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Agroclimatic requirements and adaptation potential to global warming of Spanish cultivars of sweet cherry (*Prunus avium* L.)

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ABSTRACT

Traditional fruit tree cultivars are an important source of agricultural biodiversity. These genotypes are well adapted to the regions where they grow, and their fruits offer distinctive features compared to the commercial cultivars that are frequently grown. We analyzed the adaptation prospects of seven sweet cherry cultivars grown in Zaragoza (Spain) to future climate conditions. We first delineated chilling and forcing phases using Partial Least Squares (PLS) regression to correlate phenology records with daily accumulations of chill and heat during the months preceding flowering. We then calculated chill requirements using three chill models (Chilling Hours, Utah and Dynamic) and forcing requirements using one heat model (Growing Degree Hours, GDH). Results indicated that the chilling and forcing requirements ranged between 26.1 and 60.2 CP (chill portions) and from 5473 to 8030 GDH, respectively. We then assessed the cultivars' potential to adapt to a warmer future using climate projections and comparing the chill requirements with the expected chill accumulation under two global warming scenarios, RCP4.5 (effective reduction of greenhouse gas emissions) and RCP8.5 (very high greenhouse gas emissions), by two time horizons, 2050 and 2085, with temperature projections from fifteen Global Climate Models (GCM). These projections established that chill accumulation has consistently decreased over the last 30 years, but temperate trees have shown regular breaking of dormancy, bud burst and blooming. Future chill levels are expected to continue decreasing given the sustained warming trend, so there is no guarantee that sufficient winter chill will be observed in the medium to long term if the warming trend continues. For three out of the seven cultivars we analyzed, most global climate models predict medium or low risks by 2050 and 2085 under the RCP4.5 scenario. Under the RCP8.5 scenario, particularly by the end of the 21st century (i.e. 2085), four of the cultivars with high chill needs are expected to not to meet their chill requirements very often.

1. Introduction

Sweet cherry has experienced an important cultivar renewal in recent decades. New cultivars released from numerous breeding programs worldwide are replacing the cultivars that have traditionally been grown in sweet cherry growing regions (Quero-García et al., 2017). While these new cultivars frequently aim to offer improved farming and/or market-related traits to farmers, their intensified use may represent a threat to agricultural biodiversity (Quero-García et al., 2017). Cultivar collections and germplasm banks are possible strategies to ensure the conservation of traditional cultivars that may present interesting traits to adapt fruit production to future climatic conditions (Fowler and Hodgkin, 2004). Exploiting available genetic resources from cultivar collections can be a crucial contribution for sustaining fruit production under challenging environmental conditions.

Aragón, in northeastern Spain, is one of the main sweet cherry producing regions of the country. In 2021, the region produced about 30,000 tons of fruit, representing 41% of the total domestic production (MAPA, 2022). Accordingly, the Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA) preserves an important cultivar collection that includes several traditional Spanish cultivars (CITA, 2022a, 2022b). Among these, 'Ambrunés', 'Pico Colorado' and 'Pico Negro' are harvested stemless (denominated as "Picotas" in Spain) and marketed under the Protected Designation of Origin (PDO) 'Cereza del

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Jerte' (Cereza del Jerte, 2022). Fruits from these cultivars are small with dark flesh and slightly more acidic than fruits of other sweet cherry cultivars (Serradilla et al., 2012). 'Cristobalina' is a non-commercial cultivar with extra-early flowering and fruit ripening behavior. This spontaneous self-compatible mutant originated in Castellón, at the southeast coast of Spain (Wunsch and Hormaza, 2004). 'Blanca de Provenza' bears white fruits, which are often considered more suitable for the fruit processing industry. Fruits of this cultivar oxidize rapidly, producing an undesirable brown color that makes their commercialization for fresh consumption difficult. 'Taleguera brillante' presents high-quality fruits with a dark and bright appearance, a condition that is particularly appreciated in the markets of Aragón. Finally, 'Ramón Oliva' presents highly appreciated fruits (Gella et al., 2001). The specific characteristics of these cultivars make their fruit stand out in local and national markets. Several of these specific characteristics, e.g. flowering and harvest dates as well as fruiting traits, are continually recorded for research purposes for multiple genotypes preserved at CITA's cultivar collection (Herrero, 1964). Among these, flowering records may be of great utility to assess adaptation of sweet cherry cultivars to the impacts of climate change.

In sweet cherry and other deciduous species, the moment of flowering depends on temperatures that occurred during the previous autumn and winter (Kurokura et al., 2013). During these months, temperate fruit trees present a dormant state that is characterized by the absence of growth and by frost resistance (Rohde and Bhalerao, 2007). In a deep dormant state (i.e. endo-dormancy), buds and other structures protect the meristems, which are unable to resume growth even under suitable conditions. To recover their growth capacity and break endo-dormancy, meristems need exposure to cold conditions for a cultivar-specific period. Then, during the eco-dormancy phase, growth resumption can occur after exposure to warm temperatures (Lang et al., 1987). The delineation of endo-dormancy, in which trees respond to cold conditions (chilling), and eco-dormancy, in which trees respond to warm conditions (forcing), is one of the biggest challenges for dormancy researchers. Such delineation of phases is often achieved through experimental or statistical approaches (Fadón et al., 2020).

Experimental determination of the chilling and forcing phases usually consists of transferring shoots or young potted trees from field conditions (cold) to a growing chamber with warm conditions throughout winter and monitoring bud growth after a certain period in this environment (Brown and Kotob, 1957; Fadón and Rodrigo, 2018). In this method, the end of endo-dormancy and beginning of eco-dormancy is often determined as the transfer date that leads to a particular share of buds (often 50%) in a given developmental state (Fadón and Rodrigo, 2018). The statistical methodology requires long-term phenology records, which are correlated through Partial Least Squares (PLS) regression with the environmental conditions (e.g. daily temperatures) during the months preceding the developmental stage of interest. PLS regression analysis has emerged as a suitable statistical approach to delineate the most probable periods for chill and heat accumulation in temperate species (Luedeling et al., 2013; Luedeling and Gassner, 2012). The agroclimatic requirements are then estimated, using one or more temperature models (Fishman et al., 1987; Richardson et al., 1974; Weinberger, 1950), as the observed chill and heat during the delineated periods.

The adaptation of sweet cherry cultivars to future climate conditions depends on their phenology response to rising temperatures during the dormancy period. Insufficient winter chill can lead to severe problems during the flowering period, including abnormal flower development, heterogenous blooming, bud break failure and, ultimately, bud abortion (Erez, 2000). Given that chill accumulation can become a major limiting factor under warm growing conditions, comparing the chilling requirements of a certain cultivar with the expected chill availability of a fruit-producing region for medium and long-term horizons is a promising strategy to gain insights on its adaptive potential to the impacts of global warming (Luedeling, 2012). While estimating future chill levels may still be considered controversial, mainly due to considerable differences between currently available chill models (Fernandez et al., 2020b; Luedeling and Brown, 2011), forecasting future conditions has been greatly facilitated by increasingly reliable Global Climate Models (GCMs). GCMs are complex mathematical representations of major climate system components (e.g. atmosphere, land surface, ocean, sea ice) and their interactions (IPCC, 2014). When coupled with global warming scenarios (e.g. Representative Concentration Pathways – RCPs), GCMs enable researchers to forecast future climate conditions. GCM outputs are widely used in a number of fields, including water management, transportation, urban planning and agriculture, to assist relevant stakeholders in making adaptation decisions.

Here, we estimated the temperature requirements during dormancy of seven Spanish sweet cherry cultivars grown in Zaragoza, northeastern Spain and forecasted their expected performance under Zaragoza's future climate. To this end, we first delineated chilling and forcing phases using Partial Least Squares (PLS) regression to correlate between 14 and 24 years of phenology records (depending on the cultivar) with daily accumulations of chill and heat during the months preceding flowering. We then calculated chill requirements using three chill models (Chilling Hours, Utah and Dynamic) and forcing requirements using one heat model (Growing Degree Hours). To provide an assessment of the adaptation potential of these cultivars to a warmer future, we used climate projections. We compared the chill requirements with the expected chill accumulation (according to the Dynamic model) under two global warming scenarios (RCP4.5 and RCP8.5) by two time horizons (2050 and 2085) using temperature projections from fifteen GCMs.

2. Materials and methods

2.1. Plant material and phenology monitoring

We evaluated long-term flowering dates collected for seven Spanish sweet cherry cultivars ('Ambrunes', 'Blanca de Provenza', 'Cristobalina', 'Pico Colorado', 'Pico Negro', 'Ramón Oliva' and 'Taleguera Brillante') cultivated in a germplasm collection at the Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA; 41.72° N; 0.81° W; 220 m. a.s.l.) in Zaragoza, Spain.

Tree phenology in spring was monitored every two days for between 14 and 24 seasons, depending on the cultivar, between 1991 and 2022 (Table 1). Full bloom was recorded when the F stage of the Baggiolini phenology code (Baggiolini, 1952) was observed in most of the available trees per cultivar (three replicates). For comparison, the F stage of the Baggiolini scale corresponds to stage 65 of the BBCH phenology scale (Fadón et al., 2015; Meier, 2001).

2.2. Determination of chilling and forcing periods

Chilling and forcing periods were determined through Partial Least Squares (PLS) regression analysis (Luedeling et al., 2013; Luedeling and

Table 1
Availability of phenology records for seven sweet cherry cultivars grown in Zaragoza, Spain.

Cultivar	Nº of years	Years with records
Cristobalina	14	2009 – 2022
Ramón Oliva	24	1991 – 2001; 2009 – 2019; 2021 – 2022
Pico Negro	24	1991 – 2001; 2009 – 2019; 2021 – 2022
Ambrunés	24	1991 – 2001; 2009 – 2019; 2021 – 2022
Pico Colorado	24	1991 – 2001; 2009 – 2019; 2021 – 2022
Taleguera Brillante	24	1991 – 2001; 2009 – 2019; 2021 – 2022
Blanca de Provenza	23	1991 – 2001; 2009 – 2011; 2013–2019; 2021 – 2022

Gassner, 2012). PLS regression allowed us to relate sweet cherry bloom dates with the daily accumulation of chill (in Chill Portions – CP) and heat (in Growing Degree Hours – GDH) that occurred during the 8 months preceding bloom. To facilitate the interpretation of results, we implemented all analyses using an 11-day running mean function applied to both daily chill and heat accumulation, which. The 11-day running mean provides both high temporal resolution and clearly recognizable patterns, obtaining better results than when using mean daily temperatures or monthly mean temperatures (Luedeling and Gassner, 2012). PLS regression analysis produces two main outputs: the model coefficients, which indicate the strength and the direction of the influence, and the variable-importance-in-the-projection (VIP) scores, which highlight the importance of each independent variable in a PLS regression model (Luedeling et al., 2013; Luedeling and Gassner, 2012). To delineate the chilling and forcing periods, we examined the PLS regression outputs, looking for extended and consistent periods of negative model coefficients for chill and heat accumulation. In both cases, negative model coefficients during the delineated period would indicate that higher levels of chill and heat, respectively, are associated with earlier bloom dates. We later used both delineated periods to estimate the agroclimatic requirements of the seven cultivars assessed in this study.

2.3. Climate characterization and estimation of chill and heat requirements

Zaragoza features an Arid Cold steppe climate classified as BSk according to the Köppen scale (Köppen, 1900; Kottek et al., 2006). According to weather data recorded since 1973, the annual mean temperature at the experimental site is 15 °C, with July being the warmest month (average temperature of 24.5 °C) and January being the coldest period (average temperature of 6.3 °C).

Hourly temperatures, which are required for estimating agroclimatic metrics, were derived from daily temperature extremes obtained from a meteorological station located at the experimental site. We used functions from Almorox et al. (2005) and Linvill (1990) implemented in the chillR package for R (Luedeling and Fernandez, 2022) to estimate hourly temperatures based on an idealized daily temperature curve. This curve is described by a combination of two mathematical equations: a sine function for daytime warming and a logarithmic decay function for nighttime cooling (Linvill, 1990). The transition points between the two parts were determined by sunrise and sunset, and the duration of the parts was related to daylength (calculated with the equations developed by Spencer (1971) and Almorox et al., 2005 based on the latitude).

We computed chill accumulation for the chilling period that was delineated through PLS regression. To this end, we applied the Chilling Hours, Utah and Dynamic models, which are widely used in dormancy-related studies as well as in temperate orchard management. The Chilling Hours model defines a “Chilling Hour” (CH) as one hour with temperatures between 0 and 7.2 °C (Hutchins, 1932, as cited by Weinberger, 1950). The Utah model proposes the use of “Chill Units” (CU), which are computed using different chill effectiveness weights that are assigned to various temperature ranges. The Dynamic model defines the use of “Chill Portions” (CP), which accrue through a two-step process where a precursor of chill is formed under cool conditions and later converted to a permanent CP through a second process that shows optimum effectiveness at moderate temperatures (Fishman et al., 1987).

To estimate heat requirements of the evaluated cultivars, we quantified heat accumulation between the start of the forcing phase delineated through PLS regression and the flowering date. For this analysis, we used the Growing Degree Hours (GDH) model, which considers temperatures between 4 ºC and 25 ºC as contributing to active growth (Anderson et al., 1986).

The final chill and heat requirements for each cultivar were aggregated by computing the mean value across all years used in the PLS regression analysis. Additionally, we computed the standard deviation to provide an estimate of uncertainty around the mean.

2.4. Flowering response to chill and heat accumulation

To characterize the relationship between flowering dates and the accumulation of chill and heat, we plotted bloom dates against mean temperature during both the chilling and forcing periods. We used the Kriging method to interpolate a continuous surface of flowering dates, which represented the timing of flowering as a function of mean temperature during the chilling and forcing periods (Guo et al., 2015a; Martínez-Lüscher et al., 2017; Oliver and Webster, 1990). We then visualized the assessed relationship through a surface contour plot.

2.5. Historic and future weather scenarios

To provide an assessment of the likely performance of dormant sweet cherry cultivars in Zaragoza under various scenarios, we evaluated observations recorded in-situ as well as synthetic temperature data generated for historic and future periods. We first analyzed the observed trend in chill accumulation between 1973 and 2022 using records collected by the meteorological station placed at the experimental site.

To better identify long-term trends that can result from global warming and to reduce the effect of year-to-year variation, we generated historic weather scenarios that characterize typical agroclimatic conditions that may have occurred in Zaragoza given the conditions of a particular year. We followed the methods described by Fernandez et al. (2020a) with minor modifications. In brief, we produced representative temperature scenarios for the years 1980, 1990, 2000, 2010, and 2020 using temperature data recorded on site. For each of these years, we determined typical mean daily minimum and maximum temperatures for each month by applying a 15-year running mean function across all recorded monthly extreme temperatures for the respective month for all years on record. By using functions in the chillR package (Luedeling, 2021), we then applied these five typical temperature scenarios to the RMAWGEN weather generator (Cordano and Eccel, 2014) to produce 100 replicates of plausible winter seasons for each scenario year.

We used the procedure described above to predict future agroclimatic conditions in Zaragoza. As input for the weather generator in this case, we used monthly means of daily temperature extremes obtained from the ClimateWizard database (Girvetz et al., 2009), which is maintained by the International Center for Tropical Agriculture (CIAT). ClimateWizard offers temperature projections by 15 Global Climate Models (GCMs; Table 2) for two Representative Concentration Pathway scenarios (RCP4.5 and RCP8.5) and for a number of time horizons. RCP4.5 and RCP8.5 represent total radiative forcing of 4.5 W m^{-2} and 8.5 W m^{-2} caused by atmospheric greenhouse gases by 2100 (IPCC, 2014). While the RCP4.5 scenario illustrates a situation in which authorities institute some policies that are effective to reduce emissions, RCP8.5 is a scenario with very high greenhouse gas emissions (IPCC, 2014). For both RCPs, we obtained future temperature scenarios for the middle (represented by mean conditions between 2035 and 2065) and for the end of the 21st century (mean conditions between 2070 and 2100). These two time horizons were represented by their central years 2050 and 2085, respectively. We used 60 future scenarios (each representing one combination of GCM, RCP and time horizon) to feed the weather generator and produce 100 replicates of plausible winter seasons given the expected environmental conditions.

2.6. Estimation of chill availability for observed and simulated scenarios

We estimated chill availability (in CP according to the Dynamic model) for a species-aggregated period (the earliest start date and the latest end date) that represented the most likely occurrence of the chilling phase delineated through PLS regression (between October 26th and January 27th every winter season). In addition, we computed chill

Table 2
Global Climate Models used for future temperature projections in Zaragoza, Spain.

Organization	Model version	Abbreviation	Reference and/or link
Beijing Climate Center	Climate System Model 1.1	bcc-csm1–1	http://forecast.bcccsm.ncc-cma.net/ web/channel-43.htm Wu (2012)
Beijing Normal University	Earth System Model	BNU-ESM	Ji et al. (2014)
Canadian Centre for Climate Modelling and Analysis	Canadian Earth System Model – Version 2	CanESM2	Chylek et al. (2011)
Community Earth System Model	Version 1 – BioGeoChemical model enabled	CESM1-BGC	Lindsay et al. (2014)
Model for Interdisciplinary Research On Climate	Earth System Model	MIROC-ESM	Watanabe et al. (2011)
Centre National de Recherches Météorologiques	Climate Model 5	CNRM-CM5	www.umr-cnrm.fr/spip.php?article126%26lang=en
Australian Community Climate and Earth	System Simulator 1.0	ACCESS1–0	Bi et al. (2013)
Commonwealth Scientific and Industrial Research Organisation	Mark3.6.0	CSIRO-Mk3–6–0	Rotstayn et al. (2009)
Geophysical Fluid Dynamics Laboratory	Earth Model 3	GFDL-CM3	Donner et al. (2011)
	Earth System Model 2 G	GFDL-ESM2G	Delworth et al. (2006) https://www.gfdl.noaa.gov/earth-system-model/
	Earth System Model 2 M	GFDL-ESM2M	
Institute of Numerical Mathematics	Climate Model version 4	Inmcm4	Volodin et al. (2010)
Institute Pierre – Simon Laplace	Climate Model 5 A Low Resolution	IPSL-CM5A-LR	https://cmc.ipsl.fr/ipsl-climate-models/ipsl-cm5/
	Climate Model 5A Mid Resolution	IPSL-CM5A-MR	
Community Climate System	Model 4	CCSM4	

availability for cultivar-specific periods to provide a more detailed analysis (see these results in the supplementary materials). We note that by adopting a fixed chilling period throughout the years we were unable to account for probable shifts in the occurrence of the chilling phase due to global warming or fluctuations caused by natural interseasonal variation.

Since the Dynamic model requires hourly temperature as input, we derived these observations from daily minimum and maximum temperature data that were obtained from the temperature generation procedure. To this end, we used the approach described in section *"Climate characterization and estimation of chill and heat requirements"*.

2.7. Assessing the probable impacts of climate change on chill requirement fulfillment

To provide an estimate of future chill-related risks and assess the possible impacts of climate change on the cultivation of sweet cherry in Zaragoza, we calculated the probability of meeting the chill requirement of the seven cultivars. We followed the methods described by Delgado et al. (2021a), with minor modifications. We account for uncertainty around the estimation of CR, which we represent by the standard deviation across the years used in the PLS regression. To this end, we randomly sampled 1000 values within the range *"mean CR ± sd"* that are likely to represent the chill requirement as estimated through PLS regression. We then computed the probability of CR fulfillment as the share of seasons (out of 100) for which the estimated chill availability exceeds each of the sampled chill requirements. We summarized the results of this analysis by computing the median probability of CR fulfillment across 1000 values.

2.8. Data preparation and implementation of analyses

All analyses, including the PLS regressions, temperature generation and computation of dormancy-related metrics were conducted using the chillR v.0.72.4 package (Luedeling, 2021) in the R v.4.1.0 programming environment (R Core Team, 2021). The assessment of the probability of CR fulfillment under future scenarios was implemented using functions of the decisionSupport v.1.111 package (Luedeling et al., 2022).

3. Results

3.1. Flowering dates of Spanish sweet cherry cultivars in Zaragoza

Flowering dates ranged between early-March and early-April for the seven Spanish sweet cherry cultivars we analyzed (Fig. 1). While 'Cristobalina' presented an extra-early flowering behavior with an average flowering date on March 10th, the remaining cultivars analyzed in our study displayed an average bloom date about 15 – 22 days later than 'Cristobalina'.

3.2. Chilling and forcing periods in Spanish sweet cherry cultivars

Chilling and forcing periods were delineated through PLS regression analysis with daily chill (in CP) and daily heat (in GDH) as independent variables and bloom dates as the response variable (Fig. 2). Chilling periods ranged from 36 to 89 days for the cultivars 'Cristobalina' and 'Blanca de Provenza', respectively. Start dates occurred between October 26th and November 16th and end dates between December 21st and January 27th. During these periods, results showed several days that clearly contribute to the accumulation of chill, with negative and significant ($VIP > 0.8$) model coefficients (Fig. 2). However, we also identified a few days with model coefficients that were classified as less relevant (lower VIP score). Since the majority of days during the delineated periods appeared to be consistently correlated with earlier bloom dates, probably indicating a clear dormant state, chilling periods were considered to be continuous (horizontal blue rectangles in Fig. 2).

When evaluating heat accumulation on a daily basis, PLS regression results offered a consistent period of important negative model coefficients that started between January 5th and February 2nd and ended around bloom in most cases (horizontal red rectangles in Fig. 2). The length of forcing periods varied little among cultivars, lasting between 41 days in 'Blanca de Provenza' and 65 days in 'Cristobalina'. The forcing period did not directly follow the chilling period, but was preceded by a transition phase during which no significant coefficients were identified using either daily accumulations of winter chill or spring heat. Neither chill nor heat was quantified during this transition period.

3.3. Agroclimatic requirements based on long-term flowering records

We estimated the agroclimatic requirements of sweet cherry cultivars based on the chilling and forcing periods identified through PLS regression. We used three chill models (Dynamic, Chilling Hours, and Utah) and one heat model (Growing Degree Hours model) for this estimation. Whereas 'Cristobalina' presented the lowest chill requirement, the cultivar 'Blanca de Provenza' presented the highest chill need. Chill requirements ranged between 26.1 ± 1.4 CP and 60.2 ± 3.1 CP when

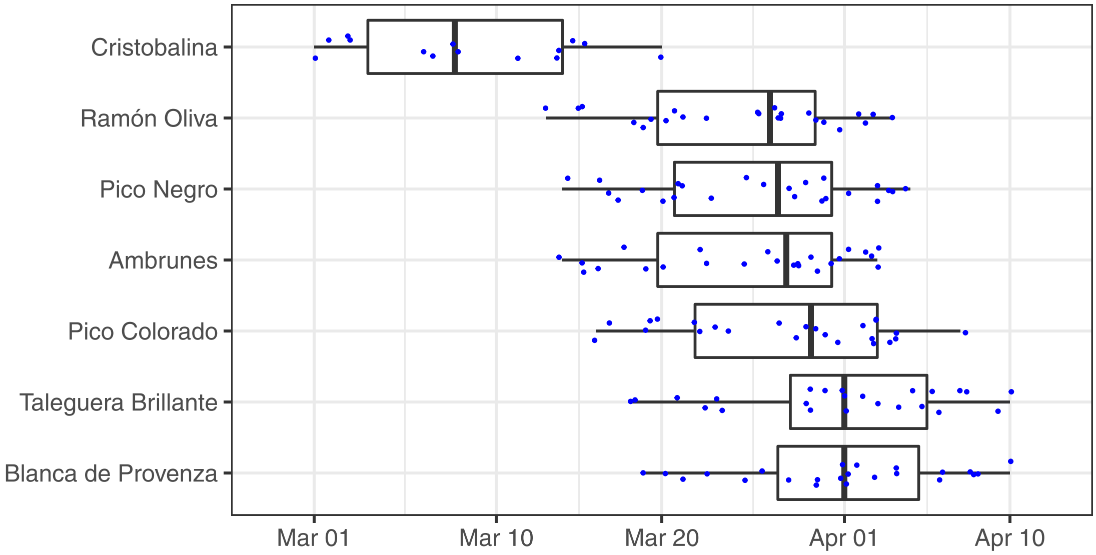

Fig. 1. Flowering dates of seven Spanish sweet cherry cultivars grown in Zaragoza (northeastern Spain) during the period 1991 – 2022. Blue dots and boxplots represent between 14 and 24 observations, depending on the cultivar. In the boxplots, the vertical line in the middle of each boxplot indicates the median, whereas the hinges correspond to the interquartile range (IQR, percentiles 25th to 75th). The whiskers on each side of the boxes represent the greatest value that is located within 1.5 times the IQR.

calculated with the Dynamic model, from 570 ± 68 CU to 1250 ± 87 CU when calculated with the Utah model, and from 395 ± 107 CH to 910 ± 108 CH when the Chilling Hours model was used. Heat requirements ranged between 5594 ± 467 GDH for 'Cristobalina' and 8142 ± 773 GDH for 'Taleguera Brillante'.

3.4. *Flowering response to temperature during the chilling and forcing periods*

We analyzed the bloom response to temperature conditions during the chilling and forcing periods. For this assessment, we defined flowering as a function of mean temperature during both the chilling and forcing periods (Fig. 3). When excluding the results obtained for 'Cristobalina' and 'Blanca de Provenza', the response surface showed contour lines with a slight positive slope, suggesting that flowering is triggered by both the chilling and forcing phase (Fig. 3). The results obtained for the cultivars 'Cristobalina' and 'Blanca de Provenza' may be of particular interest (Fig. 3). The extra-early flowering cultivar 'Cristobalina' showed horizontal contour lines, indicating that flowering dates are mainly determined by the forcing period (Fig. 3). In the case of the late flowering cultivar 'Blanca de Provenza' many of the lines seem much steeper, suggesting that temperature during the chilling phase has a strong influence on the occurrence of flowering (Fig. 3).

3.5. *Historic and future winter chill*

Chill accumulation decreased considerably during the period that we delineated as the cultivar-aggregated chilling phase (from the earliest start date to the latest end date and regardless of the cultivar; Fig. 4). Based on the simulated historic scenarios, chill accumulation ranged between 81.3 and 89.6 CP (25th - 75th interval) for the reference year 1980, whereas only between 69.0 and 76.9 CP were estimated for the reference year 2020. This reduction implied that chill accumulation in some years may have been barely sufficient for meeting the chill requirement of some cultivars with high chilling needs (Fig. 4). Our projections indicate that insufficient winter chill may become a frequent scenario for the middle and the end of the 21st century.

Considering the less dramatic RCP4.5 scenario, only four climate models (BNU-ESM, CanESM2, CESM1-BGC and GFDL-ESM2G) predicted a situation in which chill accumulation exceeds chill requirements by 2050 and 2085. In case humanity fails to implement significant measures to reduce GHG emissions (RCP8.5 scenario), most models suggested a risky situation for the fulfillment of chill requirements in high-chill cultivars. This is particularly relevant by 2085, a time horizon for which most models predicted median chill levels below 65 CP.

For more accurate predictions on the adaptation of each cultivar to future climatic conditions, we calculated the future chill accumulation for the specific chill period delineated with PLS regression analysis (supplementary Fig. 2 - 6). In this case, all the cultivars appeared threatened by the reduction of chilling during each specific period even in the less dramatic RCP4.5 scenario. The main difference between both predictions is that in the first case, we considered a longer period for chill accumulation, thus we assumed that low temperatures outside the cultivar-specific chill period also contribute to dormancy release. Against our initial hypothesis, the aggregated chilling phase proved more suitable to delineate the differential effect of global warming on the cultivars.

3.6. *CR fulfillment in past and future climates*

We determined the frequency of CR fulfillment (considering the aggregated chill period) between 1973 and 2022 as well as the likelihood of meeting this requirement in the future using the estimates of the cultivar-specific CR (measured in Chill Portions and summarized in Table 2). Our results suggest that most of the cultivars fulfilled their chill requirements between 1973 and 2022 (Fig. 5). Whereas the cultivars 'Taleguera Brillante' and 'Blanca de Provenza' presented an observed probability of fulfilling its CR of 70% and 60% respectively, we observed a similar situation when the historic simulated scenarios were evaluated (Fig. 5). (Table 3).

By 2050 and 2085 under the RCP4.5 scenario, most global climate models predicted a relatively low-risk profile (80–100%) for cultivars 'Cristobalina', 'Pico colorado', and 'Ramón Oliva'; a medium risk profile (40–90%) for cultivars 'Pico Negro' and 'Ambrunés'; and a high risk of CR unfulfillment (10–40%) for cultivars 'Taleguera Brillante' and 'Blanca de Provenza' (Fig. 5).

Under the RCP8.5 scenario, particularly by the end of the 21st century (i.e. 2085), four of the seven cultivars analyzed in this study are expected to frequently fail to fulfill their chilling requirements (Fig. 5). For these cultivars, most GCMs forecast a small chance of CR fulfillment

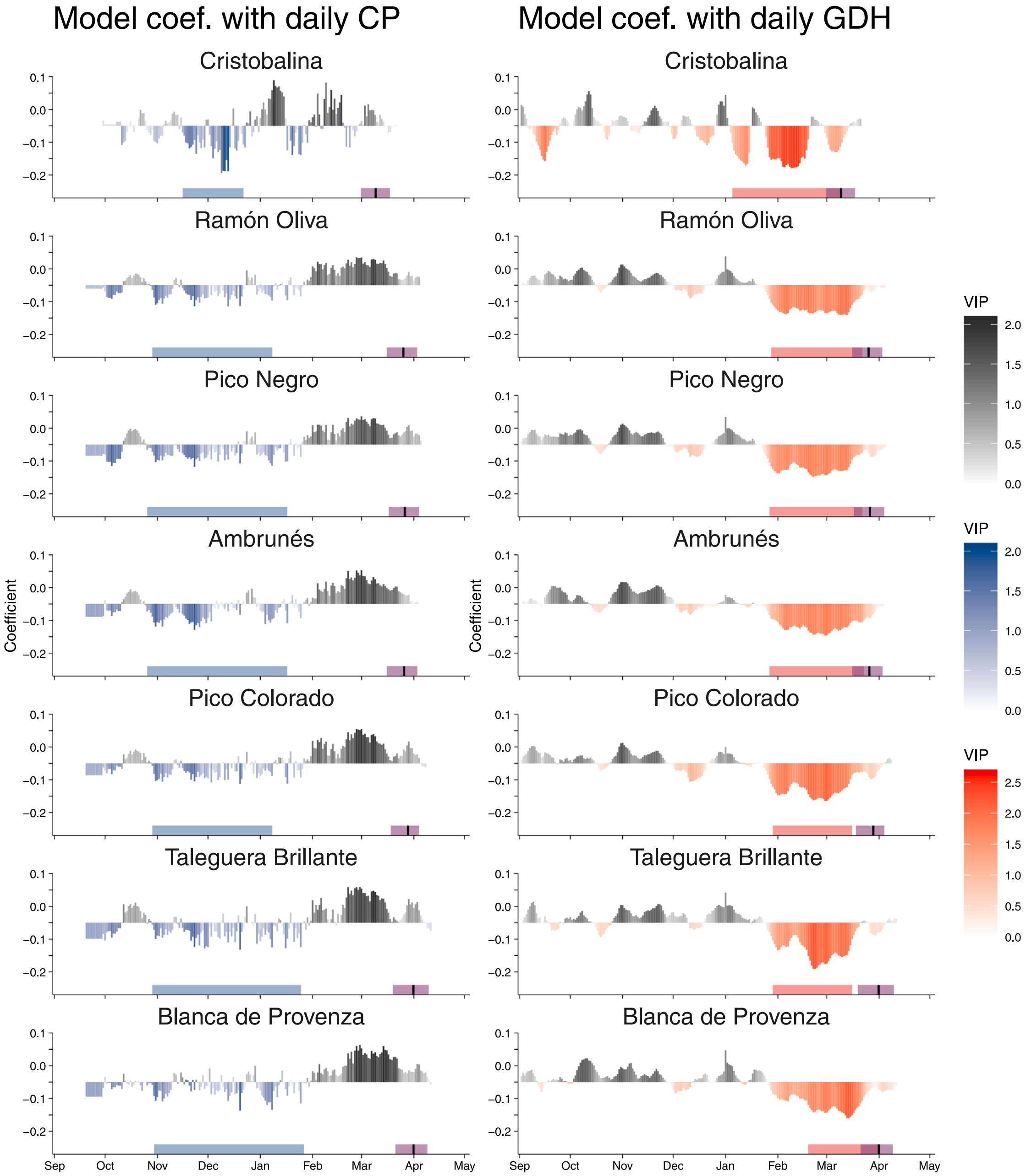

Fig. 2. Partial Least Squares regression analysis between flowering dates of seven Spanish sweet cherry cultivars grown in Zaragoza (northeastern Spain) and daily accumulations of winter chill (in CP according to the Dynamic model in the left panel) and spring heat (in GDH according to the Growing Degree Hours model in the right panel). Whereas the direction of vertical bars in each plot indicates days with positive or negative model coefficients, the color of the bars represents the Variable Importance in the Projection (VIP) score (with blue and red for negative coefficients for chill and heat, respectively, and gray for positive coefficients in both panels). Horizontal thick bars at the bottom of each plot indicate the delineated chilling (blue) and forcing periods (red) and the range of observed flowering dates (purple). The vertical dark purple line in bars that show the flowering range indicates the median bloom date across all years with records.

(the majority of the GCMs showing values > 30%). Although there is large variation among GCM estimates, other two cultivars, ‘Pico Colorado’ and ‘Ramón Oliva’, may also face a challenging situation regarding CR fulfillment under this combination of global warming scenario and time horizon. ‘Cristobalina’ is the only cultivar expected to fulfill its CR in all cases.

4. Discussion

4.1. Agroclimatic requirements of Spanish sweet cherry cultivars

Depending on the cultivar, chilling and forcing requirements in our study ranged between 26.1 and 60.2 CP and from 5473 to 8030 GDH, respectively. According to our knowledge, we produced the first estimates for the cultivars ‘Blanca de Provenza’ and ‘Pico Negro’. For the remaining five cultivars, chilling requirements had been previously calculated through the experimental approach (Tabuenca, 1983). When compared to the former assessment, our estimations for these five cultivars resulted in lower chill requirements. Whereas we estimated CRs of 788 ± 107 CH, 672 ± 106 CH and 910 ± 108 CH for ‘Ambrunés’, ‘Pico Colorado’ and ‘Taleguera Brillante’, respectively, Tabuenca (1983) grouped these cultivars in the range 1000 – 1100 CH. For ‘Ramón Oliva’ and ‘Cristobalina’, we determined 672 ± 106 CH and 395 ± 107 CH, respectively, while the earlier study reported between 900 and 1000 CH

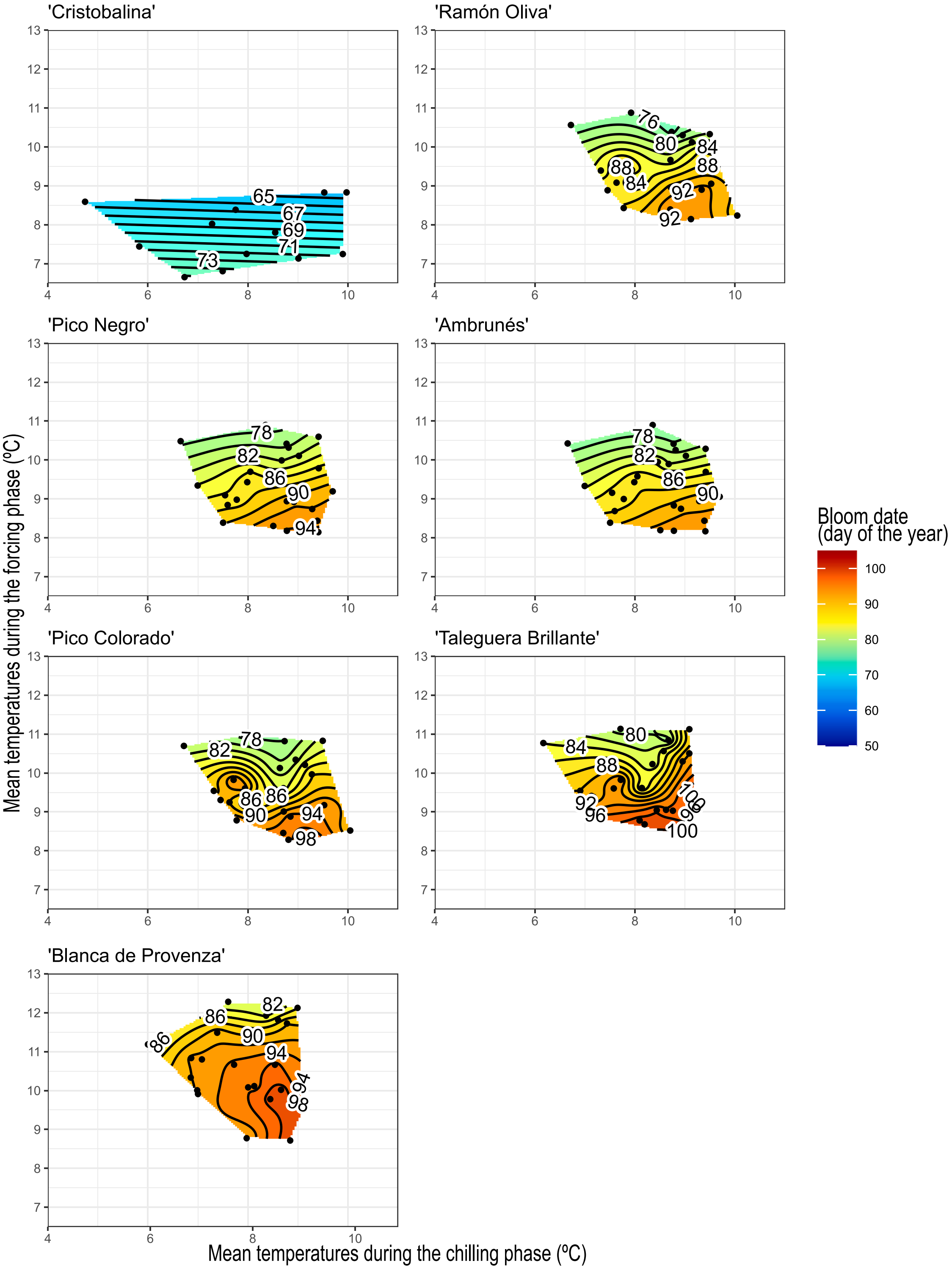

Fig. 3. Flowering dates as a function of mean temperature during the chilling and forcing periods as determined through PLS regression analysis. We show results for seven Spanish sweet cherry cultivars grown in Zaragoza (northeastern Spain). The color surface and contour lines represent predicted flowering dates based on actual observations (black dots).

for ‘Ramón Oliva’ and < 800 CH for ‘Cristobalina’ (Tabuenca, 1983). Due to its extraordinarily early flowering behavior, ‘Cristobalina’ is of special interest for phenology studies (Calle et al., 2020). Chill requirements in this cultivar have therefore been assessed in several other studies (Alburquerque et al., 2008; Campoy et al., 2019; Fadón et al., 2018). Our results from the statistical approach (395 ± 107 CU or 26.1 ± 1.4 CP) are similar to those reported in experimental work conducted in Murcia, a relatively warm region of Spain (397 CU or 30.4 CP) (Alburquerque et al., 2008). On the other hand, our results are much lower than the values reported in a recent experimental study (687 ± 83 CU) conducted at the same location (Fadón et al., 2018). When using the Dynamic model to estimate chill needs, we determined a CR about 38% lower (26.1 versus 42 CP) than the results obtained in Bordeaux, France by Campoy et al. (2019). Inconsistencies in CR estimations between

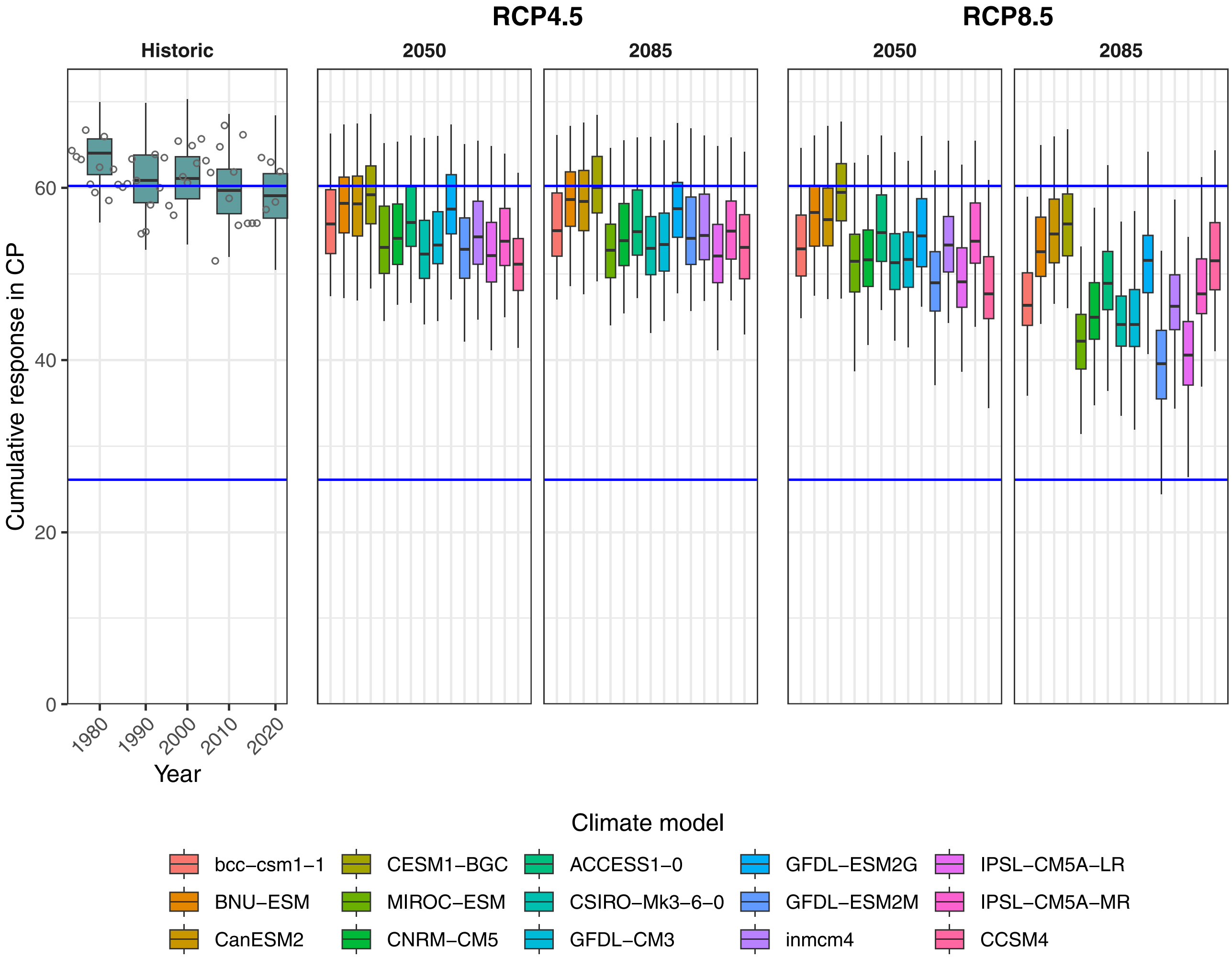

Fig. 4. Historic and projected future winter chill during the estimated period for chill accumulation (October 26th - January 27th) aggregated across 7 Spanish sweet cherry cultivars from Zaragoza, Spain. Whereas actual chill accumulation between 1973 and 2021 is shown by empty dots in the “Historic” panel, chill accumulation according to historic simulated weather scenarios is presented in boxplots for the reference years 1980, 1990, 2000, 2010, and 2020. The remaining four panels on the right show chill accumulation under future scenarios defined by two Representative Concentration Pathways (RCP4.5 or RCP8.5) by two-time horizons (2050 and 2085). In each of these panels, boxplots illustrate the plausible chill distributions produced by a weather generator according to temperature projections by 15 climate models. Blue lines indicate the CR of ‘Cristobalina’ and ‘Blanca de Provenza’, the cultivars with the lowest and highest CR, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

studies that analyze the same cultivar have been widely reported in the past (Fadón et al., 2020; Luedeling, 2012). The use of different methodologies (experimental versus statistical), the determination of CRs in regions with very different climatic conditions, and the use of temperature models that respond differently to the particular climates appear to be the most plausible causes of reported inconsistencies. These inconsistencies limit the potential of farmers to adapt temperate fruit orchards to future challenges since the information obtained elsewhere is difficult to transfer and apply.

4.2. PLS analysis for phenology prediction

For accurate interpretation of results, we must consider the pros and cons of delineating chilling and forcing phases through PLS regression. PLS regression analysis is, at present, among the most promising statistical methods to determine the chilling and forcing periods in temperate fruit tree species. PLS regression analysis has been widely applied to datasets of several temperate fruit species that are cultivated in temperate as well as Mediterranean climate regions (Benmoussa et al., 2017b, 2017a; Delgado et al., 2021b; Díez-Palet et al., 2019; Fadón et al., 2021; Guo et al., 2015b; Martínez-Lüscher et al., 2017). Where phenology and weather records are not a constraint, PLS regression is easy to apply through the R programing environment. The ‘chillR’ package was designed for conducting phenology analyses in temperate fruit trees (Luedeling and Fernandez, 2022). Throughout the years, ‘chillR’ has been frequently updated with the newest advances in the field (Luedeling and Fernandez, 2022). These and other advantages make PLS regression analysis a convenient method to estimate agroclimatic requirements in temperate species.

PLS regression analysis, on the other hand, also presents some disadvantages that can prevent its use and dissemination. Although some evidence suggests that interseasonal variation is more important than the final number of seasons (Fernandez et al., 2021), one of the biggest limitations of PLS regression is the need for long-term phenology and weather records (Luedeling and Gassner, 2012 suggested >20 years). This requirement makes it impossible to apply PLS regression analysis to new cultivar releases, unless experimental data is generated through relatively expensive trials (Fernandez et al., 2021). In addition, phenology and weather records are scarce in many countries, even for cultivars that are traditionally grown in these regions. Once the data need is surpassed, the method challenges the judgment of researchers to produce coherent results. Such a challenging situation originates from

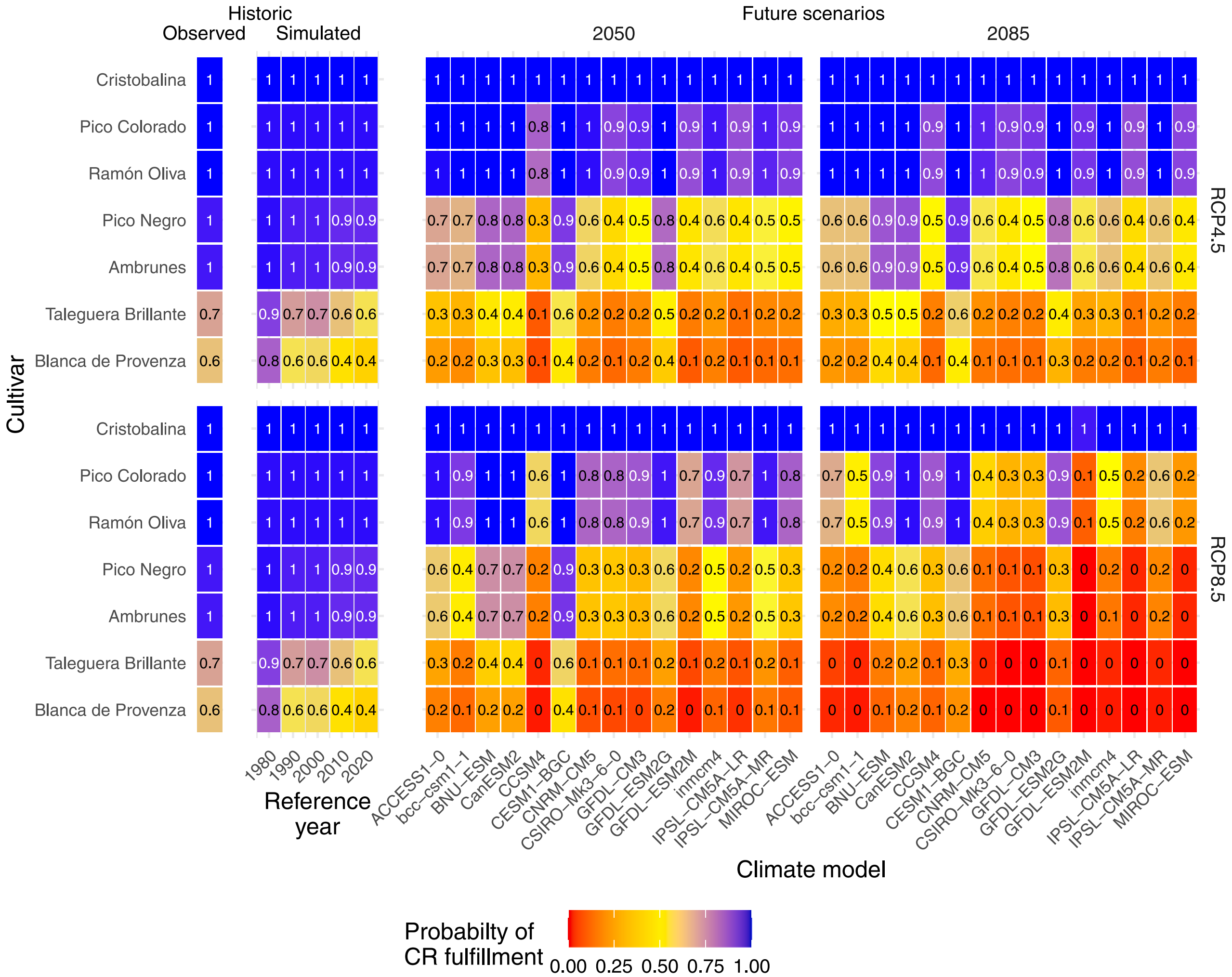

Fig. 5. Probability of satisfying the estimated cultivar-specific chill requirements (calculated as Chill Portions, see Table 2) of 7 Spanish cultivars of sweet cherry in Zaragoza (northeastern Spain) for two RCP scenarios (RCP4.5 and RCP8.5), three time horizons (historic, 2050 and 2085) and 15 global climate models.

Table 3

Average chilling and forcing periods for between 14 and 24 years in the interval 1991 – 2022 and agroclimatic requirements (mean ± standard deviation) estimated for 7 Spanish cultivars of sweet cherry grown in Zaragoza (northeastern Spain). We computed chill requirements according to the Dynamic (in CP), Chilling Hours (in CH) and Utah (in CU) models. The Growing Degree Hours model (in GDH) was used to estimate heat requirements.

Cultivar	Chilling					Forcing	
	Period		Accumulation			Period	Accumulation
	Start	End	CP *mean* ± *sd*	CU *mean* ± *sd*	CH *mean* ± *sd*	Start	GDH *mean* ± *sd*
Cristobalina	16 Nov	21 Dec	26.1 ± 1.4	570 ± 68	395 ± 107	05 Jan	5473 ± 461
Ramón Oliva	29 Oct	08 Jan	46.5 ± 3.1	949 ± 100	672 ± 106	28 Jan	6872 ± 543
Pico Negro	26 Oct	17 Jan	53.6 ± 3.5	1086 ± 112	788 ± 107	27 Jan	7140 ± 629
Ambrunes	26 Oct	17 Jan	53.6 ± 3.5	1086 ± 112	788 ± 107	27 Jan	7004 ± 570
Pico Colorado	29 Oct	08 Jan	46.5 ± 3.1	949 ± 100	672 ± 106	29 Jan	7365 ± 588
Taleguera Brillante	29 Oct	25 Jan	58.8 ± 3.4	1211 ± 100	881 ± 112	29 Jan	8030 ± 796
Blanca de Provenza	30 Oct	27 Jan	60.2 ± 3.1	1250 ± 87	910 ± 108	19 Feb	6457 ± 774

the outputs of PLS regression analysis, which usually leave room for interpretation. Researchers need to interpret PLS regression outputs considering the biological understanding of dormancy. In the present study, for example, PLS analysis showed consistent periods of chill influence in October and November, but low and unimportant coefficients in December and January. Since our biological understanding suggests that these months greatly contribute to dormancy release, we could not ignore their importance despite them showing less apparent results. This can make the delineation of the end of the chilling period difficult. Similar situations were also reported in other temperate climate regions where PLS regression has been applied (Delgado et al., 2021b; Díez-Palet et al., 2019; Fadón et al., 2021; Guo et al., 2014; Luedeling et al., 2013; Martínez-Lüscher et al., 2017). When used for phenology assessments, PLS regression analysis may become unable to detect a clear signal during periods with constantly cold temperatures despite using more than 20 years of data. In some cases, long-term datasets do not guarantee adequate interannual variation for the analysis to detect a clear signal for the conditions that promote bloom. To obtain meaningful results, phenology and dormancy researchers must be aware of the limitations of this approach.

Interaction between the chilling and forcing periods, which has been proposed in the past by various authors (Darbyshire et al., 2020, 2016; Harrington et al., 2010; Kaufmann and Blanke, 2019; Luedeling et al., 2021), can be difficult to infer through PLS regression analysis. In our study, the delineation of chilling and forcing periods with PLS analysis generated a period with an unclear signal. This period was located between the chilling and forcing phases and occurred approximately from the end of January to the beginning of February. According to the proposed interaction between chilling and forcing, cold temperatures during this transition period may still contribute to the accumulation of chill. To some extent, significant heat in this phase may even compensate for the need for chill. However, the nature of this interaction remains mostly unclear. Further research can help dormancy scientists decipher the validity and extent of the proposed heat-for-chill-compensation effect. If confirmed, the chill-heat interaction may introduce new insights on climate change adaptation strategies.

4.3. Adaptation of Spanish cultivars to future climatic conditions in a particular region

Chill accumulation has consistently decreased over the past 30 years and future chill levels are expected to continue decreasing given the sustained warming trend. Significant winter chill losses are predicted under future scenarios at global (Luedeling, 2012; Luedeling et al., 2011; Luedeling and Brown, 2011) and regional scales (del Barrio et al., 2021; Buerkert et al., 2020; Luedeling et al., 2009; Rodríguez et al., 2019). Despite the historic reduction in chill accumulation in the study region, temperate trees from Zaragoza have shown regular breaking of dormancy, bud burst and blooming. This observation may indicate that winter temperatures have been adequate to fulfill the chill requirements of these cultivars. There is no guarantee, however, that sufficient winter chill will be observed in the medium to long term in this and climatically similar regions if the warming trend continues.

Projection of cultivarcultivar performance under future conditions resulted in apparent contradictory predictions between consideration of cultivar-aggregated chilling phase or the cultivar-specific chill period. We considered that the cultivar-aggregated chilling better predicted the differential effect of global warming on the cultivars. However, using this period does not provide much information on whether low temperatures outside the cultivar-specific chill period also contribute to dormancy release. Further experiments will be required to answer this question. It is worth noting that use of the experimental method to determine chilling periods results in variable periods from year to year for a particular cultivar depending on winter temperatures (Fadón et al., 2020; Herrera et al., 2022).

Most of the projections of future chill availability may suggest insufficient chill levels, being critical the situation for four of the seven cultivars analyzed by the end of the century under the RCP8.5. However, temperate species may display, to some extent, a certain plasticity in completing their normal cycle and adapt to the shift as global warming progresses (Fu et al., 2015; Guo et al., 2015a). In a previous study, we proposed a four-step scale that relates the phenological response of trees to the effects of global warming on orchard viability (Fadón et al., 2021). According to this classification, the response of the early flowering cultivar ‘Cristobalina’ under future scenarios can fit in stage (i). Stage (i) represents a clear advance in spring phenology, probably due to the relative importance of the forcing phase in determining spring phenology events. As global warming progresses, there is more accumulation of heat that can accelerate eco-dormancy release. The response of intermediate-flowering cultivars, including ‘Ramón Oliva’, and ‘Pico Colorado’, may fit into stage (ii), which suggests that no phenological changes occur during the study period, because phenology advances in response to more heat during forcing and phenology delays in response to warming during the chilling phase can cancel each other out (Fadón et al., 2021; Guo et al., 2015a). Finally, ‘Blanca de Provenza’ (with the highest chill requirement), may be expected to fall in stage (iii) under future scenarios, which suggests that greater warming might generate flowering delays that are caused by conditions that are challenging for dormancy release. This classification is in agreement with the observed response of commercial cultivars to climate change (Fadón et al., 2021). We suggest that there may still be room for adaptation to the progressive advance of rising temperatures. Orchards that are currently impacted by global warming have already shown significant delays in the date of flowering as well as severe consequences for fruit production in pistachios and local almond cultivars in Tunisia in unusually warm-winter years (Benmoussa et al., 2017b, 2017a). In these cases, further temperature increments can be expected to prevent dormancy release altogether and seriously compromise the trees’ annual cycle. Temperate fruit growers from locations that are severely affected by the impacts of climate change require, ideally, a portfolio with numerous alternatives to adapt their orchards to future conditions and convert these systems to resilient industries.

5. Conclusions

We determined the agro-climatic requirements and the adaptability to future climatic conditions of seven Spanish sweet cherry cultivars maintained at the germplasm collection of CITA in Zaragoza, Spain. The majority of the cultivars showed chill requirements that range between 46 and 60 CP, suggesting that their suitability may be restricted to regions with medium- and high-chill profiles. According to our improved chill-related risk profile assessment, cultivars such as ‘Pico Negro’, ‘Ambrunés’, ‘Taleguera Brillante’, and ‘Blanca de Provenza’, may face some challenging situations in overcoming dormancy in the medium and long term in Zaragoza under the high-emissions scenario (RCP8.5). ‘Cristobalina’, ‘Pico Colorado’ and ‘Ramón Oliva’ might be the safest options to secure fruit production in the worst-case scenario by 2050. Among the evaluated cultivars, ‘Cristobalina’ may be of particular interest given its very low chill requirements (about 26 CP) and early flowering behavior. Such traits are expected to help breeders in developing new low-chill cultivars that can adapt to future conditions in the study region, as well as in other regions that are more strongly affected by the impacts of climate change.

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CRediT authorship contribution statement

Erica Fadón: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, and Visualization. **Eduardo Fernandez**: Methodology, Software, Visualization, Writing – review & editing. **Eike Luedeling**: Methodology, Software, Writing – review & editing, and Funding acquisition. **Javier Rodrigo**: Conceptualization, Data curation, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Javier Rodrigo reports financial support was provided by Spanish Ministry of Science and Innovation. Eike Luedeling reports financial support was provided by German Federal Ministry for Education and Research. Javier Rodrigo reports financial support was provided by Government of Aragón.

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126774.

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