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1 **Title:** Yield potential definition of the chilling requirement reveals likely underestimation of
2 the risk of climate change on winter chill accumulation

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12

13 **Abstract**

14 Evaluation of chilling requirements of cultivars of temperate fruit trees provides key
15 information to assess regional suitability, according to winter chill, for both industry expansion
16 and ongoing profitability as climate change progresses. Traditional methods for calculating
17 chilling requirements use climate controlled chambers and define chilling requirements using a
18 fixed bud burst percentage, usually close to 50% (CR-50%). However, this CR-50% definition
19 may estimate chilling requirements that lead to flowering percentages that are lower than
20 required for orchards to be commercially viable. We used sweet cherry to analyse the traditional
21 method for calculating chilling requirements (CR-50%) and compared the results with a more
22 restrictive method, where the chilling requirement was defined by a 90% bud break level (CR_m-

23 90%). For sweet cherry, this higher requirement of flowering success (90% as opposed to 50%)
24 better represents grower production needs as a greater number of flowers lead to greater
25 potential yield. To investigate the future risk of insufficient chill based on alternate calculations
26 of the chilling requirement, climate projections of winter chill suitability across Europe were
27 calculated using CR-50% and CR_m-90%. Regional suitability across the landscape was highly
28 dependent on the method used to define chilling requirements and differences were found for
29 both cold and mild winter areas. Our results suggest that bud break percentage levels used in
30 the assessment of chilling requirements for sweet cherry influence production risks of current
31 and future production areas. The use of traditional methods to determine chilling requirements
32 can result in an underestimation of productivity chilling requirements for tree crops like sweet
33 cherry which rely on a high conversion of flowers to mature fruit to obtain profitable yields.
34 This underestimation may have negative consequences for the fruit industry as climate change
35 advances with climate risk underestimated.

36 Keywords: *Prunus avium*, sweet cherry, flowering, temperature, phenology, projections

37

38 **Introduction**

39 Temperate deciduous fruit trees represent an important economic and food resource.
40 Maintaining and expanding temperate fruit production is an industry priority and is likely to
41 become more challenging under anthropogenic climate change. One aspect of tree physiology
42 which will likely be influenced by climate change is sufficient accumulation of winter chilling
43 (Luedeling et al. 2011). In temperate fruit trees, the timing of bud break and flowering is highly
44 correlated with a proper release of endodormancy, or rest, which is controlled by the exposure
45 to cold temperatures in winter (Saure 1985). During this rest period a certain exposure to cold
46 temperatures, defined as the chilling requirement, must be satisfied prior to the bud being
47 released from endodormancy (Lang et al. 1987). This period of rest prevents bud break in
48 response to conditions suitable for growth conditions, such as a warm spell in winter, which
49 would then expose sensitive tissues to subsequent damaging cold conditions. The consequences
50 of insufficient chill accumulation have been extensively studied and include delayed, light,
51 irregular and prolonged bud break and flowering (Samish 1953; Erez and Couvillon 1987; Erez
52 2000) as well as damage to bud development including deformed buds (Petri and Leite 2004;
53 Viti et al. 2008). Within the context of climate change, these sub-optimal production outcomes
54 may increase in frequency (Guy 2014). To predict such potential impacts to assist with orchard
55 climate adaptation and guide breeding strategies, evaluation of cultivar specific chilling
56 requirements (CR) is needed (Dennis 2003; Campoy et al. 2011; Chuine et al. 2016).

57 Precise determination of the CR is not possible under field conditions. As such, various
58 experimental methods have been used to evaluate dormancy depth (Cook et al. 2017; Vitra et
59 al. 2017), date of dormancy release (Dennis 2003; Dantec et al. 2014; Castède et al. 2014;
60 Chmielewski and Götz 2016) and to assess the relationship between bud break and chilling and
61 forcing temperatures (Harrington et al. 2010; Luedeling and Gassner 2012; Andreini et al. 2014;
62 Laube et al. 2014). Forcing experiments using controlled climate chambers have been

63 commonly used to assess bud dormancy progression since the method was first proposed for
64 the evaluation of CR in peach (Bennet 1949; Weinberger 1950) . This approach involves
65 sampling tree cuttings through autumn and winter and evaluating bud break after they have
66 been exposed to warm temperatures in a controlled climate chamber (Tabuenca 1967; Dennis
67 2003; Vitasse and Basler 2014). In implementing this methodology two main criteria have been
68 used to determine CR: 1) percentage of floral or vegetative bud break within a given period of
69 time in the chamber (e.g. 50% break after 10 days) and 2) the time required in the forcing
70 chamber to reach a given stage of development (e.g. bud break) (Saure 1985; Dennis 2003). the
71 first approach often determines CR as the chill accumulation in the field leading to 30-50% bud
72 break after 7 to 10 days in the forcing chamber (Hauagge and Cummins 1991; Ruiz et al. 2007;
73 Viti et al. 2010; Campoy et al. 2012; Castède et al. 2014). This criteria varies by study with for
74 instance, CR being determined after the emergence of only 3-4 flowers in the forcing chamber
75 (Chmielewski and Götz 2016; Götz et al. 2017).

76 These criteria may not adequately represent CR that are required for profitable fruit production,
77 in particular for crops which require high conversion of floral buds to fruit (e.g. sweet cherry).
78 These businesses rely on high and consistent bud break rates which set a high yield potential.
79 Poor rates of floral and vegetative bud break, that is the proportion of floral and vegetative buds
80 that truly open, can have a major impact on temperate fruit crop productivity (Erez 2000). For
81 small fruits, such as sweet cherry, a large number of viable flowers is required to reach
82 commercial productivity, with a maximum bloom level ideal. Therefore, setting a CR value
83 which only leads to 30-50% bud break may underestimate the CR needed for commercial
84 profitability. This in turn will misjudge the potential risk of climate change on cherry
85 production.

86 In this work, one of the most commonly employed methods in temperate fruit trees to estimate
87 CR (chilling accumulation in field that leads to 50% bud break after 10 days forcing) was used

88 for sweet cherry and was contrasted with a modified method that sets a higher bud break
89 percentage to better match requirements for high yield potential (90% bud break). We used CR
90 determined from both methods to create climate change projections of the potential risk of
91 insufficient chill accumulation for sweet cherry across Europe. This work emphasises the need
92 to evaluate CR in terms of the minimum requirement of chill for commercial viability to best
93 prepare industry and breeding programs for expansion and climate change.

94

95 **Materials and methods**

96 *Bud break observations*

97 We chose four sweet cherry cultivars for analysis encapsulating a presumed range in CR based
98 on flowering dates (Fig. 1). The trees used for the experiments were grown following
99 commercial orchard management in the fruit tree experimental orchards of the Institut National
100 de la Recherche Agronomique (INRA)-Bordeaux research centre, located in Bourran, in Lot-
101 et-Garonne (France, 44°19'N 0°24'E, 70m asl) and 60 km away in Toulence, in Gironde
102 (France, 44°34'N 0°16'W, 8m asl). Cultivars 'Cristobalina' and 'Regina' were grown in
103 Bourran, 'Fertard' in Toulence and 'Burlat' in both sites. Dates for beginning of flowering (5-
104 10% open flowers, BBCH 61; Fadón et al., 2015) and maturity (BBCH 89) were recorded for
105 the four cultivars between 2000 and 2017 in order to define the differences among cultivars.
106 For the experimental data, two or three branches bearing floral buds were randomly cut from
107 the two trees per cultivar and placed in a climate-controlled chamber under forcing conditions
108 (25°C, 16h light/8h dark) each fortnight between 1st September and 8th April (2015-2016 and
109 2016-2017 seasons), except for 'Cristobalina' which was sampled only in the 2015-2016
110 season.,. Every two or three days the total number of floral buds that reached bud break (BBCH
111 stage 53; Fadón et al. 2015) was recorded. Bud break percentage was calculated as the

112 percentage of flower buds at BBCH stage 53 in relation to the total number of floral buds on
113 the branches.

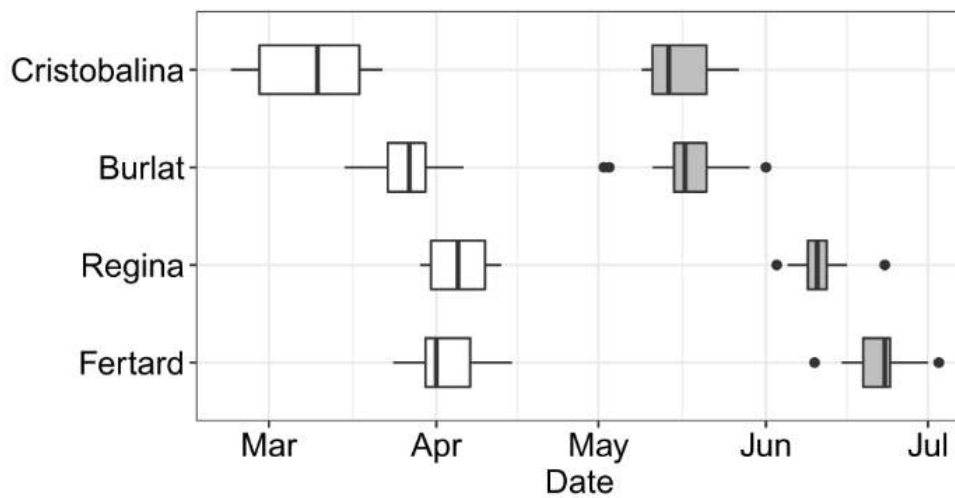


Fig. 1 Range of flowering (white boxes) and maturity (grey boxes) dates for the four studied cultivars (2000 – 2017)

114

115 *Chill requirement estimation*

116 Chill was calculated in chill portion (CP) using the Dynamic chill model (Fishman et al. 1987),
117 which has previously been found to be the best fitting chill model among several tested models
118 for a range of fruit tree species (Albuquerque et al. 2008; Luedeling et al. 2009b, 2013a;
119 Campoy et al. 2011; Guo et al. 2013).

120 To calculate CP hourly, we collected mean temperatures from local weather stations (years
121 2015-2017, INRA CLIMATIK, <https://intranet.inra.fr/climatik>, stations 47038002 and
122 33533002 for Bourran and Toulence, respectively). CP were calculated using the original model
123 parameters provided in the R package chillR (Luedeling et al. 2013b; Luedeling 2018). Chill
124 was accumulated from October 1st until the sampling date.

125 To assess CR, we used two methods. Firstly, we applied the commonly used approach which
126 defines CR as the accumulated chill in the field which leads to 50% of the buds surpassing stage
127 BBCH 55 after 10 days in forcing conditions (CR-50%) (Ruiz et al. 2007; Albuquerque et al.

128 2008; Campoy et al. 2012; Sánchez-Pérez et al. 2012; Azizi Gannouni et al. 2017). Secondly,
129 we used a similar approach but with a longer period in forcing conditions (2-3 weeks) and a
130 higher bud break percentage, 90%, required to define CR ($CR_m-90\%$).

131

132 *Future climate data*

133 For the analyses of future climate risk, we used two gridded datasets of temperatures in Europe.
134 These were regionally downscaled climate datasets for historical and projected temperature
135 made available by EURO-CORDEX (<http://www.euro-cordex.net>; Jacob et al., 2014). This
136 dataset used the SMHI-RCA4 regional change model (50 km resolution, EUR-44) with
137 projection data from the climate models MOHC-HadGEM2-ES and NOAA-GFDL-GFDL-
138 ESM2M. Two scenarios (RCP 4.5 and RCP 8.5) were assessed for each climate model. We
139 corrected the differences for the temperatures between EURO-CORDEX projections and
140 recorded data using the European observation (E-OBS) gridded temperature dataset with 0.25°
141 resolution (v.14; Haylock et al., 2008). For the bias correction, we calculated the average
142 anomaly grid as the mean temperature difference between the E-OBS and regional climate
143 model datasets for 1978-2005. Gridded annual chill accumulation values were then calculated
144 for the datasets (E-OBS, MOHC-HadGEM2_ES and NOAA-GFDL-GFDL-ESM2M), after
145 adding the anomaly grid to the RCM datasets.

146 Hourly temperatures were generated for the three climate datasets using the R package chillR
147 (Luedeling 2018) which uses a sine curve and a logarithmic function for day-time and night-
148 time temperatures, respectively. Chill was then accumulated between October 1st and March
149 31st.

150 Safe winter chill (SWC; Luedeling et al., 2009b) was used to estimate future production risk in
151 Europe based on winter chilling conditions for each cultivar and for the two CR estimated using
152 the two methods. SWC is the amount of winter chill that can be reliably expected in 90% of all

153 years, or the 10th percentile of the dataset. Here this corresponds to the data within each of the
154 time periods analysed (1975-2005, 2026-2050, 2075-2100). This metric is meaningful to fruit
155 producers, because failure to meet chilling requirements in more than 10% of years is likely to
156 render production uneconomical (Luedeling et al. 2009a).

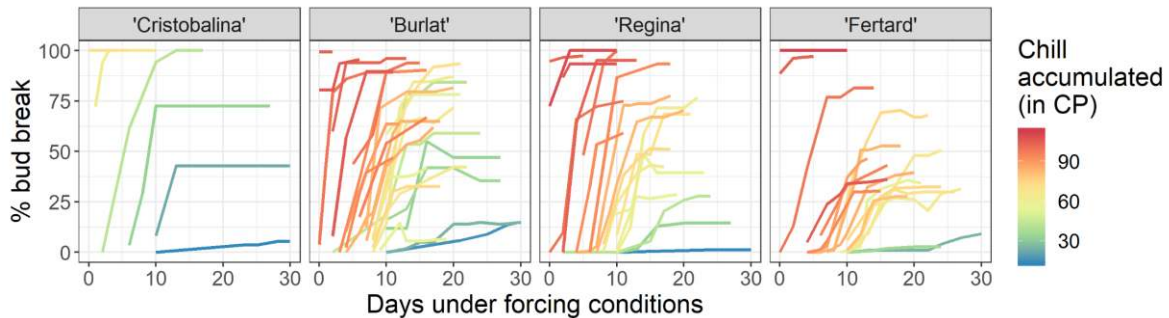


Fig. 2 Floral bud break percentage for the four cultivars with various field chill accumulation values (in chill portions). Note that no results for 'Cristobalina' were recorded for chill accumulation greater than 69 CP as bud burst had begun in the field.

157

158 **Results**

159 *Bud break percentage based on chill accumulation*

160 Evaluation of bud break response to accumulated chill in the field prior to cuttings revealed that
161 low - but not nil - bud break percentages were observed for branches that had been sampled in
162 the early season (mid-November; Fig. 2). These results suggest that early ('Cristobalina') and
163 mid-flowering ('Burlat') cultivars could slightly respond (i.e. less than 5% bud burst) to forcing
164 temperatures after accumulating only 13 CP. The rate of bud break percentage increased as
165 more chill was accumulated in the field. Using 'Burlat' as an example, bud break percentage
166 increase markedly faster for branches that accumulated at least 90 CP than for branches sampled
167 earlier during chill accumulation (e.g. 32 CP). The maximum bud break percentage, illustrated
168 by the plateau for each line, (Fig. 2) also increased with more chill accumulation. These results
169 indicate that the amount of accumulated chill primarily drives bud break percentages as the
170 buds were all exposed the same amount of time to forcing temperatures (Fig. 2).
171 The response of bud break percentage to accumulated chill notably differ between cultivars.

172 For example, the early flowering cultivar ‘Cristobalina’ (i.e. low-chill cultivar) was found to
 173 have higher bud break potential (45% bud break) after low levels of accumulated chill (32 CP)
 174 whereas the late flowering (i.e. high-chill cultivar) cultivar ‘Regina’ only reached 14.5% bud
 175 break after accumulating 32 CP. For the late flowering cultivars to meet the equivalent 45%
 176 bud break, 53 CP and 65 CP were needed for ‘Regina’ and ‘Fertard’, respectively. We also
 177 observed this pattern for the capacity to reach high bud break percentage. After accumulating
 178 40 CP, ‘Cristobalina’ and ‘Burlat’ reached 100% and 84% bud break, respectively, whereas the
 179 late flowering cultivars (‘Regina’ and ‘Fertard’) only reached 28% and 16% bud break,
 180 respectively (Fig. 3, Fig. S1).

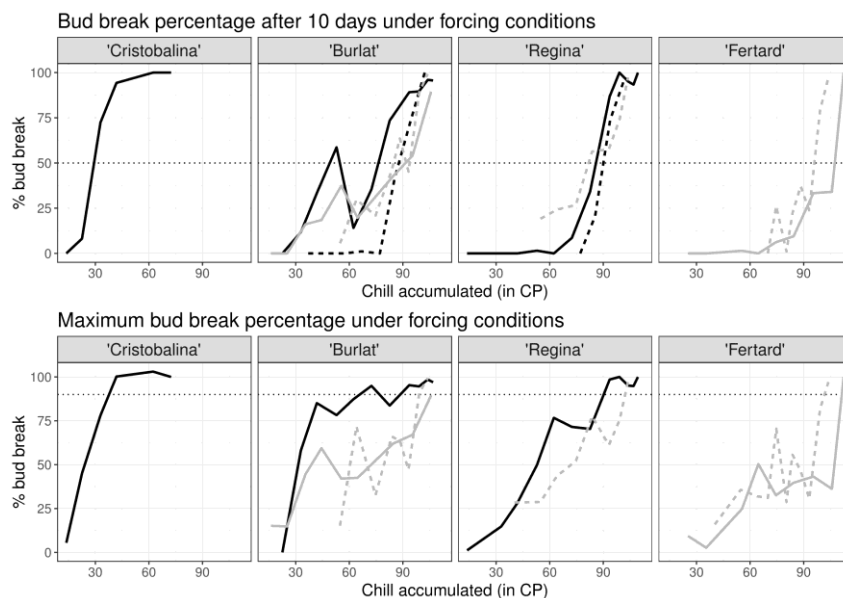


Fig. 3 Bud break data used to calculate CR-50% and CR_m-90%. Upper panel: bud break percentage after 10 days under forcing conditions; lower panel: maximal bud break percentage reached under forcing conditions. Horizontal dotted lines represent the 50% and 90% thresholds for CR-50% and CR_m-90% respectively. Black and grey lines represent data for cultivars grown in Bourran and Toulence, respectively. Solid lines are for 2015-2016 data while dashed lines are for 2016-2017 data

181

182 *Chilling requirement estimation*

183 Chilling requirement values calculated using the common approach (CR-50%) were highly
 184 variable between years (Fig. 3, Table 1). The CR range calculated using a 90% bud break
 185 threshold (CR_m-90%) were less variable.

186 Taking the average chill accumulation to reach 50% and 90% bud break, CR for each cultivar
 187 were estimated (Table 1). CR differs with cultivar and by the method used to evaluate it but the
 188 CR estimated by CR_m-90% are all higher than CR-50%.

189

Table 1 Chill requirement values (CP) between the four cultivars and the method used to calculate CR. Bold values are the mean CR recorded.

	CR-50%	CR _m -90%
'Cristobalina'	29 CP	42 CP
'Burlat'	77, 86, 89, 91 CP (86 CP)	94, 99, 106 CP (92 CP)
'Regina'	82, 85, 90 CP (86 CP)	94, 104 CP (99 CP)
'Fertard'	96, 105 CP (101 CP)	104, 112 CP (108 CP)

190

191 *Future risk due to insufficient chill*

192 Estimation of the risk of insufficient chill accumulation across Europe based on the two
 193 methods to determine CR (Table 1) exposed areas potentially unsuitable for the cultivation of
 194 each sweet cherry cultivar (Figs 4, 5, S2 and S3). We focused on MOHC-HadGEM2-ES, rcp8.5,
 195 projecting the highest increase in temperatures (most pessimistic; Fig. 4) and NOAA-GFDL-
 196 GFDL-ESM2M, rcp4.5, projecting the lowest increase in temperatures (optimistic; Fig. 5).
 197 Areas defined in Figures 4 and 5 reveal that for the four cultivars, the regions at risk of not
 198 meeting CR increase substantially by 2075-2100 using both estimations of CR (CR-50% and
 199 CR_m-90%). The area at risk is larger for CR_m-90% than for CR-50% for both scenarios. Areas
 200 coloured in pink, show the areas that meet CR according to CR-50% but not according to CR_m-
 201 90% (Figs 4 and 5). Therefore, these pink areas show the difference of estimated risk of
 202 insufficient chill depending on the method used to define CR. The difference in risk based on
 203 CR methodology is particularly evident for the high-chill cultivar 'Regina'. Under both climate

204 scenarios, a large area of Europe will not meet CR_m-90% whereas using CR-50% a much
205 smaller area of risk was found (Figs 4 and 5).

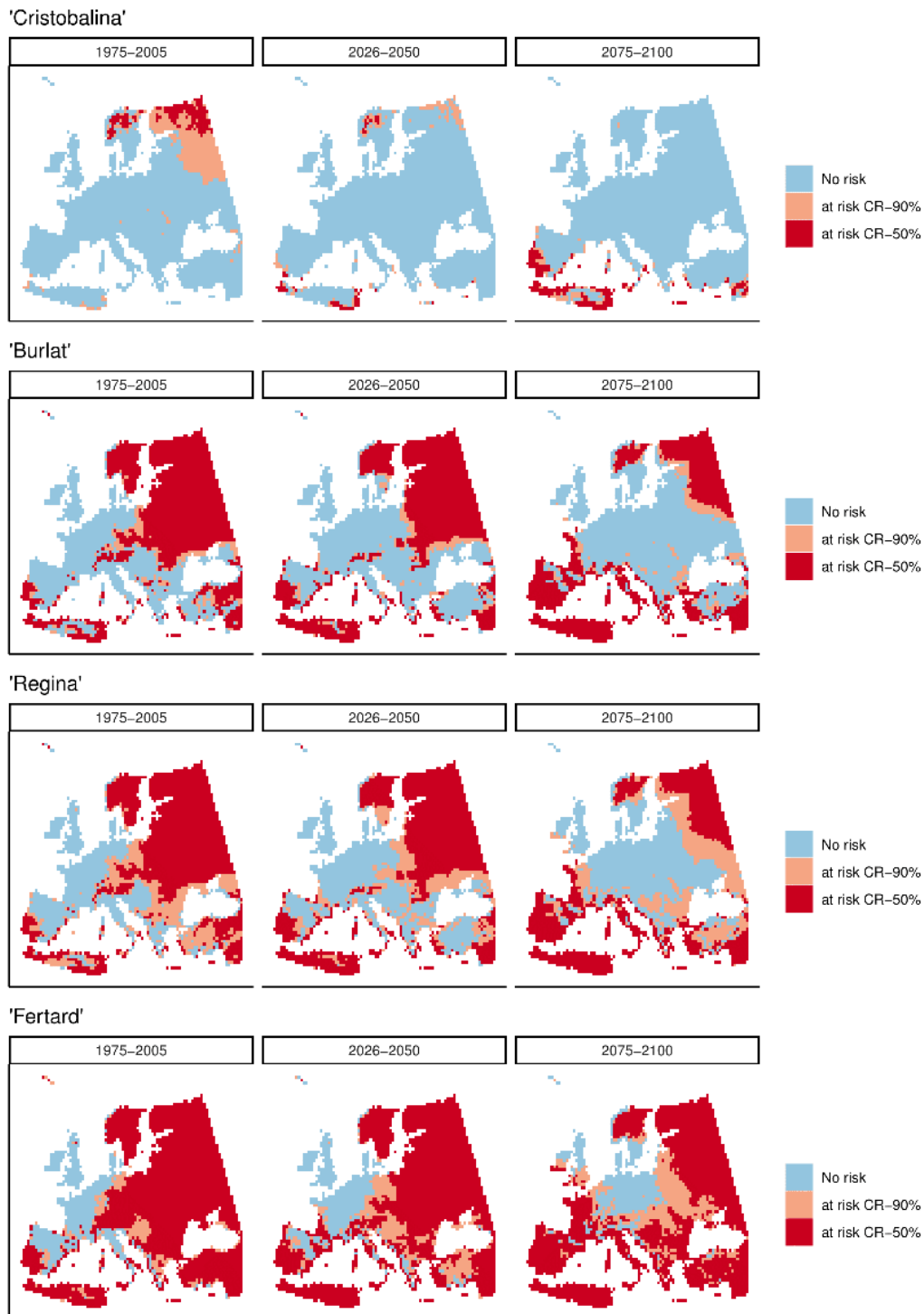


Fig. 4 Maps of Europe showing where safe winter chill (10th percentile) will not meet chilling requirements as estimated by forcing experiments (CR-50%; red areas) and by optimal bud break rate (CR_m-90%; pink and red areas) for the four cultivars. Blue indicates CR will be met for both CR values. Thresholds for the chilling requirements calculated in Table1 were used. Scenario MOHC-HadGEM2-ES, rcp8.5, projects the highest increase in temperatures (most pessimistic)

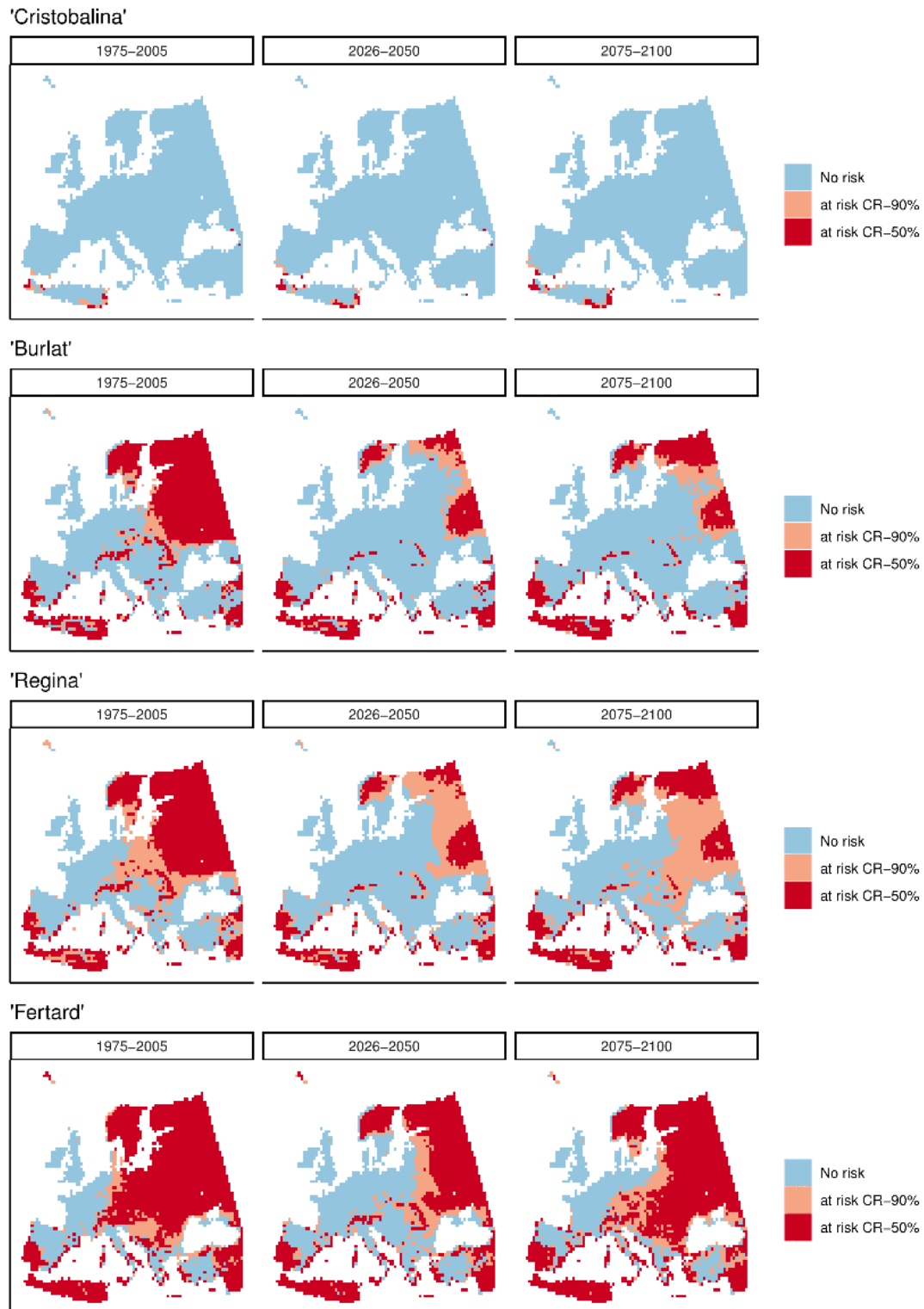


Fig. 5 Maps of Europe showing where safe winter chill (10th percentile) will not meet chilling requirements as estimated by forcing experiments (CR-50%; red areas) and by optimal bud break rate (CRm-90%; pink and red areas) for the four cultivars. Blue indicates CR will be met for both CR values. Thresholds for the chilling requirements calculated in Table1 were used. Scenario NOAA-GFDL-GFDL-ESM2M, rcp4.5, projects the lowest increase in temperatures (most optimistic)

207 **Discussion**

208 *Bud break percentage in response to chill accumulation*

209 We evaluated bud break responses to various levels of chill accumulation in the field using
210 forcing experiments on cultivars with contrasting chill requirements. The rate of bud break
211 gradually increased with accumulated chill in the field, thus confirming that chill primarily
212 drives the capacity of the buds to burst. Greater chill accumulation increased the maximum bud
213 break percentage but with a different maximum response between cultivars (Fig. 3). Overall,
214 the results indicate that the amount of accumulated chill can substantially limit the percentage
215 of bud break even under optimal growth conditions (Fig. S1). This is especially true for the
216 early flowering cultivar ‘Cristobalina’ which shows a very strict control of bud break percentage
217 by the amount of chill accumulated with limited effect of heat accumulation (Fig. 4; Fig. S1).
218 In addition, according to our data, there is a limit to the effect of heat on the bud break
219 percentage. When bud break percentages were considered as a response to chill and heat
220 accumulation (Fig. S1), results suggest that for a given chill accumulation bud break might
221 never reach 100%. For example, bud break percentage in ‘Regina’ fails to reach 60% if chill
222 accumulation is under 60 CP regardless of the level of heat accumulated. This provides a clear
223 chill requirement limit on maximum bud break percentage.

224 The interaction of chilling with heat requirements and bud break was also shown in different
225 temperate *Rosaceae*: cherry (Measham et al. 2017), peach (Couvillon and Erez 1985; Okie and
226 Blackburn 2011), sour cherry (Felker and Robitaille 1985), apple (Powell 1986) and pear
227 (Spiegel-Roy and Halston 1979); and in a notable group of forest species (Laube et al. 2014).
228 This interaction has been associated to a ‘residual effect of dormancy’ (Erez 2000), a parameter
229 indicating the distance to optimal chilling, and therefore, productivity (Okie and Blackburn
230 2011). This term is used when crops show symptoms of insufficient chilling (e.g. light bud
231 break or fruit set and uneven foliation) even after satisfaction of their CR, usually corresponding

232 to CR-30% or CR-50% (Campoy et al. 2011). Therefore, increasing the required bud break
233 percentage when assessing CR will provide a more reliable measure of CR which should
234 minimise productivity problems associated with the ‘residual effect of dormancy’ for new
235 growing areas and improve commercial viability. Other studies that have calculated CR for
236 species that set yield potential based on flower numbers (e.g. almond; Egea et al. 2003), may
237 also consider recalculation of CR based on a commercial bud break requirement to assist with
238 current and future industry planning.

239

240 *Chilling requirement calculation*

241 The chill accumulation necessary to reach 90% (CR_m-90%) of flower bud break was found to
242 be higher than the chilling requirements estimated with the common forcing method (CR-50%)
243 as shown in Table 1. This reflects that the traditional assessment of chilling requirements may
244 underestimate the CR needed to reach commercial productivity in sweet cherry. It would not
245 be advisable to choose CR-100% (100% bud break in the controlled environments) as a small
246 percentage (i.e. 10%) allows for a buffer for minor physiological problems or accidental bud
247 drop during the manipulation of plant material on growth chambers.

248 The potential underestimation of CR due to experimental design may be trivial for temperate
249 areas characterised by cold winters, where chill accumulation in the field normally exceeds the
250 CR of all cultivars with both CR-50% and CR_m-90% easily achieved. For locations with more
251 marginal chill accumulation, assessments of suitability based on CR-50% instead of CR_m-90%
252 will likely have a more significant impact. The underestimation of CR could lead to
253 unexpectedly higher frequency and severity of productivity problems due to insufficient
254 chilling fulfilment. This will be particularly applicable to low-chill cultivars that are grown in
255 mild winter climates which are usually oriented to the profitable early-market (Egea et al. 2010).

256 Values for both CR-50% and CR_m-90% were highly variable between years and sites, although
257 less variable for CR_m-90%. Similar variability was been reported for sweet cherry in Australia
258 (Measham et al. 2017) and apricot in Spain and South Africa (Campoy et al. 2012). This
259 variability in CR estimation should be appreciated when considering production risk. One
260 potential source of variability in recorded CR is the chill model that we used in the analysis.
261 Indeed, the Dynamic model, used here to quantify chilling, was developed for Mediterranean
262 regions, and therefore may not be suitable for colder climates. However, past studies have
263 shown that, regardless of the climatic conditions, the Dynamic model is currently the most
264 accurate model to use for predicting chill requirements (Luedeling et al. 2011; Luedeling 2012).
265 Further investigation will be necessary to evaluate the accuracy of the model to ensure the
266 robustness of our analysis and predictions. This line of enquiry would similarly benefit other
267 assessments of CR in small fruit temperate species such as sweet cherry (Albuquerque et al.
268 2008) or almond (Egea et al. 2003) and projections of winter chill (Luedeling et al. 2011). It
269 would also be valuable to better understand the source of plasticity in bud responses to cold in
270 order to improve chill models for contrasted climatic conditions.

271

272 *Future production risk due to insufficient chill*

273 The projections of chill accumulation provide new evidence of climate change risks for the
274 cultivation of sweet cherry across Europe. Risk of insufficient chill accumulation increased with
275 the chilling requirement of the cultivar and the method used to calculate it (CR-50% or CR_m-
276 90%). In the Mediterranean basin (a marginal chill area), only extra-low chill cultivars, such as
277 ‘Cristobalina’, were found suitable across the 21st century. However, for high-chill cultivars,
278 suitable areas were restricted and almost the whole of the continental Europe recorded risk,
279 especially using the CR_m-90% estimation (Figs. 4 and 5). These results highlighting CR
280 underestimation compounded by warming winters provide a warning message concerning the

281 sustainability of sweet cherry production in Europe and provide a case for breeders to develop
282 cultivars adapted to the upcoming climatic conditions. This is especially pertinent for species
283 for which no low-chill cultivars have been bred so far, such as sweet cherry and apricot.

284 Adaptation options other than new cultivars or new growing regions are currently available to
285 growers. In particular, dormancy breaking agents can be used to compensate for insufficient
286 chilling (Erez 2000). Greater understanding of these agents' ability to compensate for
287 insufficient chill under climate change is required to understand if these provide an enduring
288 adaptation strategy. Reliance on these products may not be a sustainable option with regulations
289 in recent years restricting product allowable (e.g. Dormex®).

290 These projections were made using two GCMs. Ideally, a full ensemble of models would be
291 used to assess potential impact (e.g. CMIP 5; Taylor et al. 2012)). Here, we used two models
292 among the limited set available with data for this assessment (projections with daily temperature
293 data). For the purposes of this assessment, this was sufficient to illustrate changes in risk based
294 on CR definitions and a greater set of scenarios may be used to further explore the risk analysis.
295 Furthermore, this analysis used gridded temperature data that may not always be representative
296 of microclimates within orchards and as such, thus these risk projection results should be
297 considered a guide only.

298

299 *Climate change: a shift in growing areas and cultivars.*

300 For the most pessimistic climate scenario (Fig. 4), the projections show notable risk for chill
301 fulfilment of high chill cultivars in areas currently considered as sufficiently cold, i.e. Greece,
302 Italy, France and British Isles. This highlights that high chill cultivars will need to be replaced
303 with lower chill cultivars. However, these cultivar replacements need to be considered within
304 the wider agri-climate setting. For example, cultivars with lower chill requirements tend to be
305 characterised by earlier flowering dates, especially under warming spring temperatures and may

306 therefore be at higher risk of early-season frost damage (Bigler and Bugmann 2018; Vitasse et
307 al. 2018). Selection of appropriate cultivars therefore require a wider risk assessment to avoid
308 maladaptation.

309 Interestingly, new areas suitable for cultivars with relatively high chill requirements appear in
310 North-Eastern Europe by the end the century. This result stems from experiments which
311 indicated temperatures below 0 to -2°C are not effective for chill accumulation as they might
312 inhibit all cellular functions and this low temperature restriction has been included in most
313 models of chil (e.g. (Richardson et al. 1974; Fishman et al. 1987; Hänninen 1990).
314 Consequently, current climatic conditions that are too cold to satisfy chill requirements,
315 according to current understanding of chill accumulation, will improve in suitability for chill
316 accumulation and illustrates new production areas suitable for fruit tree cultivation. Again, other
317 agri-climate risks (e.g. frost risk, water availability) need to be evaluated prior to establishing
318 new growing regions.

319 Overall, this paper reveals that the method used to assess chilling requirements does have an
320 important impact on assessments of the regional and cultivar suitability of sweet cherry. To
321 more broadly understand the risk warming will pose to crops that need a high bloom load for
322 profitability we propose the evaluation of chilling requirements using higher percentages of bud
323 break (around 90%) over a longer period under forcing conditions. This approach should be
324 undertaken to assess chilling requirements for the evaluation of new cultivars. These findings
325 can help inform selections made by breeders to develop climate adapted cultivars and for
326 growers to better understand current and future production risk in current and new growing
327 areas.

328

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339 projection data.

340

341 **References**

- 342 Albuquerque N, Garc ıa-Montiel F, Carrillo A, Burgos L (2008) Chilling and heat requirements
343 of sweet cherry cultivars and the relationship between altitude and the probability of
344 satisfying the chill requirements. *Environ Exp Bot* 64:162–170. doi:
345 10.1016/j.envexpbot.2008.01.003
- 346 Andreini L, de Cort azar-Atauri IG, Chuine I, et al (2014) Understanding dormancy release in
347 apricot flower buds (*Prunus armeniaca* L.) using several process-based phenological
348 models. *Agric For Meteorol* 184:210–219. doi: 10.1016/j.agrformet.2013.10.005
- 349 Azizi Gannouni T, Campoy JA, Quero-Garc ıa J, et al (2017) Dormancy related traits and
350 adaptation of sweet cherry in Northern Africa: A case of study in two Tunisian areas. *Sci*
351 *Hortic (Amsterdam)* 219:272–279. doi: 10.1016/j.scienta.2017.03.013
- 352 Bennet J (1949) Temperature and bud rest period. *Calif Agric* 3:9–12
- 353 Bigler C, Bugmann H (2018) Climate-induced shifts in leaf unfolding and frost risk of European
354 trees and shrubs. *Sci Rep* 8:1–10. doi: 10.1038/s41598-018-27893-1
- 355 Campoy JA., Ruiz D, Egea J (2011) Dormancy in temperate fruit trees in a global warming
356 context: A review. *Sci Hortic (Amsterdam)* 130:357–372. doi:
357 10.1016/j.scienta.2011.07.011
- 358 Campoy JA, Ruiz D, Allderman L, et al (2012) The fulfilment of chilling requirements and the
359 adaptation of apricot (*Prunus armeniaca* L.) in warm winter climates: An approach in
360 Murcia (Spain) and the Western Cape (South Africa). *Eur J Agron* 37:43–55. doi:
361 10.1016/j.eja.2011.10.004
- 362 Cast ede S, Campoy JA, Quero-Garc ıa J, et al (2014) Genetic determinism of phenological traits
363 highly affected by climate change in *Prunus avium*: flowering date dissected into chilling
364 and heat requirements. *New Phytol* 202:703–15. doi: 10.1111/nph.12658
- 365 Chmielewski FM, G otz KP (2016) Performance of models for the beginning of sweet cherry
366 blossom under current and changed climate conditions. *Agric For Meteorol* 218–219:85–
367 91. doi: 10.1016/j.agrformet.2015.11.022
- 368 Chuine I, Bonhomme M, Legave JM, et al (2016) Can phenological models predict tree
369 phenology accurately in the future? The unrevealed hurdle of endodormancy break. *Glob*
370 *Chang Biol* 22:3444–3460. doi: 10.1111/gcb.13383
- 371 Cook NC, Calitz FJ, Allderman LA, et al (2017) Diverse patterns in dormancy progression of

- 372 apple buds under variable winter conditions. *Sci Hort* 226:307–315. doi:
373 10.1016/j.scienta.2017.08.028
- 374 Couvillon GA, Erez A (1985) Influence of prolonged exposure to chilling temperatures on bud
375 break and heat requirement for bloom of several fruit species. *J Am Soc hort Sci* 110:47–
376 50
- 377 Dantec CF, Vitasse Y, Bonhomme M, et al (2014) Chilling and heat requirements for leaf
378 unfolding in European beech and sessile oak populations at the southern limit of their
379 distribution range. *Int J Biometeorol* 58:1853–1864. doi: 10.1007/s00484-014-0787-7
- 380 Dennis F (2003) Problems in standardizing methods for evaluating the chilling requirements
381 for the breaking of dormancy in buds of woody plants. *Hort Sci* 38:347–350
- 382 Egea J, Ortega E, Martinez-Gomez P, Dicenta F (2003) Chilling and heat requirements of
383 almond cultivars for flowering. *Environ Exp Bot* 50:79–85
- 384 Egea J, Rubio M, Campoy JA, et al (2010) “Mirlo Blanco”, “Mirlo anaranjado”, and “Mirlo
385 Rojo”: Three new very early-season apricots for the fresh market. *HortScience* 45:1893–
386 1894
- 387 Erez A (2000) Bud Dormancy; Phenomenon, Problems and Solutions in the Tropics and
388 Subtropics. In: *Temperate Fruit Crops in Warm Climates*. pp 17–48
- 389 Erez A, Couvillon GA (1987) Characterization of the moderate temperature effect on peach bud
390 rest. *J Am Soc hort Sci* 112:677–680
- 391 Fadón E, Herrero M, Rodrigo J (2015) Flower development in sweet cherry framed in the
392 BBCH scale. *Sci Hort* (Amsterdam) 192:141–147. doi: 10.1016/j.scienta.2015.05.027
- 393 Felker FC, Robitaille HA (1985) Chilling accumulation and rest of sour cherry flower buds. *J*
394 *Am Soc Hort Sci* 110:227–232
- 395 Fishman S, Erez A, Couvillon GA (1987) The temperature dependence of dormancy breaking
396 in plants: Mathematical analysis of a two-step model involving a cooperative transition. *J*
397 *Theor Biol* 124:473–483. doi: 10.1016/S0022-5193(87)80221-7
- 398 Götz KP, Chmielewski FM, Gödeke K, et al (2017) Assessment of amino acids during winter
399 rest and ontogenetic development in sweet cherry buds (*Prunus avium* L.). *Sci Hort*
400 (Amsterdam) 222:102–110. doi: 10.1016/j.scienta.2017.05.001
- 401 Guo L, Dai J, Ranjitkar S, et al (2013) Response of chestnut phenology in China to climate
402 variation and change. *Agric For Meteorol* 180:164–172. doi:
403 10.1016/j.agrformet.2013.06.004
- 404 Guy R (2014) The early bud gets to warm. *New Phytol* 202:7–9. doi: 10.1111/nph.12728
- 405 Hänninen H (1990) Modelling bud dormancy release in trees from cool and temperate regions.
406 *Acta For. Fenn.* 213:1–47
- 407 Harrington CA., Gould PJ, St.Clair JB (2010) Modeling the effects of winter environment on
408 dormancy release of Douglas-fir. *For Ecol Manage* 259:798–808. doi:
409 10.1016/j.foreco.2009.06.018
- 410 Hauagge R, Cummins JN (1991) Seasonal variation in intensity of bud dormancy in apple
411 cultivars and related *Malus* species. *J Am Soc Hort Sci* 116:107–115
- 412 Haylock MR, Hofstra N, Klein Tank AMG, et al (2008) A European daily high-resolution
413 gridded data set of surface temperature and precipitation for 1950–2006. *J Geophys Res*
414 *Atmos* 113:D20119. doi: 10.1029/2008JD010201
- 415 Jacob D, Petersen J, Eggert B, et al (2014) EURO-CORDEX: New high-resolution climate

- 416 change projections for European impact research. *Reg Environ Chang* 14:563–578. doi:
417 10.1007/s10113-013-0499-2
- 418 Lang G, Early J, Martin G, Darnell R (1987) Endo-, para-, and ecodormancy: physiological
419 terminology and classification for dormancy research. *Hort Sci* 22:371–377
- 420 Laube J, Sparks TH, Estrella N, et al (2014) Chilling outweighs photoperiod in preventing
421 precocious spring development. *Glob Chang Biol* 20:170–82. doi: 10.1111/gcb.12360
- 422 Luedeling E (2018) chillR: Statistical Methods for Phenology Analysis in Temperate Fruit
423 Trees. R package version 0.70.6
- 424 Luedeling E (2012) Climate change impacts on winter chill for temperate fruit and nut
425 production: A review. *Sci Hortic* 144:218–229. doi: 10.1016/j.scienta.2012.07.011
- 426 Luedeling E, Gassner A (2012) Partial Least Squares Regression for analyzing walnut
427 phenology in California. *Agric For Meteorol* 158–159:43–52. doi:
428 10.1016/j.agrformet.2011.10.020
- 429 Luedeling E, Girvetz EH, Semenov MA, Brown PH (2011) Climate change affects winter chill
430 for temperate fruit and nut trees. *PLoS One* 6:. doi: 10.1371/journal.pone.0020155
- 431 Luedeling E, Guo L, Dai J, et al (2013a) Differential responses of trees to temperature variation
432 during the chilling and forcing phases. *Agric For Meteorol* 181:33–42. doi:
433 10.1016/j.agrformet.2013.06.018
- 434 Luedeling E, Kunz A, Blanke MM (2013b) Identification of chilling and heat requirements of
435 cherry trees—a statistical approach. *Int J Biometeorol* 57:679–89. doi: 10.1007/s00484-012-
436 0594-y
- 437 Luedeling E, Zhang M, Girvetz EH (2009a) Climatic changes lead to declining winter chill for
438 fruit and nut trees in California during 1950–2099. *PLoS One* 4:. doi:
439 10.1371/journal.pone.0006166
- 440 Luedeling E, Zhang M, Luedeling V, Girvetz EH (2009b) Sensitivity of winter chill models for
441 fruit and nut trees to climatic changes expected in California’s Central Valley. *Agric*
442 *Ecosyst Environ* 133:23–31. doi: 10.1016/j.agee.2009.04.016
- 443 Measham PF, Darbyshire R, Turpin SR, Murphy-White S (2017) Complexity in chill
444 calculations: A case study in cherries. *Sci Hortic* 216:134–140. doi:
445 10.1016/j.scienta.2017.01.006
- 446 Okie WR, Blackburn B (2011) Increasing chilling reduces heat requirement for floral budbreak
447 in peach. *HortScience* 46:245–252
- 448 Petri JL, Leite GB (2004) Consequences of Insufficient Winter Chilling on Apple Tree Bud-
449 break. *Acta Hortic* 662:53–60
- 450 Powell LE (1986) The chilling requirement in apple and its role in regulating time of flowering
451 in spring in cold-winter climates. *Acta Hortic* 179:1–11
- 452 Richardson E, Seeley SD, Walker D (1974) A model for estimating the completion of rest for
453 Redhaven and Elberta peach trees. *Hort Sci* 9:331–332
- 454 Ruiz D, Campoy JA, Egea J (2007) Chilling and heat requirements of apricot cultivars for
455 flowering. *Environ Exp Bot* 61:254–263. doi: 10.1016/j.envexpbot.2007.06.008
- 456 Samish RM (1953) Dormancy in woody plants. *Annu Rev Plant Physiol* 5:183–204. doi:
457 10.1146/annurev.pp.05.060154.001151
- 458 Sánchez-Pérez R, Dicenta F, Martínez-Gómez P (2012) Inheritance of chilling and heat
459 requirements for flowering in almond and QTL analysis. *Tree Genet Genomes* 8:379–389.

- 460 doi: 10.1007/s11295-011-0448-5
- 461 Saure M (1985) Dormancy release in deciduous fruit trees. *Hortic Rev (Am Soc Hortic Sci)*
- 462 7:239–299
- 463 Spiegel-Roy P, Halston FH (1979) Chilling and Post-Dormant Heat Requirement as Selection
- 464 Criteria for Late-Flowering Pears. *J Hortic Sci* 54:115–120
- 465 Tabuenca M (1967) Necesidades de frio invernal de variedades deciruelo. *An Aula Dei* 8:383–
- 466 391
- 467 Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design.
- 468 *Bull Am Meteorol Soc* 93:485–498. doi: 10.1175/BAMS-D-11-00094.1
- 469 Vitasse Y, Basler D (2014) Is the use of cuttings a good proxy to explore phenological responses
- 470 of temperate forests in warming and photoperiod experiments? *Tree Physiol* 34:174–83.
- 471 doi: 10.1093/treephys/tpt116
- 472 Vitasse Y, Schneider L, Rixen C, et al (2018) Increase in the risk of exposure of forest and fruit
- 473 trees to spring frosts at higher elevations in Switzerland over the last four decades. *Agric*
- 474 *For Meteorol* 248:60–69. doi: 10.1016/j.agrformet.2017.09.005
- 475 Viti R, Andreini L, Ruiz D, et al (2010) Effect of climatic conditions on the overcoming of
- 476 dormancy in apricot flower buds in two Mediterranean areas: Murcia (Spain) and Tuscany
- 477 (Italy). *Sci Hortic* 124:217–224. doi: 10.1016/j.scienta.2010.01.001
- 478 Viti R, Bartolini S, Andreini L (2008) Apricot Flower Bud Development : Main Biological ,
- 479 Physiological and Environmental Aspects Related to the Appearance of Anomalies. *Int J*
- 480 *Plant Dev Biol* 2:25–34
- 481 Vitra A, Lenz A, Vitasse Y (2017) Frost hardening and dehardening potential in temperate trees
- 482 from winter to budburst. *New Phytol* 216:113–123. doi: 10.1111/nph.14698
- 483 Weinberger J (1950) Chilling requirements of peach varieties. *Proc Am Soc Hortic Sci* 56:122–
- 484 128
- 485