Table 6 Average beginning of cherry blossom (BF) in Berlin-Dahlem and Geisenheim in the historical WETTREG run (1971–2000) and in the 3 time-slices of the scenarios run (RCP 8.5)

Site (period)	BF (DOY)	s (days)	Min (DOY)	Max (DOY)	Δ(SC-HIS) (days)	t_1(M30) (DOY)	s (days)
Berlin-Dahlem							
1971–2000	112d/111d	8.0/6.7	90/92	134/128		324a	7.9
2011–2040	106c/106c	8.7/7.3	85/87	128/123	− 6/− 5	331b	7.9
2041–2070	100b/100b	7.6/6.6	78/81	129/128	− 12/-11	338c	7.5
2071–2100	94a/94a	6.7/5.8	74/78	110/109	− 18/-17	344d	5.9
Geisenheim							
1971–2000	98d/99d	9.2/7.9	73/76	119/119		329a	7.8
2011–2040	92c/93c	8.3/7.5	71/75	116/118	−6/−6	335b	7.4
2041–2070	87b/88b	6.0/5.7	71/72	112/115	−11/−11	342c	6.2
2071–2100	82a/82a	4.8/4.5	67/70	95/99	−16/−17	348d	5.7

Different letters indicate significant differences of means, Tukey-HSD test, $\alpha \le 0.01$

s standard deviation of all WETTREG realisations, *Min* absolutely earliest blossoming date, *Max* absolutely latest blossoming date of all WETTREG realisations for M20/M30 and M20*/M30*, *Δ(SC-HIS)* shift in the beginning of cherry blossom, related to the historical run, t_1 calculated date of dormancy release in M30

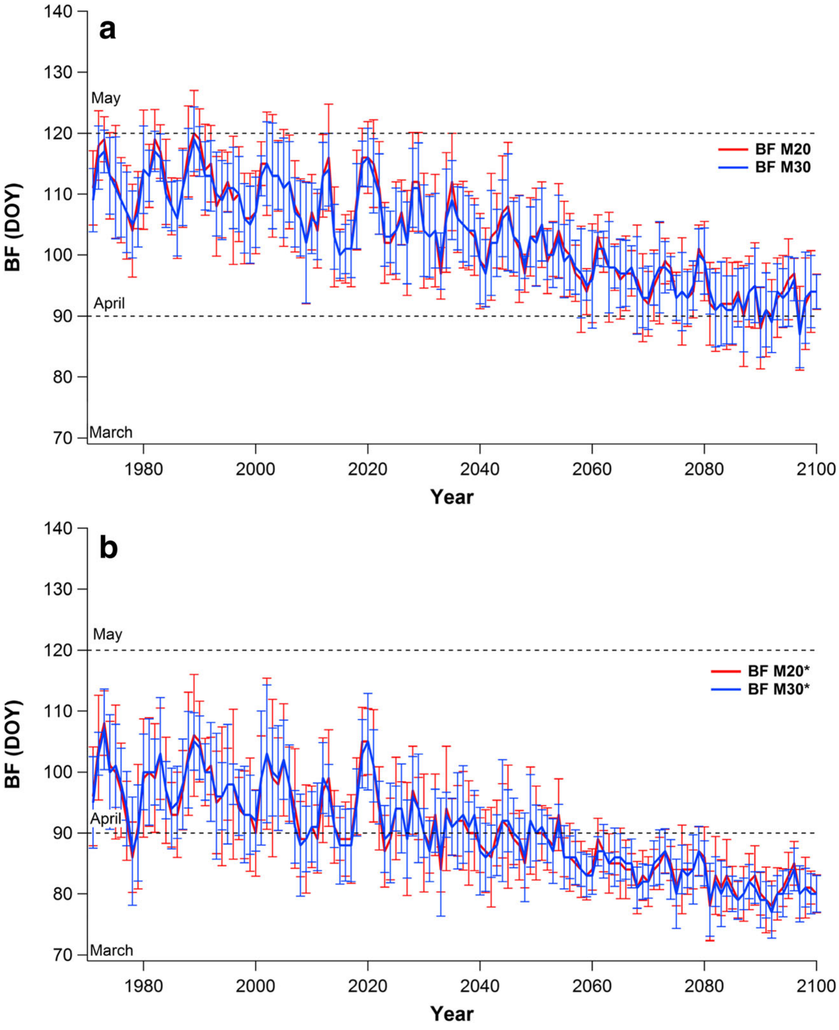

Fig. 3 Calculated beginning of sweet cherry blossom 1971–2100 (BF) in Berlin-Dahlem (**a**) and in Geisenheim (**b**) with models M20 and M30; for Geisenheim cultivar adjusted (M20*, M30*). 1971–2000 historical run of WETTREG, 2001–2100 scenario RCP 8.5. Error bars show the standard deviation of 10 WETTREG realisations. DOY, day of year

Table 7 Mean absolute frequency (AF) of light, medium and strong frost during cherry blossom in Berlin-Dahlem in the historical WETTREG run (1971–2000) and in the 3 time-slices of the scenarios run (RCP 8.5)

Period	AF (days)	s (days)	Min/year (days)	Max/year (days)
Light frosts				
1971–2000	7.7a/7.2a	0.60/0.58	1/1	15/13
2011–2040	10.2a/10.6a	0.68/0.72	6/5	20/20
2041–2070	9.2a/10.4b	0.65/0.72	4/6	16/19
2071–2100	7.7a/8.1a	0.55/0.57	5/4	12/12
Medium frosts				
1971–2000	1.8a/1.2a	0.28/0.19	0/0	4/3
2011–2040	2.0a/2.2a	0.28/0.27	0/0	7/8
2041–2070	1.8a/1.8a	0.26/0.24	0/0	3/4
2071–2100	1.8a/1.9a	0.25/0.27	0/1	6/6
Strong frosts				
1971–2000	0.0a/0.0a	0.00/0.00	0/0	0/0
2011–2040	0.0a/0.1a	0.00/0.02	0/0	0/1
2041–2070	0.1a/0.1a	0.02/0.02	0/0	1/1
2071–2100	0.0a/0.0a	0.00/0.00	0/0	0/0

Data are given for the projected blossoming period with M20/M30; different letters indicate significant differences in means, Kruskal–Wallis test, $\alpha \leq 0.01$

s standard deviation of all WETTREG realisations, *Min* absolutely lowest frequency, *Max* absolutely highest frequency per year of all WETTREG realisations

Table 8 Mean absolute frequency (AF) of light, medium and strong frost during cherry blossom in Geisenheim in the historical WETTREG run (1971–2000) and in the 3 time-slices of the scenarios run (RCP 8.5)

Period	AF (days)	s (days)	Min/year (days)	Max/year (days)
Light frosts				
1971–2000	9.5b/7.8b	0.79/0.64	5/1	15/16
2011–2040	6.0a/6.8b	0.49/0.54	1/2	10/14
2041–2070	2.3a/2.5a	0.25/0.28	0/0	6/4
2071–2100	0.9a/0.9a	0.12/0.12	0/0	3/2
Medium frosts				
1971–2000	2.1b/1.8b	0.30/0.28	0/0	4/3
2011–2040	1.4b/1.0a	0.24/0.16	0/0	4/4
2041–2070	0.6a/0.6a	0.11/0.11	0/0	2/2
2071–2100	0.0a/0.0a	0.00/0.00	0/0	0/0
Strong frosts				
1971–2000	0.1a/0.1a	0.02/0.02	0/0	1/1
2011–2040	0.4a/0.4a	0.07/0.07	0/0	3/3
2041–2070	0.1a/0.1a	0.02/0.02	0/0	1/1
2071–2100	0.0a/0.0a	0.00/0.00	0/0	0/0

Data are given for the projected blossoming period with M20*/M30*; different letters indicate significant differences in means, Kruskal–Wallis test, $\alpha \leq 0.01$

s standard deviation of all WETTREG realisations, *Min* absolutely lowest frequency, *Max* absolutely highest frequency per year of all WETTREG realisations

additionally presuppose a critical amount of chill before this compensatory effect between chilling and forcing can start. This approach is an alternative way to handle the sometimes very long phase of ecodormancy in order to avoid a too early or too late prediction of tree blossom, but it is also a kind of indirect bias correction within the model. For this reason, we conclude that the handling of ecodormancy phase in phenological models must be revised.

(b) Additionally, we validated the models M20 and M30, which were developed and validated for the site conditions in Berlin-Dahlem, at another site in Germany (external validation). After cultivar adjustment of BF in Geisenheim, the RMSE dropped from 5.35 days (M20) and 6.16 days (M30) to 3.28 days (M20*) and 4.04 days (M30*, Fig. 1b). Without cultivar correction, BF in Geisenheim was always slightly later because the models were originally calibrated for 'Summit'.

(c) Finally, in a previous study (Chmielewski and Götz 2016), we tested the behaviour of M20 and M30 for a distinctly warmer climate at Berlin-Dahlem, which led to a beginning of cherry blossom on 3 March, 1 month earlier than observed in the orchard. Models used in this study were able to calculate this date correctly, while other not physiologically validated models completely failed, such as the sequential CF model without DL term in the forcing approach.

Climate change can additionally lead to an insufficient chilling fulfilment due to rising air temperatures (e.g. Luedeling 2012; Darbyshire et al. 2011; Measham et al. 2017). For current climate conditions (1971–2000), the mean

Table 9 Mean total frost damage (FD_{tot}) for Berlin-Dahlem and Geisenheim in the historical WETTREG run (1971–2000) and in the 3 time-slices of the scenarios run (RCP 8.5)

Site (period)	FD_{tot} (%)	s (%)	Absolutely highest FD_{tot} (%)
Berlin-Dahlem			
1971–2000	2.4a/1.9a	8.65/6.43	85.3/71.3
2011–2040	3.2a/3.6a	9.20/10.06	79.5/90.8
2041–2070	3.2a/3.3a	10.15/9.84	96.6/96.6
2071–2100	2.5a/2.7a	8.02/8.50	59.6/60.0
Geisenheim			
1971–2000	3.2b/2.8b	11.60/10.89	84.0/86.9
2011–2040	2.1b/2.2b	8.55/8.60	100.0/100.0
2041–2070	0.9a/0.9a	3.62/3.87	73.1/73.1
2071–2100	0.1a/0.1a	0.23/0.40	6.4/9.7

Different letters indicate significant differences of means, Kruskal–Wallis test, $\alpha \leq 0.01$

s standard deviation of all WETTREG realisations for M20/M30 and M20*/M30* date of endodormancy release (t_1) was 20 November (324 DOY) in Berlin-Dahlem and 25 November (329 DOY) in Geisenheim (Table 6). The slightly later date of t_1 in Geisenheim is the result of higher air temperatures at this location. At the end of this century (2071–2100), this date will be reached in Berlin-Dahlem on 10 December and in Geisenheim on 14 December. This means that for RCP 8.5, the chilling requirement of 'Summit' will be fulfilled on average until the end of the year. Even the absolutely latest date for t_1 was 361 DOY in the time-slice (2071–2100) in Geisenheim. For this reason, M20, which starts the accumulation of PTU at a constant date (34 DOY), showed very similar results compared to M30. This shows that pure F models can also be used to calculate the timing of phenological events for distinctly warmer climate conditions if endodormancy release always happens before the accumulation of forcing temperatures in the F model starts.

In this study, we assumed that 'Burlat', which has been grown for the last 17 years in Geisenheim, has nearly the same chilling requirement as 'Summit' because we were not able to carry out any physiological experiments to calculate C* for 'Burlat'. Field studies, which determined the chilling and heat requirement for cherry cultivars in SE Spain (Alburquerque et al. 2008), showed that early blossoming varieties require less chilling than late blooming cultivars (range 30.4–57.6 CP). For 'Burlat', they found a chilling requirement of 48 CP, which is very close to C* of 'Summit'. At both sites, C*('Burlat') = 48 CP were fulfilled only 13 days later than C*('Summit') = 39 CP, so that endodormancy was always broken before M20 started to accumulate PTU. Statistical investigations by Luedeling et al. (2013a, b) pointed to much higher C* values for a medium-late blossoming cherry cultivar (*Schneiders späte Knorpelkirsche*) in Klein-Altendorf, Germany. For this cultivar, they calculated a chilling requirement of 68.6 ± 5.7 CP (Luedeling et al. 2013a) and even 104.2 ± 8.9 CP (Luedeling et al. 2013b). The authors claimed that the latter C* is closer to the truth. For cultivars with a very high chilling demand, pure forcing models, such as M20, cannot be used to calculate shifts in BF for warmer climate conditions. Investigations by Vitasse et al. (2011) and Chuine et al. (2016) showed that in this case distinct differences in the projections between pure F and C/F models can occur. F models showed a stronger trend in leaf flushing or beginning of blossom than CF models because the latter can only start forcing accumulation if endodormancy is broken in the model.

Our results showed that to the end of this century, the beginning of cherry blossom can advance by nearly 17 days at both sites. This phenological shift is mainly related to rising air temperatures between February and April in Berlin-Dahlem and Geisenheim of $T(24)$ = 2.7 °C and $T(24)$ = 2.6 °C, respectively (Table 5). In the past (1951–2015), $T(24)$ rose in Berlin-Dahlem by 2.4 °C and in Geisenheim by 1.7 °C and caused an advancement in BF by − 12 and − 15 days, respectively (Table 1). The stronger trend in BF of 6.5 days/°C in Geisenheim, compared to Berlin-Dahlem (4.8 days/°C), was mainly related to the cultivation of earlier blossoming species since 1972. This indicates that cultivar adaptations must be considered if climate-related trends in phenological time series are investigated.

Climate change and late frost risk

Our investigations showed that in the future, the frequency of frost events and the resulting mean total frost damage did not significantly change in Berlin-Dahlem and gradually decreased in Geisenheim. From these results, we can conclude that the earlier BF does not necessarily have to lead to a higher frost risk. The reason is that the minimum temperatures which currently is observed in April [1971–2000—Berlin-Dahlem $T_n(4) = 4.4$ °C, Geisenheim $T_n(4) = 5.5$ °C, Table 5] in the future (2071–2100, RCP 8.5) will already be observed in March [Berlin-Dahlem $T_n(3)$ = 4.2 °C, Geisenheim $T_n(3)$ = 5.1 °C]. Thus, we can confirm the findings of Scheifinger et al. (2003), who found that the last date of spring frost occurred earlier, synchronously with plant development. Pulatov et al. (2015) also showed a reduced frost risk for some European potato growing areas, which are currently most prone to frost damage. We additionally found that the risk for very strong frost damages in individual years, which can strongly affect the cherry yield, stays unchanged until 2071 (Table 9). Only in the period 2071–2100 the maximum frost damages were clearly reduced, stronger at the milder site in Geisenheim than at the semi-continental site in Berlin-Dahlem. The frequency of high pressure systems, which causes radiative spring frosts, is generally higher in semi-continental climates. Additionally, cold air masses from east can lead to advective frosts, which are less frequent in milder regions (Wypych et al. 2016).

Uncertainties of this study

Next to phenological models, results of this study strongly depend on the regional climate projections. For this kind of study, mainly a realistic simulation of minimum temperature is necessary. Not only changes in mean minimum temperature are relevant but also in its seasonal variability. In this study, we have used the up-to-date statistical regionalisation model WETTREG. An advantage of WETTREG is that the data are available for stations and usually no bias correction for the model output is necessary because the downscaling procedure was adjusted with the historical observations from the weather stations. We only found a small bias, mainly between the observed and modelled frequency of light frost events (Table 3 vs. Tables 7 and 8).

Generally, for this kind of study, temperatures in a high spatial resolution are needed because data on a 10 × 10 km grid are too coarse to represent the variance of minimum temperatures at the local (station) scale. Investigation by Rigby and Porporato (2008) showed that frost risk to vegetation is sensitive to daily temperature variance. Preliminary investigations for this study on the basis of gridded data from the CORDEX-EUR-11 simulations with 12.5 km resolution (Jacob et al. 2013) showed that already for current climate conditions, the frequency of frost events was strongly reduced in these model outputs compared to the observations at both stations. Therefore, gridded data with much higher resolution are required from local climate models, which are currently still rare.

Frost damages are the result of very complex biological and environmental processes. In this study, we assumed that the cultivars 'Summit' and 'Burlat' have the same frost sensitivity during blossom. Salazar-Gutiérrez et al. (2014) found slightly varying thresholds for killing frosts among apple cultivars. However, Cittadini et al. (2006) found only very little differences in frost damage risk among six cherry cultivars, grown at six locations. Thus, they concluded that cultivar selection alone seems to be insufficient to avoid active frost control methods in risky locations.

In this study, we used daily minimum temperatures to calculate the frost damage. On windy days and in the case of advective spring frosts, minimum temperature is probably a useful parameter to calculate frost damages. However, in the case of radiation frosts on clear and calm nights, the temperature of buds and flowers can be lower than the air temperature, depending on the radiation balance of the crop stand, so that the damage would be higher than calculated in this study. Models which calculate the canopy temperature of a crop stand are relatively complicated and thus were not used in this study.

Additionally, the use of daily minimum temperature was a necessary simplification in this study. These temperatures do not allow considering the exact exposure time to low temperatures during a frost event, which is also decisive for the frost damage. For this reason, we assumed a standard exposure time of 1 h. For instance, in the night from 19 to 20 April 2017, negative temperatures for several hours, up to − 3.0 °C, caused severe frost damages in many parts of Germany. The frost damage in our experimental orchard in Berlin-Dahlem for 'Summit' was almost 75%, not observed in the last 12 years.

Conclusions

This study provided an example on how frost damages can be calculated for changed climate conditions during fruit tree blossom. From this study, we can derive the following results:

1. The occurrence of late frost showed a high temporal and regional variability for historical and future climate conditions.
2. The earlier timing of cherry blossom in the future did not lead necessarily to a higher frequency of frost events or to stronger frost damages during cherry blossom.
3. Strong frost events in individual years can occur nearly up to the end of this century.
4. Carefully validated phenological models (internal, external validation, validation for changed climate conditions and knowledge of endodormancy release) are the precondition for such studies.
5. Cultivar changes must be considered if climate related trends in phenological studies are calculated.

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