

1 Warming winters and cultivar resilience in sweet cherry: agroclimatic  
2 requirements and future suitability under Mediterranean-continental  
3 conditions

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12 KEYWORDS: chilling requirements, climate change, dormancy, endodormancy, global  
13 warming, *Prunus avium*

14

15 ABSTRACT

16 Warming winters are increasingly altering the dormancy and flowering dynamics  
17 of temperate fruit trees. In this study, we assess the adaptation potential of 22 North  
18 American sweet cherry (*Prunus avium* L.) cultivars to future climate conditions in  
19 Zaragoza (Ebro Valley, Spain), a representative Mediterranean-continental site.  
20 Endodormancy release and flowering were characterized over two contrasting seasons  
21 (2022–2023 and 2023–2024) to determine cultivar-specific agroclimatic requirements.  
22 Chill and heat accumulation were quantified using the Dynamic, Chilling Hours, and Utah  
23 Models for chill, and the Growing Degree Hours Model for heat. Historical trends (1974–  
24 2024) and future projections from 18 Global Climate Models (GCMs) under two Shared  
25 Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) were analyzed to assess the  
26 probability of chilling fulfillment. Historical analysis revealed a 6–8 CP decline since 1980,  
27 confirming progressive warming. The exceptionally warm 2023–2024 winter recorded

28 the lowest chill accumulation in 50 years and was associated with flowering delays  
29 across all cultivars. Cultivar-specific analyses indicated a broad range of chilling  
30 requirements (37.6–66.6 CP), with high-chill cultivars showing increased risk of  
31 incomplete dormancy release under warmer winters. Projections suggest that while most  
32 cultivars may remain viable by mid-century (2050), by 2085 adaptation challenges will  
33 intensify, particularly under SSP5, where all cultivars show risk of insufficient chill for at  
34 least one GCM. These findings provide empirical evidence that warming winters are  
35 reshaping sweet cherry dormancy and offer a probabilistic framework to guide cultivar  
36 selection and adaptation strategies under ongoing climate change.

## 38 1. Introduction

39 Global climate change is increasingly disrupting the thermal regimes that govern  
40 plant phenology and productivity in temperate fruit systems. Irregular weather patterns  
41 and extreme events are already impacting agriculture worldwide (Cogato et al., 2019).  
42 Fruit orchards in the Mediterranean Basin are increasingly affected by the reduction of  
43 chill accumulation during winter (Fernandez et al., 2023), which particularly threatens  
44 temperate fruit trees and poses a major challenge in Spain (Egea et al., 2022; Osorio-  
45 Marín et al., 2024). Rising winter temperature alter phenological cycles, as temperature  
46 is the primary driver of developmental processes (Chmielewski et al., 2004; Fadón et al.,  
47 2021). Thus, identifying climate-adaptation challenges and characterizing suitable  
48 species and cultivars capable of coping with future climate conditions is essential for the  
49 sustainability of temperate fruit production in affected regions.

50 Temperate trees such as sweet cherry (*Prunus avium* L.) enter a winter dormancy  
51 stage to withstand low temperatures. Dormancy enables survival by ceasing  
52 meristematic activity and protecting flower and leaf primordia within buds. Growth can  
53 only resume after the accumulation of sufficient winter chill, which restores the capacity  
54 to grow, and the subsequent accumulation of heat, which triggers flowering in spring  
55 (Faust et al., 1997). Dormancy is traditionally divided into two phases: endodormancy —  
56 regulated by internal factors— and ecodormancy —driven by environmental factors.  
57 Thus, dormancy is particularly sensitive to rising winter temperatures, since chill  
58 accumulation during endodormancy and heat accumulation during ecodormancy are  
59 essential for dormancy release (Lang et al., 1987).

60 Winter temperatures are projected to increase markedly in key agricultural  
61 regions worldwide in the coming decades (Luedeling et al., 2009). Spain ranks among  
62 the regions most affected by global warming, with estimated mean temperature  
63 increases of 1.8–2.1 °C up to 2022 (Arellano et al., 2025) and further rises of 3–7 °C  
64 expected during the 21st century, depending on the scenario (Carvalho et al., 2021).  
65 These trends directly lead to reductions in winter chill accumulation, thereby disrupting

66 key physiological processes that may result in irregular flowering (Elloumi et al., 2024;  
67 Legave et al., 2015), desynchronization between pollinators and pollen donors in self-  
68 incompatible cultivars (Guerrero et al., 2024), higher risk of spring frosts due to early  
69 flowering (Fernandez et al., 2023), delayed or irregular budburst (Barba-Espín et al.,  
70 2022; Erez, 2000), bud break anomalies (Bonhomme et al., 2005), reduced fruit set  
71 (Egea et al., 2022; Hedhly et al., 2007), variations in fruit quality (Gracia et al., 2025),  
72 and ultimately reduced yield potential (Benmoussa et al., 2018; Fernandez et al., 2021).

73 Agroclimatic requirements —chill and heat— are cultivar-specific (Castède et al.,  
74 2014) and determine the adaptability of each cultivar to particular growing regions  
75 (Fadón et al., 2020a). Flowering timing results from the combined effect of winter chill  
76 and subsequent heat, and can be advanced by lower temperatures during  
77 endodormancy and/or warmer temperatures during ecodormancy (Fadón et al., 2021).  
78 Delineating dormancy phases is challenging, as no visible changes occur in bud  
79 appearance during the transition. Instead, endo- and eco-dormancy phases are usually  
80 assessed using two main approaches: statistical or experimental methods (Fadón et al.,  
81 2020a). Statistical analyses relate flowering dates to daily temperature records from the  
82 previous months using correlation (Alonso et al., 2005) or Partial Least Squares (PLS)  
83 regression (Luedeling et al., 2013). However, these statistical approaches require long-  
84 term datasets —typically at least 20 years— which are often unavailable for newly  
85 released or previously unstudied cultivars. Experimental methodologies assess when  
86 buds recover the capacity to grow. Specifically, shoots are periodically collected during  
87 winter, then exposed to controlled forcing conditions (7–10 days). Floral buds are  
88 monitored for changes in weight (Brown and Kotob, 1957) or phenological state (Bennett,  
89 1949), and their growth after the forcing treatment indicates the date of endodormancy  
90 release. Once endodormancy is defined, ecodormancy extends from that date until  
91 budburst, which indicates growth resumption (Lang et al., 1987).

92 Identifying the agroclimatic requirements of cultivars is increasingly important for  
93 selecting well-adapted cultivars under global warming, ensuring orchard productivity.

94 Coupling cultivar requirements with climate projections provides a valuable strategy to  
95 anticipate adaptation under ongoing warming. Weather projections are based on the  
96 Global Climate Models (GCMs) derived from the Coupled Model Intercomparison Project  
97 Phase 6 (CMIP6) (Eyring et al., 2016) together with the new future scenarios known as  
98 Shared Socioeconomic Pathways (SSPs) presented in the Sixth Assessment Report  
99 from the Intergovernmental Panel on Climate Change (AR6, IPCC 2023) (Calvin et al.,  
100 2023). These projections can be used as a scientific tool to generate future predictions  
101 of chill and heat availability in a given region. Temperate fruit trees, such as sweet cherry,  
102 require both sufficient winter chill and adequate heat to ensure commercial production,  
103 and their long-term viability depends on the balance between agroclimatic requirements  
104 and local climatic conditions (Fadón et al., 2020a; Luedeling et al., 2013).

105 In this work, we assess the adaptation potential of 22 sweet cherry cultivars bred  
106 in North America to future climatic conditions in Zaragoza, located in the Ebro Valley, a  
107 major cherry-growing region in Spain. First, we experimentally characterized the  
108 agroclimatic requirements of these cultivars. We then analyzed whether the chilling  
109 requirements (CR) of each cultivar will be fulfilled in the future by forecasting winter chill  
110 availability under two climatic scenarios (SSP2-4.5 and SSP5-8.5). These findings will  
111 support growers, technicians, and stakeholders in making informed decisions, enhancing  
112 orchard resilience under global warming and securing food production.

113

114 2. Materials and Methods

115 2.1. *Plant material and localization*

116 Twenty-two sweet cherry cultivars released in North America (USA and Canada)  
117 were analyzed (Table 1). Trees were grown in a germplasm collection at “Centro de  
118 Investigación y Tecnología Agroalimentaria de Aragón” (CITA; 41.72° N; 0.81° W; 220  
119 ma.s.l.) in Zaragoza, Spain. Zaragoza, in northeastern Spain, has a continental  
120 Mediterranean climate (Camarero et al., 2021). Winters are generally mild, with below-  
121 zero temperatures occurring intermittently. Summers are dry and can be quite warm,  
122 with highs often surpassing 30°C (AEMET, 2025).

123 Table 1. List of the 22 sweet cherry cultivars analyzed, including their breeding  
124 program and country of origin.

Country	Breeding Program	Cultivar
Canada	Pacific Agri-Food Research Centre in Summerland	'Cristalina', 'Sandon Rose', 'Sandra Rose', 'Sentennial', 'Skeena', 'Sonata', 'Staccato', 'Sumele', 'Sunburst', 'Sweetheart', 'Symphony', 'Van'
USA	Bradford Genetics	'Sequoia'
	University of California, Davis	'Coral Champagne'
	New York State Agricultural Experiment Station, Geneva	'Hartland'
	Seth Lewelling	'Bing'
	Washington State University	'Cashmere', 'Chelan', 'Cowiche', 'Index', 'Selah', 'Tieton'

125 2.2. *Temperature records*

126 A long-term daily maximum and minimum temperature record of Zaragoza  
127 (1974–2024) was acquired from the GSOD (Global Surface Summary of the Day)  
128 database, maintained by the National Oceanic and Atmospheric Administration (NOAA)  
129 (NCEI, 1999). Daily minimum and maximum temperatures were converted into hourly  
130 temperatures by an idealized daily temperature curve combining a sine function for  
131 daytime warming and a logarithmic decay for nighttime cooling, based on site latitude  
132 (Almorox et al., 2005; Linvill, 1990).

133 2.3. *Experimental determination of endodormancy release and flowering*  
134 *characterization.*

135 Endodormancy release and flowering were estimated for each cultivar during two  
136 consecutive winters, 2022–2023 and 2023–2024. The experimental determination of  
137 endodormancy release was carried out by collecting five shoots per cultivar weekly  
138 during winter (November to February). Shoots with homogeneous characteristics were  
139 selected, 15–30 cm in length and 0.5–1 cm in diameter, each with a minimum of 10  
140 flower buds. Dormancy status was assessed by observing the response of the flower  
141 buds after eight days in a growth chamber (Fadón and Rodrigo, 2018). To do so, we  
142 weighed a group of ten flower buds gathered from the field. Then, we placed the shoots  
143 on florist foam soaked with water and kept them in a growth chamber at  $22 \pm 1$  °C with  
144 a 12-hour light photoperiod. The endodormancy release date was defined when flower  
145 buds showed a weight increase of at least 30% after eight days in the chamber (Brown  
146 and Kotob, 1957).

147 Phenology was monitored every two days during late winter and spring,  
148 registering the earliest, the most frequent, and the most advanced flowering  
149 developmental stage according to the Baggiolini phenological scale (Baggiolini, 1952).  
150 We considered full bloom when at least 50% of the flowers were at stage 65 on the BBCH  
151 scale (Fadón et al., 2015), corresponding to phenological stage F (Baggiolini, 1952).

#### 152 *2.4. Assessment of the chill and heat requirements*

153 The agroclimatic requirements of the cultivars were determined by quantifying  
154 chill and heat accumulation across the endo- and ecodormancy phases over the two  
155 seasons studied (2022–2023 and 2023–2024). Chill requirements were computed from  
156 1 November until the endodormancy release date, while heat requirements for flowering  
157 were quantified from endodormancy release to full bloom.

158 We used three chill models. The Chilling Hours Model considers one Chilling  
159 Hour (CH) for each hour with temperatures between 0 and 7.2 °C (Hutchins, 1932;  
160 Weinberger, 1950). The Utah Model assigns one Chilling Unit (CU) as equivalent to an  
161 hour with temperatures between 2.5 and 9.1 °C, 0.5 CU for 1.5–2.4 °C and 9.2–12.4 °C,  
162 no CU accumulation for <1.4 °C or 12.5–15.9 °C, and negative accumulation for >16 °C

163 (-0.5 between 16–17.9 °C; -1 above 18 °C) (Richardson et al., 1974). The Dynamic Model  
164 describes chill accumulation as a two-step process, where cold temperatures lead to the  
165 formation of a precursor of the dormancy breaking factor (PDBF), and warm  
166 temperatures negate the PDBF. After a threshold amount of PDBF is formed, it is  
167 irreversibly converted into the dormancy-breaking factor (DBF). This accumulation is  
168 quantified in Chilling Portions (CP) (Fishman et al., 1987). Most of the analyses focused  
169 primarily on CP values, given their higher accuracy compared with other models  
170 (Luedeling and Brown, 2011) and better estimation of chill requirements in temperate  
171 fruit trees (Fernandez et al., 2020b).

172 We used the Growing Degree Hours (GDH) model to quantify heat, which defines  
173 one GDH as one hour at 1 °C above a base temperature of 4.5 °C. Values of GDH were  
174 determined by subtracting 4.5 °C from hourly temperatures within the range 4.5°–25 °C;  
175 higher temperatures were capped at 25 °C, resulting in a maximum accumulation of 20.5  
176 GDH per hour (Anderson et al., 1986).

### 177 *2.5. Historic and Future winter chill projections*

178 To evaluate temporal changes in chill availability, we analyzed observations  
179 recorded in-situ as well as synthetic temperature data generated for historic and future  
180 periods following established procedures (Caspersen et al., 2025a; Fernandez et al.,  
181 2021) with minor adjustments.

182 To better identify long-term trends that can result from global warming and to  
183 reduce the effect of year-to-year variation, representative temperature scenarios were  
184 generated for the years 1980, 1990, 2000, 2010, and 2020 based on temperature  
185 records from 1974 to 2024. For each year, typical mean daily minimum and maximum  
186 temperatures were calculated for each month by applying a 15-year running mean  
187 function across all recorded monthly extremes. We created 100 synthetic weather time  
188 series for each scenario with the RMAWGEN weather generator (version 1.3.7; Cordano  
189 and Eccel, 2016). The simulated temperatures provide a more accurate representation

190 of the local climate compared to the real observed conditions, which may be influenced  
191 by extreme events or unusual occurrences (Shinwari et al., 2025).

192 Future projections were obtained for 18 GCMs (Supplementary Table 1) from the  
193 Climate Data Store (Copernicus Climate Change Service, 2021). Simulations included  
194 scenarios for two SSPs: SSP245 and SSP585, designated as SSP2 and SSP5 hereafter,  
195 respectively. SSP2 represents a ‘middle-of-the-road’ pathway, combining moderate  
196 socioeconomic growth with intermediate mitigation efforts that yield a radiative forcing  
197 around  $4.5 \text{ W/m}^2$ , and SSP5 is the ‘fossil fuel development’, which assumes rapid  
198 development based on fossil energies with limited mitigation, resulting in radiative forcing  
199 near  $8.5 \text{ W/m}^2$  (Calvin et al., 2023). Projections were obtained for two-time horizons: mid-  
200 century (2035–2065; hereafter 2050) and late-century (2070–2100; hereafter 2085). For  
201 each combination of SSP, time horizon, and GCM, hourly temperature series were  
202 downscaled, and chill accumulation was computed using the Dynamic Model (CP).

#### 203 *2.6. Probability of chilling fulfillment in future scenarios*

204 Potential impact of climate change on sweet cherry cultivation was evaluated by  
205 assessing the probability of chill fulfillment for the 22 cultivars for each combination of  
206 SSP, time horizon, and GCM. To identify the minimum reliable chill that growers can  
207 expect, we used the Safe Winter Chill (SWC), which corresponds to the 10th percentile  
208 of a chill accumulation distribution and represents the chill level that is exceeded in 90%  
209 of years (Luedeling et al., 2009). This implies that the maximum risk for an orchard to  
210 remain profitable is missing CR 1 out of 10 years. This metric enables the identification  
211 of cultivars that may fail to satisfy their CR and could become unviable under certain  
212 scenarios and regions, supporting adaptation strategies to future climate change  
213 conditions.

214 According to the protocol by Delgado et al. (2021) and Fadón et al. (2023a), we  
215 estimated uncertainty in CR by sampling 1000 values within the range of “mean CR  $\pm$   
216 SD” to represent CR plasticity of each cultivar. Then, we determined the probability of  
217 chilling fulfillment by comparing the 1000 sampled CR values with chill accumulation

218 from 100 simulated seasons for each combination of SSP, time horizon, and GCM. The  
219 results were summarized as the median probability of chill fulfillment (SWC probability),  
220 expressed as a fraction between 0 and 1.

### 221 *2.7. Data processing, analysis, and visualization*

222 We calculated agroclimatic requirements, downloaded the temperature records,  
223 and filled data gaps by linear interpolation using the functions from the chillR package  
224 (version 0.76; Luedeling et al., 2024) in the R software environment (version 4.5.1; R  
225 Core Team 2025) using RStudio (Posit team, 2025). We used ggplot2 library for the  
226 visualization of the results (Wickham, 2011).

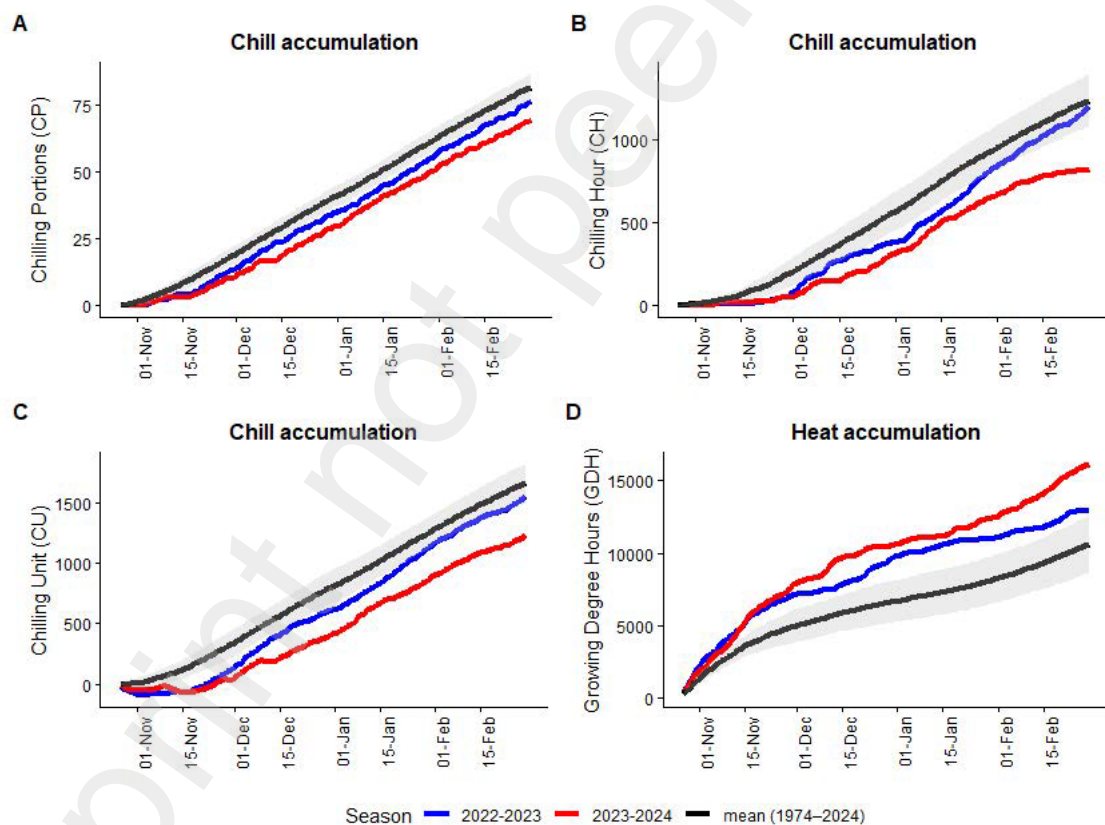
227

228 3. Results

229 3.1. Chill and heat accumulation across the seasons

230 The pattern of chill and heat accumulation differed greatly between the two  
231 seasons studied (2022–2023 and 2023–2024) (Fig. 1). Chill started at the beginning of  
232 November in both seasons, and by the end of February, chill and heat accumulation  
233 reached 76.6 CP, 1196 CH, 1624 CU, and 11125 GDH in 2022–2023, and 69.5 CP, 818  
234 CH, 1273 CU, and 14599 GDH in 2023–2024. Compared with values calculated from a  
235 50-year historical dataset (Supplementary Table 2), both seasons showed low chill  
236 accumulation values, whereas heat accumulation substantially exceeded the historic  
237 mean value.

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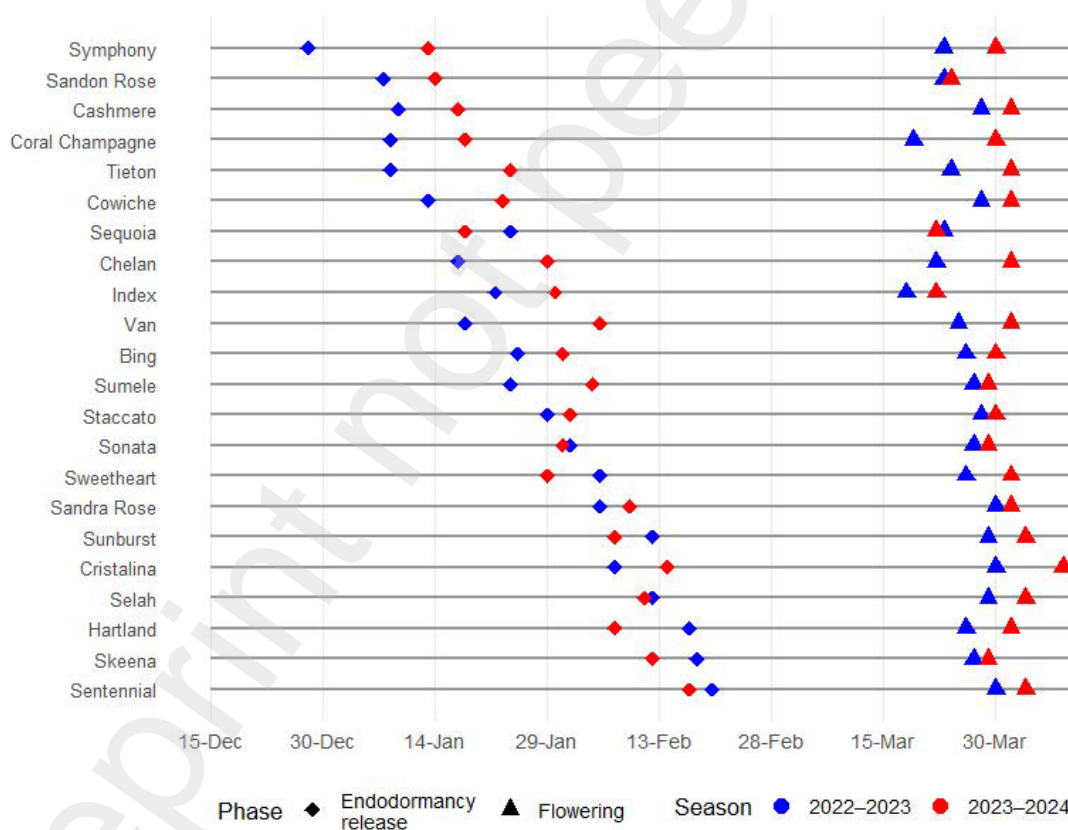
240 Figure 1. Chill and heat accumulation during two seasons (2022-2023 in blue, 2023-2024  
241 in red) and historically (1974-2024; mean in black, standard deviation as a grey shadow).  
242 (A) Chill accumulation calculated with the Dynamic Model (CP), (B) Chilling Hours (CH),  
243 (C) Utah Model (CU), and (D) heat accumulation in Growing Degree Hours (GDH). Chill  
244 and heat accumulation was calculated from November 1<sup>st</sup> to February 28<sup>th</sup>.

245 These results highlight the temperature shifts during the dormant period due to climate  
246 change in this region. Notably, the 2023–2024 season presented the lowest chill  
247 accumulation since 1974.

### 248 3.2. Endodormancy release and flowering dates

249 The date of endodormancy release was assessed empirically for the 22 cultivars  
250 analyzed (Supplementary Table 3). In both seasons, ‘Symphony’ was the earliest cultivar  
251 to release from endodormancy (December 28, 2022; January 13, 2024), whereas  
252 ‘Sentennial’ was the latest (February 20, 2023; February 17, 2024). Endodormancy  
253 release ranged from late December and late February in both seasons. As a general  
254 trend, most cultivars released from endodormancy earlier in the season 2022–2023 than  
255 in 2023–2024 (Fig. 2).

256



257

258 Figure 2. Endodormancy release dates (diamonds) and flowering dates (triangles) for  
259 two seasons (2022–2023 in blue, 2023–2024 in red).

260

261 Phenology monitoring allowed the determination of flowering dates for all cultivars  
 262 in both seasons (Supplementary Table 3). Flowering dates ranged from March 18<sup>th</sup>  
 263 ('Index') to March 30<sup>th</sup> ('Sentennial', 'Cristalina', and 'Sandra Rose') in 2022-2023, and  
 264 from March 22<sup>nd</sup> ('Sequoia') to May 8<sup>th</sup> ('Cristalina') in 2023-2024. All cultivars flowered  
 265 later during the second season, with flowering dates delayed by 1-11 days in 2023–  
 266 2024 compared to 2022-2023 (Fig. 2).

### 267 3.3. Chill and heat requirements

268 Based on endodormancy release and flowering dates, chilling and forcing periods  
 269 were delineated to calculate the agroclimatic requirements of each cultivar. CR were  
 270 obtained using three chill models [Dynamic Model (CP), Chilling Hours Model (CH), and  
 271 Utah Model (CU)], and heat requirements were calculated with the 'Growing Degree  
 272 Hours' Model (GDH) (Table 2).

273 CR ranged 37.6–66.6 CP, 445–934 CH, and 685–1330 CU. 'Symphony' had the  
 274 lowest CR ( $37.6 \pm 4.5$  CP,  $445 \pm 69$  CH and  $685 \pm 22$  CU), while 'Sentennial' had the  
 275 highest ( $66.6 \pm 5.6$  CP,  $934 \pm 210$  CH and  $1330 \pm 242$  CU). Heat requirements ranged  
 276 7095–9992 GDH, with 'Index' and 'Symphony' showing the lowest and highest values,  
 277 respectively.

278 Table 2. Agroclimatic requirements of 22 sweet cherry cultivars. Chill requirements were  
 279 calculated using the Dynamic Model (CP), Chilling Hours Model (CH), and Utah Model  
 280 (CU), and heat requirements using the Growing Degree Hours Model (GDH). Mean  $\pm$   
 281 standard deviation (SD) were estimated across two seasons (2022–2023 and 2023–  
 282 2024).

Cultivar	Chilling requirements			Heat requirements
	Chilling Portions	Chilling Hours	Chill Units	GDH
Symphony	$37.6 \pm 4.5$	$445 \pm 69$	$685 \pm 22$	$9992 \pm 929$
Sandon Rose	$40.5 \pm 1.0$	$494 \pm 15$	$752 \pm 52$	$9005 \pm 1377$
Cashmere	$41.5 \pm 1.0$	$512 \pm 15$	$788 \pm 55$	$9866 \pm 792$
Coral Champagne	$42.0 \pm 1.7$	$510 \pm 23$	$782 \pm 41$	$8480 \pm 2162$
Tieton	$43.9 \pm 4.5$	$546 \pm 76$	$821 \pm 15$	$9111 \pm 1050$
Cowiche	$45.2 \pm 1.8$	$571 \pm 26$	$856 \pm 52$	$9474 \pm 695$
Sequoia	$47.4 \pm 6.0$	$630 \pm 146$	$930 \pm 250$	$8169 \pm 1354$
Chelan	$48.2 \pm 2.8$	$632 \pm 35$	$941 \pm 35$	$8254 \pm 1622$
Index	$50.9 \pm 0.3$	$672 \pm 23$	$1006 \pm 100$	$7095 \pm 1639$
Van	$51.5 \pm 6.4$	$672 \pm 67$	$1007 \pm 24$	$8359 \pm 604$

Bing	52.5 ± 0.5	708 ± 57	1036 ± 120	8572 ± 684
Sumele	53.4 ± 2.4	720 ± 19	1057 ± 70	8460 ± 236
Staccato	54.2 ± 1.5	746 ± 98	1084 ± 174	8706 ± 379
Sonata	55.2 ± 4.4	759 ± 129	1104 ± 216	8585 ± 665
Sweetheart	55.3 ± 7.3	774 ± 167	1112 ± 276	8501 ± 1272
Sandra Rose	59.5 ± 1.5	816 ± 108	1186 ± 170	8489 ± 235
Sunburst	60.9 ± 6.4	866 ± 179	1234 ± 262	8535 ± 685
Cristalina	61.4 ± 1.2	854 ± 107	1238 ± 152	8658 ± 222
Selah	62.6 ± 3.9	874 ± 169	1259 ± 226	8277 ± 320
Hartland	62.8 ± 9.0	898 ± 223	1264 ± 304	7837 ± 1110
Skeena	64.9 ± 7.1	914 ± 214	1298 ± 266	7491 ± 472
Sentennial	66.6 ± 5.6	934 ± 210	1330 ± 242	7707 ± 70

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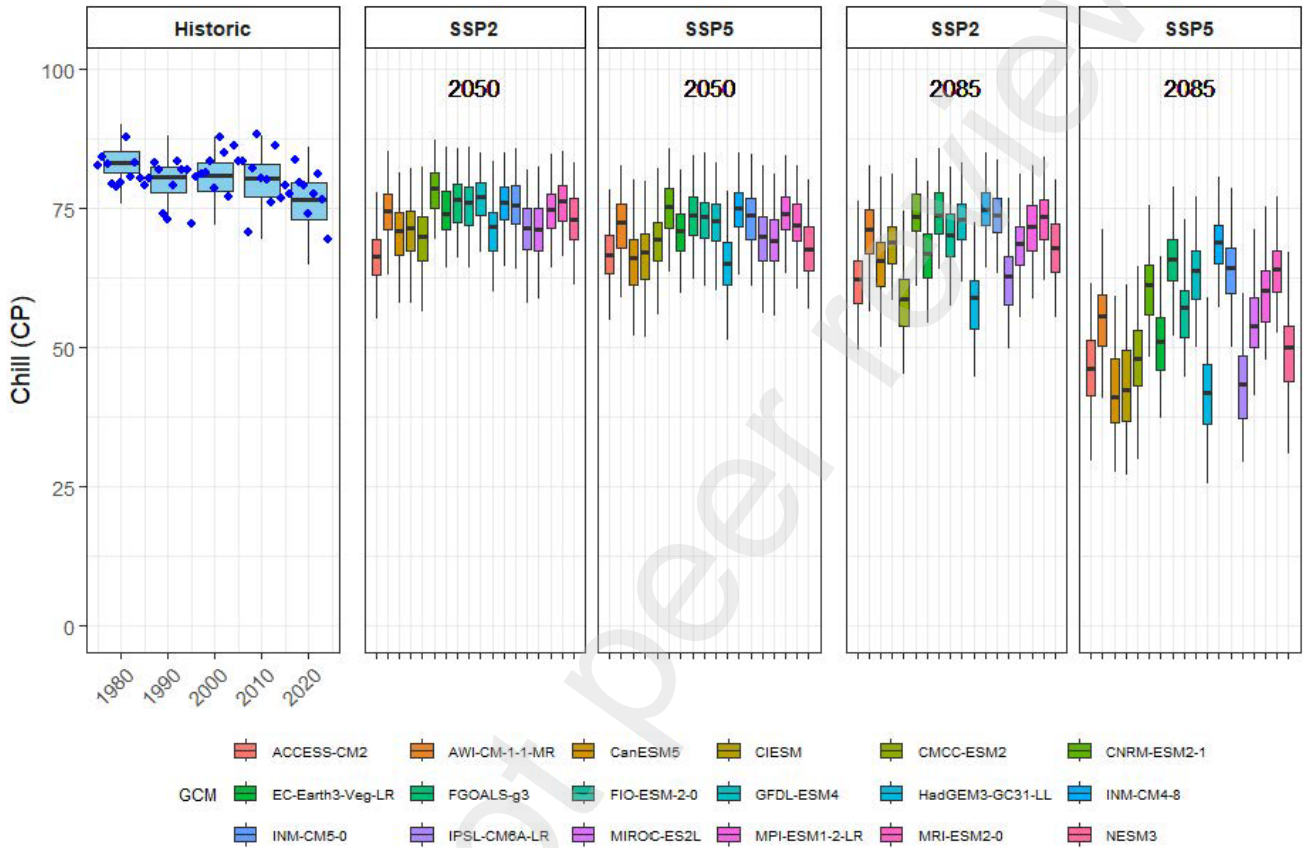
#### 284 3.4. Winter chill projections and probability of chilling fulfillment

285 Historical simulations showed a marked decline in chill availability over the last  
 286 decades (Fig. 3). Chill accumulation ranged from 81.3 to 85.1 CP (25th–75th percentile)  
 287 in 1980, and from 73 to 79.5 CP (25th–75th percentile) in 2020, indicating a decline of  
 288 approximately 6–8 CP over forty years, equivalent to a reduction of 6–10%.

289 To quantify the reduction in winter chill availability under future scenarios,  
 290 statistics were computed for all GCMs and for each combination of time horizon and  
 291 SSP. The expected chill was 69.9–76.8 CP (25th–75th percentile) for SSP2-2050, 66.9–  
 292 74.1 CP for SSP5-2050, 64.6–68.6 CP for SSP2-2085, and 49.4–58.7 CP for SSP5-  
 293 2085. These data indicate a continued decline in chill availability, moderate by 2050 but  
 294 more pronounced by 2085, particularly under SSP5 (Fig. 3).

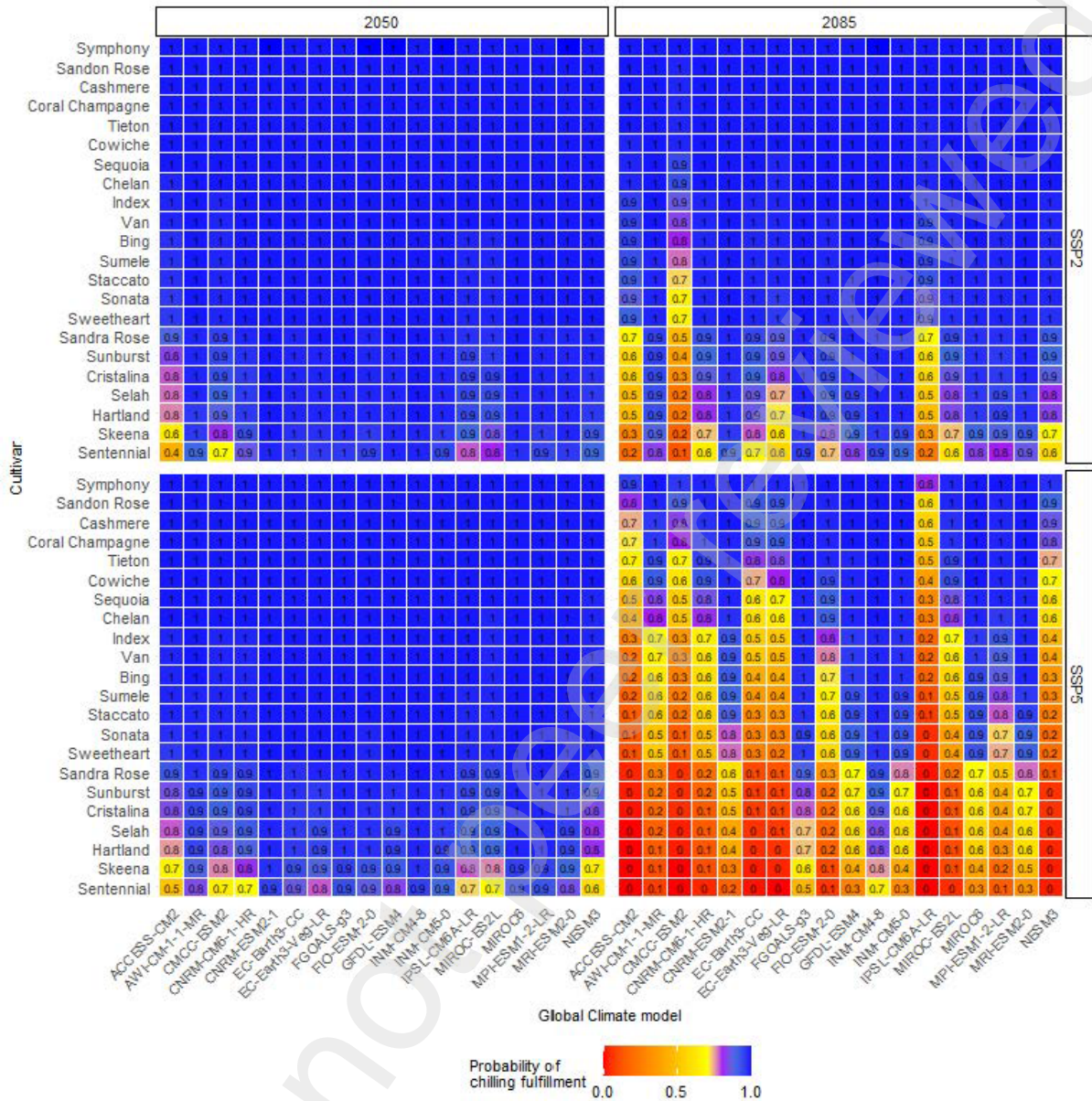
295 To predict cultivar viability, we evaluated the probability of chilling fulfillment  
 296 based on cultivar-specific CR for each GCM, time horizon, and SSP (Fig. 4). Values  
 297 below 0.9 indicate an adaptation risk, meaning CR may not be fulfilled. Results suggest  
 298 that most cultivars will remain suitable in the Ebro Valley through the mid-term (2050),  
 299 as projected chill accumulation is expected to fulfill their requirements. Exceptions  
 300 include six cultivars ('Sunburst', 'Cristalina', 'Skeena', 'Selah', 'Hartland', and  
 301 'Sentennial'), which showed a potential risk of not fulfilling their CR. By 2085, more  
 302 severe challenges are expected for most cultivars. Under SSP2-2085, 13 of 22 cultivars  
 303 ('Van', 'Bing', 'Sumele', 'Staccato', 'Sonata', 'Sweetheart', 'Sandra Rose', 'Sunburst',

304 'Cristalina', 'Skeena', 'Selah', 'Hartland' and 'Sentennial') may face adaptation according  
 305 to some GCM. However, for SSP5-2085, all cultivars fail to fulfill their CR in at least one  
 306 GCM.  
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308  
 309 Figure 3. Historic and projected chill accumulation during the chill period (1 November –  
 310 28 February) in Zaragoza, Spain. The “Historic” panel shows observed chill accumulation  
 311 (1974-2024; blue dots) and simulated scenarios for 1980, 1990, 2000, 2010, and 2020  
 312 (boxplots). The other four panels show future chill accumulation under two Shared  
 313 Socioeconomic Pathways (SSP2 and SSP5) and two-time horizons (2050 and 2085).  
 314 For all combinations of SSP and time horizon, chill accumulation was predicted using 18  
 315 global climate models (GCMs) and calculated with the Dynamic Model (CP).

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324 Figure 4. Probability of chilling requirement fulfillment for 22 sweet cherry cultivars under  
 325 future climate scenarios. Two Shared Socioeconomic Pathways (SSP2 and SSP5) and  
 326 two time horizons (2050 and 2085) were analyzed using 18 Global Climate Models  
 327 (GCMs).

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## 332 4. Discussion

333 Our results provide evidence that warming winters in Zaragoza (Ebro Valley) are  
334 already reshaping the thermal environment during the dormant period of sweet cherry.  
335 The exceptionally low chill recorded in 2023–2024, combined with above-average heat  
336 accumulation, illustrates an accelerated shift consistent with global climate change  
337 projections. Historical analyses revealed a 6–8 CP decline since 1980, confirming long-  
338 term trends toward reduced winter chilling.

### 339 4.1. Agroclimatic requirements

340 Knowledge of chill and heat requirements has become increasingly important, as  
341 these traits largely determine the regional suitability and productivity of fruit cultivars  
342 (Campoy et al., 2019). The range of CR observed in our study, 37.6–66.6 CP,  
343 underscores the genetic diversity in dormancy responses among sweet cherry cultivars.  
344 Low-CR cultivars such as 'Symphony' appear better adapted to warmer conditions, while  
345 high-CR cultivars such as 'Sentennial' are already close to their climatic limits in our  
346 region. These findings highlight the importance of CR diversity in breeding and cultivar  
347 selection for Mediterranean environments.

348 The agroclimatic requirements of 22 sweet cherry cultivars were characterized,  
349 14 of them for the first time ('Cashmere', 'Coral Champagne', 'Cowiche', 'Cristalina',  
350 'Index', 'Chelan', 'Selah', 'Sandra Rose', 'Sentennial', 'Sequoia', 'Staccato', 'Sumele',  
351 'Symphony', and 'Tieton'). By 2020, data on agroclimatic requirements were available for  
352 only 50 sweet cherry cultivars (Fadón et al., 2020b), but recent studies in Spain (Fadón  
353 et al., 2023a, 2022, 2021) and other Mediterranean countries (Azizi Gannouni et al.,  
354 2017; Imperiale et al., 2022; Palasciano and Gaeta, 2017) have expanded this number  
355 to around 100. Our results add valuable information on recently bred cultivars from major  
356 North American breeding programs.

357 The experimental approach used to determine endodormancy release is currently  
358 considered the most reliable method (Delgado et al., 2024; Guerrero et al., 2024). The  
359 CR values obtained fall within the broad range previously reported for sweet cherry (29–

360 101 CP) (Fadón et al., 2020b). However, our estimations indicated lower CR for 'Bing',  
361 'Sandon Rose' 'Sunburst', 'Sweetheart' and 'Van' than those reported previously (Azizi  
362 Gannouni et al., 2017; Fadón et al., 2021; Palasciano & Gaeta, 2017), whereas higher  
363 CR were observed for 'Sunburst' (Fadón et al., 2021).

364 Such discrepancies likely reflect methodological and climatic differences among  
365 studies. Variations in chamber conditions (temperature, duration) and bud growth  
366 evaluation criteria (weight vs. phenology) are known to introduce variability in CR  
367 determination (Delgado et al., 2024). In addition, differences in CR among regions due  
368 to climatic variability are frequently observed; therefore, it is important to use CR values  
369 obtained from regions with climatic conditions similar to the target cultivation area  
370 (Delgado et al., 2026).

371 Information on heat requirements remains scarce. Our results generally fall within  
372 previously reported ranges (Fadón et al., 2020b), though higher values were observed  
373 in some cultivars such as 'Bing', 'Hartland', 'Sandon Rose', 'Sonata', 'Sunburst' and 'Van'  
374 (Azizi Gannouni et al., 2017; Fadón et al., 2022, 2021).

375 Overall, our findings indicate lower chill and higher heat requirements than  
376 previous statistical studies (Fadón et al., 2022, 2021), differences that likely reflect both  
377 methodological approaches (empirical vs statistical) and climatic variability, including the  
378 exceptionally warm conditions of 2023–2024. The chilling and forcing phases appear to  
379 be separated by a transitional phase (Harrington et al., 2010) and it has been suggested  
380 that high heat accumulation can partially compensate for insufficient chill (Delgado et al.,  
381 2026; Harrington and Gould, 2015), reinforcing the concept of a dynamic interaction  
382 between chilling and forcing phases.

#### 383 *4.2. Contrasting patterns of dormancy release in a warmer season*

384 Historical temperature records indicate a steady decline in winter chill over the  
385 past five decades (1974–2024), with the lowest values in the last decade. The 2023–  
386 2024 winter was the warmest in 50 years, resulting in record-low chill and record-high

387 heat accumulation. Such patterns are consistent with projections of more frequent  
388 above-average temperatures under global warming (Santos et al., 2017).

389 Endodormancy release varied with winter temperature, generally occurring later  
390 during the warmer season. However, high-CR cultivars showed an earlier release,  
391 suggesting that low- and high-CR cultivars respond differently to thermal conditions.  
392 These contrasting responses support the heat compensation theory (Harrington and  
393 Gould, 2015) and contribute to a better understanding of the complex regulation of  
394 dormancy in temperate fruit trees (Fadón et al., 2020a).

395 All cultivars flowered later in the warm 2023–2024 season. Because flowering  
396 results from the interaction of chilling and forcing, this delay suggests that chilling  
397 conditions currently dominate bloom timing under Mediterranean winters, as reported for  
398 Japanese plum (Guerrero et al., 2024). If winter temperatures continue to rise, trees may  
399 fail to complete dormancy, potentially disrupting the annual growth cycle and fruiting  
400 capacity.

401 In regions with mild winters, where spring phenology is primarily driven by the  
402 chilling phase, insufficient chill can cause delays rather than advances in flowering  
403 (Caspersen et al., 2025b; Legave et al., 2013). This pattern has been reported for apricot  
404 in China (Guo et al., 2015), almond in Tunisia (Benmoussa et al., 2017), and sweet  
405 cherry in Spain (Fadón et al., 2023b, 2021).

#### 406 *4.3. Winter chill decline threatens future sweet cherry production*

407 In this study, we present future projections based on the new Shared  
408 Socioeconomic Pathways (SSPs) from the IPCC Sixth Assessment Report (AR6, 2023),  
409 which replace the previous Representative Concentration Pathways (RCPs) (IPCC,  
410 2014). These SSP-based simulations, applied for the first time in our region, confirmed  
411 a continuous decline in winter chill, moderate by 2050 under both SSPs but severe by  
412 2085, especially under SSP5 (high-emission scenario).

413 These predictions are consistent with previous studies based on RCP scenarios  
414 that forecast significant winter chill reductions worldwide (Fernandez et al., 2020a;

415 Luedeling et al., 2009), with particularly strong impacts across the Mediterranean Basin  
416 (Benmoussa et al., 2017; Fernandez et al., 2023), including several Spanish regions  
417 (Delgado et al., 2021; Egea et al., 2022; Guerrero et al., 2024), and the Ebro Valley  
418 (Fadón et al., 2023a; Santolaria et al., 2024). Our projections provide robust evidence of  
419 the ongoing decline in winter chill and emphasize the urgency of implementing mitigation  
420 and adaptation policies as temperature increases continue throughout this century  
421 (Calvin et al., 2023).

422 By integrating cultivar-specific CR with projected chill accumulation, we assessed  
423 the probability of chilling fulfillment using the Safe Winter Chill (SWC) framework. Our  
424 results indicate that high-CR cultivars may already face adaptation risks by 2050 for both  
425 SSP scenarios, and all cultivars could become vulnerable by 2085 under SSP5,  
426 potentially jeopardizing sweet cherry production in the Ebro Valley. Similar adaptation  
427 challenges have been reported for other fruit crops in Spain, including plum, peach,  
428 almond, apple, pear, and grapevine (Delgado et al., 2021; Fadón et al., 2023a, 2023c;  
429 Guerrero et al., 2024; Rodríguez et al., 2021). Our findings highlight that, without  
430 adaptive strategies, traditional cherry-growing areas such as the Ebro Valley may face  
431 increasing vulnerability to climate change.

432

433 5. Conclusion

434 This study integrates empirical measurements of agroclimatic requirements with  
435 probabilistic climate projections, providing a decision-support framework for growers and  
436 policymakers. Although limited to two seasons and one site, the results clearly  
437 demonstrate the potential of combining dormancy physiology with climate modeling to  
438 evaluate cultivar resilience. From a practical perspective, adaptation strategies should  
439 prioritize low-CR cultivars for new orchards, reconsider high-CR cultivars in warmer  
440 areas, and explore site-specific management options such as planting at higher  
441 elevations. Pollination management will also be critical given potential shifts in bloom  
442 overlap. Ultimately, genetic adaptation through breeding programs targeting reduced  
443 chilling requirements remains the most robust long-term solution to sustain sweet cherry  
444 production under ongoing climate warming.

445

446 6. Acknowledgments

447 This work was funded by the grant PRE2021-099164 funded by  
448 MCIN/AEI/10.13039/501100011033 and FSE “El FSE invierte en tu futuro” and Gobierno  
449 de  
450 Aragón—European Social Fund, European Union (Grupo Consolidado A12\_17R).

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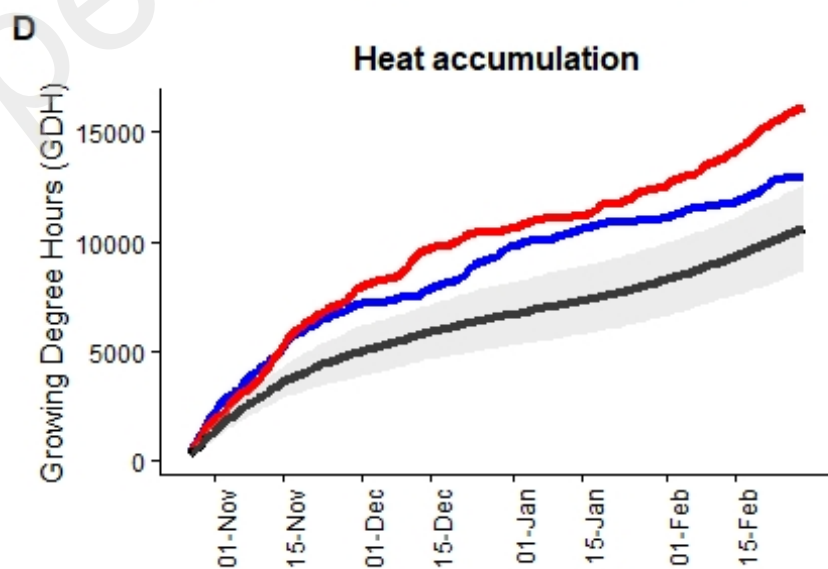
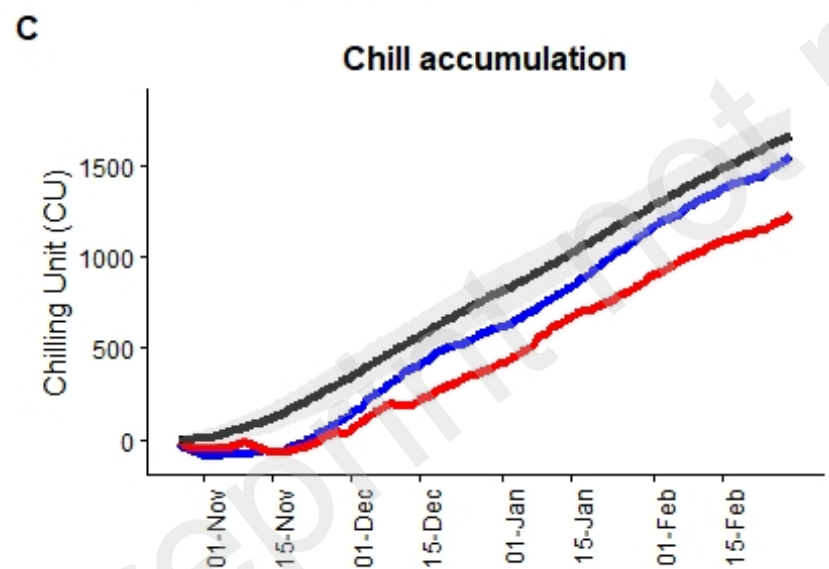
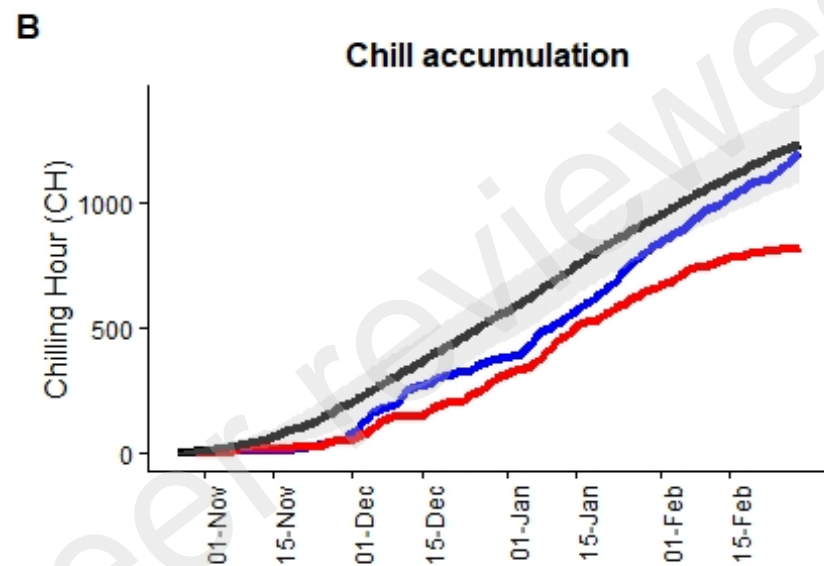
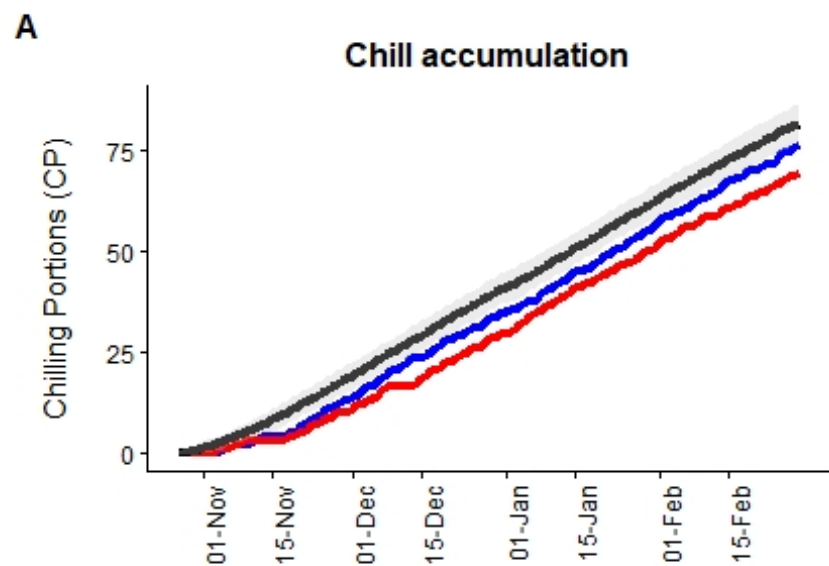
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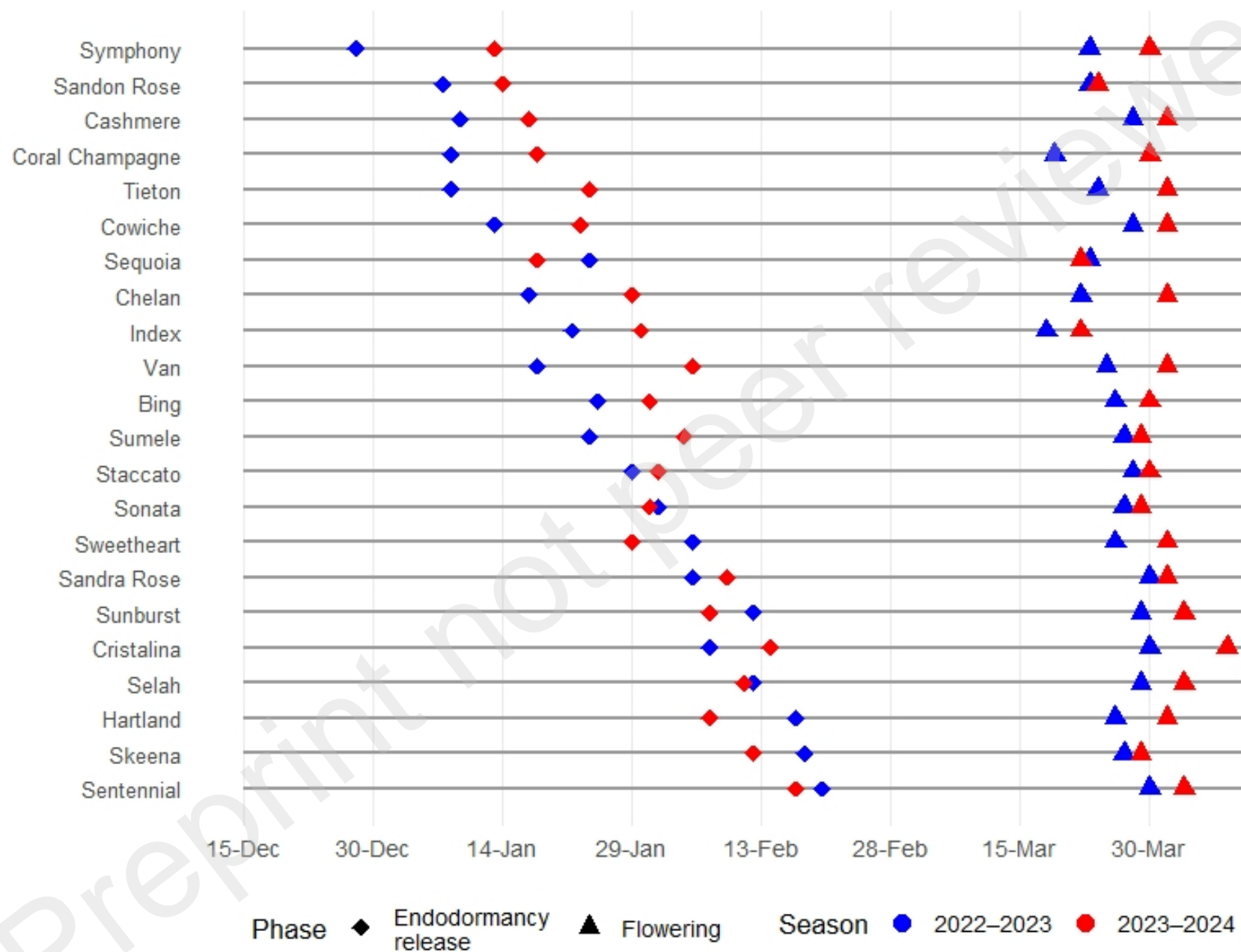
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Season — 2022-2023 — 2023-2024 — mean (1974-2024)



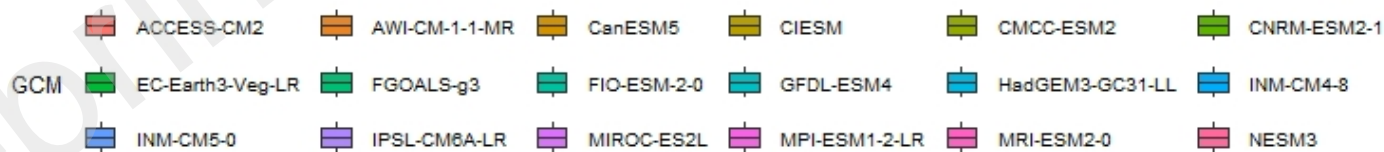
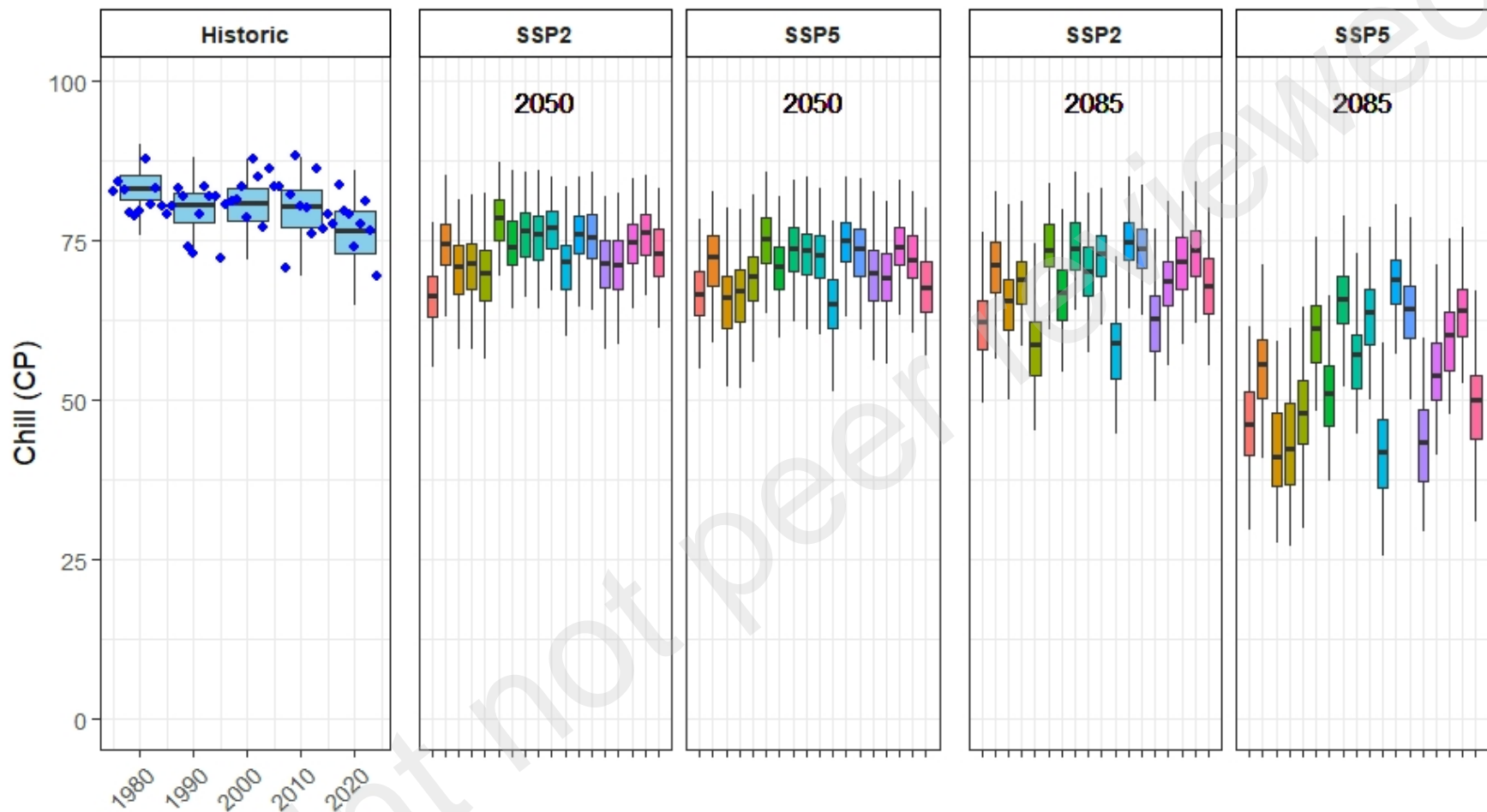




Figure 1. Chill and heat accumulation during two seasons (2022-2023 in blue, 2023-2024 in red) and historically (1974-2024; mean in black, standard deviation as a grey shadow). (A) Chill accumulation calculated with the Dynamic Model (CP), (B) Chilling Hours (CH), (C) Utah Model (CU), and (D) heat accumulation in Growing Degree Hours (GDH). Chill and heat accumulation was calculated from 1<sup>st</sup> of November to 28<sup>th</sup> of February.

Figure 2. Endodormancy release (diamonds) and flowering dates (triangles) for two seasons (2022-2023 in blue, 2023-2024 in red).

Figure 3. Historic and projected chill accumulation during the chill period (1 November – 28 February) in Zaragoza, Spain. The “Historic” panel shows observed chill accumulation (1974-2024; blue dots) and simulated scenarios for 1980, 1990, 2000, 2010, and 2020 (boxplots). The other four panels show future chill accumulation under two Shared Socioeconomic Pathways (SSP2 and SSP5) and two-time horizons (2050 and 2085). For all combinations of SSP and time horizon, chill accumulation was predicted using 18 global climate models (GCMs) and calculated with the Dynamic Model (CP).

Figure 4. Probability of chilling requirement fulfillment for 22 sweet cherry cultivars under future climate scenarios. Two Shared Socioeconomic Pathways (SSP2 and SSP5) and two time horizons (2050 and 2085) were analyzed using 18 Global Climate Models (GCMs).