



**Title:** Spatial heterogeneity in the timing of birch budburst in response to future climate warming in Ireland

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1 **Spatial heterogeneity in the timing of birch budburst in response to future climate warming in**  
2 **Ireland**

3  
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14

15 **Abstract**

16 In order to predict the impact of future climate warming on trees it is important to quantify the effect climate has on  
17 their development. Our understanding of the phenological response to environmental drivers has given rise to various  
18 mathematical models of the annual growth cycle of plants. These models simulate the timing of phenophases by  
19 quantifying the relationship between development and its triggers, typically temperature. In addition, other  
20 environmental variables have an important role in determining the timing of budburst. For example, photoperiod has  
21 been shown to have a strong influence on phenological events of a number of tree species, including *Betula pubescens*  
22 (birch). A recently developed model for birch (DORMPHOT), which integrates the effects of temperature and  
23 photoperiod on budburst, was applied to future temperature projections from a 19-member ensemble of regional  
24 climate simulations (on a 25km grid) generated as part of the ENSEMBLES project, to simulate the timing of birch  
25 budburst in Ireland each year up to the end of the present century. Gridded temperature time series data from the  
26 climate simulations were used as input to the DORMPHOT model to simulate future budburst timing. The results  
27 showed an advancing trend in the timing of birch budburst over most regions in Ireland up to 2100. Interestingly, this  
28 trend appeared greater in the northeast of the country than in the southwest where budburst is currently relatively early.  
29 These results could have implications for future forest planning, species distribution modeling, and the birch allergy  
30 season.

31

32 **Keywords:** budburst, gradient, phenological modelling, DORMPHOT, ENSEMBLES project, Ireland

33

34 **Introduction**

35 Spring phenology in plants, especially budburst and leafing in trees, has been widely and successfully used as an  
36 indicator of climate warming across Europe (Chmielewski and Rötzer 2001; Donnelly et al. 2006; Carroll et al. 2009;  
37 Gleeson et al. 2013). These authors used historical data on the timings of key phenophases coupled with

38 meteorological data and have demonstrated a close correlation between rising spring temperature and early bud burst  
39 and leafing of temperate shrubs and trees, including birch. In addition to historical data more detailed experimental  
40 data from controlled environment chambers allows for the impact of a range of environmental conditions such as  
41 photoperiod, chilling and forcing temperatures on budburst to be quantified (Caffarra et al. 2011a). Together, these  
42 data have given rise to the development of various mathematical models of the annual growth cycle of plants (Chuine  
43 2000; Caffarra et al. 2011b) which can be used to simulate the timing of budburst, provided that input driving  
44 variables, such as temperature and photoperiod are available.

45 In recent years, a large number of modelling studies forecasting potential impacts of climate change on biological  
46 systems have been conducted to support adaptation and mitigation policies and to help understand possible  
47 implications of climate change-driven alterations to ecosystems (see, for example Alig et al. 2002; Kurz et al, 2008;  
48 Morin et al. 2008; Buisson et al, 2010; Caffarra et al. 2012). Future projections of the timing of budburst of a range of  
49 tree species are potentially useful in forest and horticultural planning and management decision making. For example,  
50 earlier budburst can result in a longer growing season which may result in greater timber production and greater  
51 carbon sequestration. However, on the other hand, earlier budburst can leave trees vulnerable to damage by late frosts  
52 which have the potential to result in economic loss if fruit trees or vines are vulnerable (Gu et al. 2008; Eccel et al.  
53 2009) . Changes in the timing of phenological events have the potential to influence many biological processes such as  
54 reproductive fitness and adaptation (Brachi et al. 2012; Donnelly et al. 2012), and may also play a role in determining  
55 future species distribution (Chuine and Beaubien, 2001). Phenological changes could thus result in significant changes  
56 in regional vegetation. Furthermore, Emberlin et al.(2002) reported a strong likelihood that the pollen season would  
57 begin earlier in the season as climate warms which would have obvious implications for hay-fever sufferers but more  
58 recent research reported a lack of change in the onset of the birch pollen season in the UK over a 15-year period  
59 (1995-2010) (Newnham et al. 2012), even though this could be due to the short period taken into consideration.  
60 However, the authors demonstrated a clear correlation between the timing of the birch pollen season and March  
61 temperature so presumably if spring temperature increased in future the pollen season could conceivably occur early.  
62 These slightly differing trends suggests care should be exercised when predicting changes in the birch pollen season in  
63 response to climate warming.

64 Trends in the start of the growing season (2003-2009) across Ireland derived from satellite data revealed a southwest to  
65 northeast pattern (O'Connor et al. 2012). The start of the growing season was, on average, earlier in the southwest  
66 compared to the northeast. These results give a reliable indication of the gradient in phenology across the country but  
67 are unable to differentiate between different species. Few studies have reported a spatial response in phenology to  
68 future climate warming using processed based phenological models driven with an ensemble of projected temperatures  
69 from a range of emissions scenarios. However, in a recent publication Chung et al. (2011) reported a greater advance  
70 in the timing of peak bloom dates of cherry blossom under a higher (A2) than a lower (A1B) emission scenario, using  
71 two global climate models (ECHAM5 (A1B) and CCCMA (A2)), for the Mid-Atlantic States in the USA. They found  
72 the advance in blooming time to be greatest at the later time period (2080). In addition, their future projections suggest  
73 that peak bloom will occur earlier along coastal areas than further inland possibly driven by greater warming along the  
74 coast.

75

76 Whereas model forecasting is widely used in climate research it is important to be aware of and attempt to characterize  
77 the range of uncertainty inherent in any future simulation. In particular, uncertainty derived from simulation of both  
78 the response (response model) and the future climate should be characterized (Buisson et al. 2010). Predictions of  
79 natural climate variability and human impact on climate are inherently probabilistic, for a number of reasons such as,  
80 uncertainties in the initial conditions of forecasts, representation of key processes within the models, and uncertainties  
81 in climatic forcing factors (e.g. greenhouse gases and aerosols) (Hewitt et al. 2004). Ensemble forecasting is widely  
82 used in medium range weather forecasting (e.g. Toth et al. 1993) as a means of trying to reduce forecast uncertainties  
83 (Zhang et al. 2010). At the European Centre for Medium Range Weather Forecasts, for example, the weather  
84 prediction model is run 51 times using slightly different initial conditions which are designed to represent the  
85 uncertainties inherent in the operational analysis (Richardson et al. 2001). A similar approach is used in climate  
86 modelling. For example, in the ENSEMBLES project (Van Der Linden and Mitchell, 2009) data from coarse global  
87 climate simulations, carried out under the IPCC 2007 A1B, A2 and B2 greenhouse gas scenarios, were statistically  
88 downscaled to a 25km grid over a European area using a suite of regional climate models (RCMs).

89 In Ireland, we have previously shown that the timing of birch budburst at 4 sites is occurring earlier now than 40 years  
90 ago but the trend was only statistically significant at one site (Donnelly et al. 2006; Gleeson et al. 2013). This may be  
91 because there was a large amount of missing data and the time series may not have been long enough for the trend to  
92 be statistically significant. The aims of the current work were to (a) simulate the timing of birch budburst using a range  
93 of future climate projections and (b) to determine any spatial variation in the timing of birch budburst across the island  
94 of Ireland up to the end of the 21<sup>st</sup> century. As in the south eastern coast of Ireland the timing of birch budburst on mild  
95 years is currently among the earliest recorded in the International Phenological Gardens (Caffarra et al 2011a), due to  
96 the generally mild winters of the region, additional warming during the winter might result in lack of chilling with a  
97 delaying effect on budburst rather than further advancing it. In order to determine if past trends will continue or  
98 inverse in future as temperatures continue to rise, we used a recently developed phenological model (DORMPHOT)  
99 for birch, which integrates the effects of temperature and photoperiod on the timing of budburst, together with future  
100 temperature output from an ensemble of 19 regional climate simulations.

101

## 102 **Materials and Methods**

### 103 *Phenological data*

104 The International Phenological Gardens (IPG) network in Ireland has four sites (Valentia Observatory (Co. Kerry),  
105 JFK Arboretum (Co. Wexford), Johnstown Castle (Co. Wexford) and the National Botanic Garden (Dublin)) with  
106 phenological data records extending as far back as the 1960s. Observers record and monitor phenophases such as  
107 budburst, flowering, leaf fall, etc. for a range of species including downy birch (*Betula pubescens*). For the purpose of  
108 this work we used the day of the year when birch budburst was recorded at Valentia Observatory (51.50 N, 10.25 W)  
109 from 1969 to 2012 (the 1994 record is missing).

110

### 111 *DORMPHOT model*

112 A process-based phenological model, DORMPHOT, was developed for *Betula pubescens* (Caffarra et al. 2011a, b).  
113 The model stems from the UNIFIED model (Chuine, 2000) and simulates the date of budburst of birch, taking into  
114 account the effect of temperature and photoperiod during the phases of dormancy induction, establishment and release.  
115 Daily temperature and photoperiod from September 1 of the year preceding budburst, when dormancy induction  
116 begins, are used as input for the model. Dormancy release occurs once the threshold number of chilling units has been  
117 accumulated. Budburst timing depends on the state of chilling (whether dormancy release has occurred or not) and on  
118 the photoperiod of each day. The DORMPHOT model considers the action of cool temperatures (chilling) for  
119 dormancy release, and the action of warm temperatures (forcing) for subsequent bud growth. It describes the  
120 phenological development in terms of developmental units, calculated through fitted or experimentally measured  
121 relationships. Chilling units are accumulated during the autumn-winter and gradually increase the effect of warm  
122 temperatures on the accumulation of forcing units. The effect of photoperiod is considered at two levels. Firstly, the  
123 photoperiod (in interaction with temperature) affects the course of dormancy induction and secondly modifies the  
124 response to temperature during the phase of forcing. Thus, this model considers (i) the dormancy induction process  
125 occurring in late summer-autumn as the plant ceases growth and develops dormant buds in response to short days and  
126 cool temperatures, (ii) the action of chilling temperatures for dormancy release, (iii) the promoting effect that long  
127 photoperiod has on bud development during dormancy release and bud development.

128 The model parameters were partly derived from previous experimental studies and partly calibrated using a large  
129 combined dataset, including observations taken randomly from 7 phenological stations from different European  
130 countries: Ireland (Valentia Observatory, Johnstown Castle and JFK arboretum), Germany, Switzerland and Norway.  
131 Once calibrated, the DORMPHOT model was validated and showed a good predictive performance, and therefore out-  
132 performed previous bud burst models for birch (Caffarra et al. 2011b). The model showed a good predicting  
133 performance at Irish stations with positive modelling efficiencies (0.24 and 0.54) and mean absolute errors (MAEs)  
134 ranging from 4.7 and 5.8 days. These were the lowest among the errors produced by comparison to a range of other  
135 phenological models (Spring Warming, Unified and Linear model) (Caffarra et al. 2011b). The Valentia Observatory  
136 dataset was used entirely for calibration and its observation series was mixed with data from the other stations  
137 employed in the study; for the Valentia-only portion of the dataset the modelling efficiency of the DORMPHOT model  
138 was 0.60 and the MAE was 5 days (Caffarra, unpublished results). Once calibrated, the model showed a low bias (0.2  
139 days on average) and its performance on years with warm winter-springs (warm year index as described by Caffarra et  
140 al 2011b) was similar to its performance on the whole dataset, i.e. about 4.9 days, which points to the fact that the  
141 model does not increase its bias on warm years. In fact, this model is suitable to account for the effect of warm  
142 conditions during winter-spring because it describes the effect of the interaction of chilling, photoperiod and forcing  
143 temperature on dormancy transition as opposed to taking into account only forcing temperatures in the spring.

144

#### 145 *Climate projections*

146 In this study future temperature projections from a suite of 19 regional climate simulations from the EU-ENSEMBLES  
147 project (Van Der Linden and Mitchell, 2009) were used. Details of the driving GCMs and RCMs used, as well as the  
148 time period covered by the simulations, are provided in table 1. The IPCC (Nakicenovic et al. 2000) A1B greenhouse

149 gas emission scenario was used in all but one of the simulations, which employed the less extreme A2 scenario. In  
150 brief, the A1B emission scenario represents rapid economic growth, relatively stable population growth,  
151 interconnected world and a balance of all energy sources whereas the A2 scenario represents an increasing population  
152 in a world of independent nations with regional economic development (IPCC 2007). Daily mean temperatures were  
153 computed from daily maximum and daily minimum temperature data generated by the RCMs. For the historical period  
154 1961-1990, the mean temperature bias over Ireland for the model ensemble relative to the EOBS version 7.0 gridded  
155 dataset (Haycock et al. 2008) was -0.5 degrees (range of biases -2.1 to 0.4 degrees). Relative to the reference period  
156 1961-1990, daily mean temperatures over Ireland are projected to increase by 1.1 degrees by the period 2021-2050 and  
157 by 2.3 by 2071-2100. Therefore, the range of projected changes exceeds the ensemble mean biases compared to  
158 EOBS.

159

#### 160 *Model validation*

161 The climate models and the phenological model used in this study had already been tested in previous studies (Van  
162 Der Linden and Mitchell, 2009; Caffarra et al. 2011b). However, in order to increase the confidence in the projected  
163 trends we compared their combined average outputs with observations recorded at Valentia Observatory, where a long  
164 time series of observations was available. More precisely, we compared the average date of budburst observed at  
165 Valentia Observatory for the reference period 1969-2012 with that obtained by running the model on past observed  
166 temperatures at Valentia (phenological model applied to observed temperatures) and with that obtained by running the  
167 DORMPHOT model using temperature data at the Valentia Observatory location from the RCM ensemble for the  
168 reference period (phenological model applied to climate model data). In this last case, we calculated the average date  
169 of budburst at Valentia Observatory for each model output, and then averaged them to obtain a single statistic.

170

#### 171 *Geographical Information Systems techniques*

172 As one of the purposes of this study was to evaluate spatial variation in future budburst timing, the DORMPHOT  
173 model was implemented in the R statistical software to take full advantage of the spatial data structures available in its  
174 Geographical Information System (GIS) extensions. We obtained a “spatially enabled” DORMPHOT model that we  
175 run over Ireland. Gridded temperature datasets were imported into GIS with the raster package (Hijmans et al., 2013).  
176 All input and output data were projected on the WGS84 geodetic datum. To handle the 360 days calendar, used in  
177 some of the climate simulations, we coupled the packages *cdo*, *PCICt* (Bronaugh et al., 2013) and *lubridate*  
178 (Groenlund et al. 2011) to correctly remap the model inputs to dates in the Gregorian calendar. The *geosphere*  
179 package (Hijmans et al. 2012) was used to calculate the photoperiod data for each day of the year.

180 The DORMPHOT model was then run using the gridded daily temperature data from the 19 member ensemble of  
181 regional climate simulations, to calculate the means of the budburst date.

182

#### 183 *Statistical analysis*

184 The outputs from the spatially enabled DORMPHOT are on the same 25km grid as the input climate data for each of  
185 the 19 climate simulations. Budburst day was simulated for each cell, ensemble input and year. Subsequently, the

186 mean, 5<sup>th</sup> and 95<sup>th</sup> percentiles were calculated for each cell over the following decades 1990 – 1999 (recent past,  
187 baseline decade), 2030-2039 (near future), 2080-2089 (far future). Mean temperatures for autumn-winter temperatures  
188 (1 September to 31 March of the following year) obtained in the same way for the same decades, are shown in the  
189 three maps in Figure 1. The change in autumn-winter temperatures between the baseline decade (1990-1999) and the  
190 far future (2080-2089) is shown in the map in Figure 2. In this case the difference was calculated between mean  
191 temperatures of the baseline decade (1990-1999) and the far future (2080-2089), rather than as the mean of differences  
192 between ensemble outputs.

193 Changes in the mean budburst date for the 2 future decades were calculated relative to the 1990s. The trends in the  
194 timing of budburst were calculated for two time spans: 1990 – 2050 and 1990 – 2100, by fitting linear models to the  
195 simulated budburst date in each cell (ensemble mean). Only 11 of the 19 models were used to calculate statistics for  
196 the 2080s because these were the only simulations which extended as far as the year 2100 (Table 1).

197 For the two sites that showed extreme changes over the projected period (northeast interior at 54.75 N, 7W with the  
198 maximum advance, and southwest coast 51.50 N, 10.25 W with maximum delay) we analysed the temporal trends in  
199 the timing of attainment of dormancy interphases (i.e. dormancy induction and chilling fulfillment) simulated by  
200 DORMPHOT. This analysis was performed in order to assess whether different budburst timing trends might be  
201 caused by differences in the timing of previously attained phenophases. In fact, according to the model structure,  
202 changes in the timing of a given dormancy interphase affect the timing of the start of the following phase, with obvious  
203 consequences on the timing of final budburst.

204

## 205 **Results**

### 206 *Validation of the combined DORMPHOT and climate models*

207 During the period 1969-2012 the average observed day of the year of birch budburst at Valentia Observatory was 93. It  
208 was similar to that simulated by the phenological model using the observed temperature series (92.5) and that  
209 simulated by the phenological model using the temperature data simulated by the RCMs (91.9). The validation of the  
210 phenological model on its own and in combination with the regional climate projections supports the robustness of this  
211 approach and its use for budburst projections.

212

### 213 *Projections of budburst in the near and far future*

214 The decadal means of the ensemble means and the 5<sup>th</sup> and 95<sup>th</sup> percentiles of the simulated timing of birch budburst are  
215 shown in Figure 3, for the 1990s (recent past-baseline), 2030s (near future) and 2080s (far future).

216 The mean simulated timing of budburst in Ireland in the 2080s is on day 95 (April 5), in comparison with day 102  
217 (April 12) in the 1990s and day 99 (April 9) in the 2030s. A southwest to northeast gradient in the timing of budburst  
218 is evident in Figure 3, for each decade and percentile, with budburst occurring earliest in the southwest and latest in the  
219 northeast. Budburst timing over this gradient ranges from day 86 to day 113 in the 1990s, as compared to day 87 to day  
220 109 in the 2030s and day 88 to 103 in the 2080s. For the three decades under study, mean budburst date for Ireland is  
221 presented in Table 2, both for the ensemble mean and the 5<sup>th</sup> and 95<sup>th</sup> percentiles of the ensembles. The fact that there  
222 is an advance only in the latest date of budburst implies that annual spatial variation in spring phenology over Ireland

223 decreases as climate warms. This pattern is also shown in Figure 4, The advances in budburst timing appear to be more  
224 pronounced over the northeast of Ireland occurring 10 days earlier in the 2080s compared to the 1990s (cell centred at  
225 54.75 N, 7 W). Over the same time period there is either no change or a slight delay for southwesterly coastal regions  
226 (e.g. the grid cell centred at 51.50 N, 10.25 W show a maximum delay, i.e. +5.6 days (Fig 2)). Accordingly,  
227 phenological trends over this period appear to be most negative in the northeast (-0.12 days/year) and slightly positive  
228 in the southwest (Figure 5).

229 For these two regions, differences in phenological trends over time are not only limited to the timing of budburst but  
230 also include the timing of dormancy induction attainment and chilling fulfillment, two important phenophases that are  
231 not observable on the tree, but are simulated by the DORMPHOT model. The two plots in Figure 6 compare the  
232 temporal trends in the attainment of all simulated dormancy phases at these two extreme spots and show that the  
233 positive trend in budburst timing in the southwest is accompanied by a more pronounced positive trend in dormancy  
234 induction and chilling fulfillment, compared to the northeast (0.15 vs. 0.5 days per year and 0.2 vs. 0.07 days per year,  
235 respectively). The trends in September-March average temperature are compared with the trends in budburst date over  
236 the entire projection period in Figure 7.

237

## 238 **Discussion**

239 The Irish climate is characterized by a small annual range in temperature, and relatively high precipitation. Mean  
240 annual temperatures generally range between 9°C and 10°C with the higher values in coastal regions and lower values  
241 over high ground. (Walsh, 2012). During winter and spring prevailing southwesterly winds result in an overall  
242 southwest northeast decreasing temperature gradient (Walsh, 2012).

243

244 This gradient in temperature across the country is reflected in the earlier start to the growing season as identified by  
245 O'Connor et al. (2012) using satellite data derived from the MERIS Global Vegetation Index. Their study was  
246 conducted over a relatively short time period (2003-2009) but nonetheless revealed an earlier start of season in the  
247 southern part of the country compared to the north - a similar pattern to that we found. Our simulations for the recent  
248 past (1990s) highlight a gradient of phenological delay over Ireland from the southwest to the northeast and from the  
249 coast to the interior, resulting in the earliest simulated budburst near the southwest coast and the latest in inland  
250 regions of the northeast. The close correspondence with satellite observations (O'Connor et al. 2012) provides further  
251 validation for our future projections, in spite of a lack of direct phenological observations in the northeast.

252

253 Despite the fact that we only analysed one phenological parameter (budburst timing), that the model employed was  
254 relatively simple (only two variables in input, only one species considered) and that it was applied to a relatively small  
255 region, the spatial patterns that emerged when we assessed the impact of temperature increase on budburst were  
256 complex. According to the simulations the increase in temperature projected by climate models will not have a  
257 homogeneous effect on phenology over Ireland and budburst advance will be of different magnitudes in different  
258 regions. However, this is not unexpected, as reports from both observed and satellite phenological responses to  
259 warming are not spatially uniform (Donnelly et al. 2006; Chung et al. 2011; O'Connor et al. 2012). In particular, future



260 budburst is projected to respond to warming more strongly in the northeast of the country where budburst is currently  
261 relatively late whereas projected advances in budburst will be less pronounced in the southwest, where budburst is  
262 currently early.

263 The heterogeneity of these phenological shifts is more pronounced by what could be expected based solely on the  
264 increases in temperature over the same region: the map in Figure 2 shows that whereas temperature is expected to  
265 increase all over Ireland between 1.4 and 2°C by 2100 with a higher increase in the south compared to the north,  
266 phenology is projected to advance more in the north compared to the south, and will even be delayed in some areas, as  
267 shown by Figure 7. Such a contrasting pattern is a result of the fact that DORMPHOT addresses the interaction  
268 between photoperiod and temperature shown by the experimental evidence, rather than just establishing a relation  
269 between budburst timing and mean temperature.

270

271 These results highlight the necessity of modelling studies taking into account the actual processes behind biological  
272 responses, and show that directly linking the features of a complex system (such a plant, or a vegetation type) to  
273 climate drivers through an empirical relation may be misleading or provide an incomplete picture of the future  
274 (Pearson and Dawson, 2003; Caffarra et al. 2012; Pagel and Schurr, 2012). Whereas empirical phenological and niche  
275 models may prove accurate in the short term, they may not contain the description of responses to extreme changes in  
276 environmental drivers. For example, while phenological response rates to temperature may be useful to characterize  
277 interannual phenological shifts, when applied to much warmer temperature regimes they actually predict growth  
278 resumption as occurring in the middle of winter, which does not reflect observations from warmer regions.

279

280 The spatial variation in budburst advance over the projected period leads to a decrease in the annual gradient of  
281 budburst timing over Ireland, implying a more synchronous arrival of spring (at least for birch) over the island. This  
282 pattern is also shown in figure 2 which depicts the change in budburst timing for the 2030s and 2080s relative to the  
283 1990s. Interestingly in the area where budburst is now earliest (extreme southwesterly tip of Kerry, 51.50 N, 10.25 W)  
284 budburst timing is predicted to remain the same or even be slightly delayed. This suggests that current birch budburst  
285 timing is there at its earliest (15 March) at least for the Irish oceanic climate and any spring temperature increase will  
286 not advance it further. In fact, according to DORMPHOT, which is based on physiological evidence, dormancy  
287 transition is promoted not only by warm temperature in the spring but also by exposure to chilling temperatures during  
288 autumn-winter and by short days in autumn and long days in spring. Whereas climate warming will positively affect  
289 the first parameter it will decrease the rate of dormancy induction and winter chilling, leading to a cumulative delay in  
290 the timing of start of ecodormancy, during which warm, forcing temperatures are active. This pronounced trend of  
291 delay in the attainment of dormancy interphases can be clearly observed in graphs in Figure 6. Photoperiod is also an  
292 important factor in determining the timing of spring phenophases and shows a strong interaction with temperature in  
293 controlling budburst, both of which have been taken into account by DORMPHOT (Caffarra et al. 2011a, b). Since the  
294 annual pattern of changing day length will remain constant, phenological shifts caused by high temperatures during the  
295 winter are going to be buffered by this constant regime, as shown by our simulations. Despite the fact that dormant  
296 birch seedlings growing in climate controlled chambers with constant artificial lighting are known to resume growth as

297 early as December or January, provided that chilling is fulfilled (Myking and Heide 1995; Caffarra et al. 2011a), such  
298 an early budburst has never been observed in nature, due to the inhibiting control exerted by short photoperiods.  
299 Among the European IPG stations, Valentia Observatory, located on the southwest coast of Ireland, is one of the sites  
300 with the earliest date of birch budburst (in the past 20 years it occurred on March 31 on average, with early extremes  
301 around mid-March) pointing to a physiologically determined early limit for this species, which could be thought of as a  
302 budburst timing optimum. As climate warms this physiological limit will likely prevent the beginning of the growing  
303 season from shifting into winter months. In our long-term projections, a further warming will, on the contrary, cause a  
304 slightly positive trend in budburst timing near in the southwest, due to the progressive delay of dormancy induction  
305 and chilling fulfillment (see Figure 6). This is in sharp contrast with the less pronounced delay of intermediate  
306 phenophases in the northeast, as highlighted by our regression analysis.

307  
308 The varying spatial effect that climate warming will likely have on phenology implies that consequences will be  
309 equally varied. For plant species like birch, the growing season will start earlier only in the northeast-interior of the  
310 country, whereas changes will be minimal on the southwest coast, where the growing season at present is approaching  
311 its maximum length. The fact that, as suggested by this study, the impact of climate change on phenology will be  
312 spatially heterogeneous also implies that any species distribution change driven by phenological changes may be more  
313 complex than originally anticipated. In the case of birch, the fact that this species is near its budburst timing optimum  
314 in one Irish region implies that any further warming will advance the budburst of similar trees that are currently  
315 outside this region. Hence, if any phenology driven adaptive advantage will be initiated by warming this will primarily  
316 affect the north east of the country. This pattern may be similar for other species whose spring phenology is controlled  
317 by the interaction of different environmental triggers which prevent winter budburst and winter frost damage and  
318 which are currently close to their phenological optimum.

319  
320 A northward or an upward shift in species ranges attributable to climate warming has been widely reported for a range  
321 of regions including Ireland (Walther et al. 2002; Berry et al. 2002). Indeed, warmer winters have been cited as  
322 providing appropriate conditions for the spread of birds such as the little egret (Smiddy and O'Sullivan 1998) and the  
323 Mediterranean gull (Donald and Bekhuis 1993) to more northern parts of Ireland (Donnelly et al. 2009). Therefore,  
324 based on our projections, it is equally conceivable to suggest that some cold intolerant plants could expand their range  
325 northeast wards as climate warms.

326  
327 However, before making any inference on future species distribution or fitness it is necessary to consider a set of other  
328 important constraints such as rainfall, wind, geology and biotic pressures, which will further complicate any future  
329 projections. The development of additional species-specific models of key phenological phases is important in order  
330 to verify whether such trends in distribution pattern are common among other plant species. Linking such models  
331 within more complex distribution or vegetation models is even more important to understand how climate change  
332 could impact Irish vegetation and consequently support adequate environmental policies.

333

334 In addition to species distribution and fitness the present results might have important implications for the allergy  
335 season. As budburst in birch occurs almost at the same time as flowering, a more synchronous budburst over Ireland  
336 might mean a more synchronous allergy season. The literature indicates a tentative trend towards an earlier start to the  
337 birch pollen season in the UK (Emberlin et al. 2002; Newnham et al. 2012) and a slight decrease in birch pollen  
338 intensity in Europe (Ziello et al. 2012) as temperatures increase. At present it is not possible to draw any definitive  
339 conclusions as to the impact of climate warming on the future birch pollen season in Ireland.

340

#### 341 **Conclusions**

342 In conclusion, almost everywhere in Ireland the trend towards earlier birch budburst that has been recorded from direct  
343 observations of the timing of this phenophase is predicted to continue at least until the end of the present century.  
344 However, the spatial pattern of this advance will be heterogeneous across the island of Ireland, and will not reflect the  
345 pattern of temperature increase, as may have been expected, with greater advances being predicted for the northeast of  
346 the country compared to the southwest. Although these results reflect the results of only one species the same pattern  
347 could be expected for other temperate trees but the development of more species specific phenological models would  
348 confirm whether this holds true or not. These results highlight the necessity of modelling studies taking into account  
349 the actual processes at the base of biological responses, and show that directly linking the features of a complex system  
350 (such a plant, or a vegetation type) to temperature through an empirical relation may be misleading.

351

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358

359 **References**

- 360  
361 Alig RJ, Adams D, McCarl B (2002) Projecting impacts of global climate change the US forest and agricultural sectors  
362 and carbon budgets. *Forest Ecology and Management* 169: 3-14.
- 363  
364 Berry PM, Dawson TP, Harrison PA, Pearson RG (2002) Modelling potential impacts of climate change on the  
365 bioclimatic envelope of species in Britain and Ireland. *Global Ecology & Biogeography* 11, 453–462
- 366  
367 Brachi B, Aimé C, Glorieux C, Cuguen J, Roux F (2012) Adaptive Value of Phenological Traits in Stressful  
368 Environments: Predictions Based on Seed Production and Laboratory Natural Selection. *PLoS ONE* 7(3): e32069. doi:  
369 10.1371/journal.pone.0032069
- 370  
371 Bronaugh D (2013) PCICt: Implementation of POSIXct work-alike for 365 and 360 day calendars. R package version  
372 0.5-3. <http://CRAN.R-project.org/package=PCICt>
- 373  
374 Buisson L, Thuiller W, Casajus N, Lek S, Grenouillet G (2010) Uncertainty in ensemble forecasting of species  
375 distribution. *Global Change Biology* 16: 1145–1157
- 376  
377 Caffarra A, Donnelly A, Chuine I, Jones M (2011a) Modelling the timing of *Betula pubescens* budburst. I.  
378 Temperature and photoperiod: a conceptual model. *Climate Research* 46:147-157
- 379  
380 Caffarra A, Donnelly A, Chuine I (2011b) Modelling the timing of *Betula pubescens* budburst. II. Integrating complex  
381 effects of photoperiod into process-based models. *Climate Research* 46:159-170
- 382  
383 Caffarra A, Rinaldi M, Eccel E, Rossi V, Pertot I (2012). Modelling the impact of climate change on the interaction  
384 between grapevine and its pests and pathogens: European grapevine moth and powdery mildew. *Agriculture*  
385 *Ecosystems & Environment* 148: 89-101
- 386  
387 Carroll E, Sparks T, Donnelly A, Cooney T. (2009) Irish phenological observations from the early 20th century reveal  
388 a strong response to temperature. *Biology and Environment: Proceedings of the Royal Irish Academy*. 109: 115-126
- 389  
390 Chmielewski F M., Rötzer T. (2001) Responses of tree phenology to climatic changes across Europe. *Agricultural and*  
391 *Forest Meteorology* 108, 101-112.
- 392  
393 Chuine I (2000) A unified model for budburst of trees. *Journal of theoretical biology* 207: 337-347.
- 394  
395 Chuine I, Beaubien E. G. (2001). Phenology is a major determinant of tree species range. *Ecology Letters* 5, 500-510
- 396  
397 Chung U, Mack L, Yun JI, Kim S-H. (2011) Predicting the timing of cherry blossoms in Washington DC and Mid-  
398 Atlantic States in response to climate change. *PLoS One* 6(11):e27439.
- 399  
400 Donald P, Bekhuis J (1993) Mediterranean Gull *Larus melanocephalus*. In: Gibbons DW, Reid JW, Chapman RA *The*  
401 *New Atlas of Breeding Birds in Britain and Ireland 1988-1991*. T & AD Poyser, London, pp. 200-201
- 402  
403 Donnelly A, Salamin N Jones, MB (2006) Changes in tree phenology: an indicator of spring warming in Ireland?  
404 *Biology and Environment: Proceedings of the Royal Irish Academy*. 106(1): 47-55
- 405  
406 Donnelly A, Cooney T, Jennings E, Buscardo E., Jones M. (2009) Response of birds to climatic variability; evidence  
407 from the western fringe of Europe. *International Journal of Biometeorology* 53: 211-220

408  
409 Donnelly A, Caffarra A, Kelleher CT, O'Neill BF, Diskin E, Pletsers A, Proctor H, Stirnemann R, O'Halloran J,  
410 Peñuelas J, Hodkinson TR, Sparks T (2012) Surviving in a warmer world: environmental and genetic responses.  
411 *Climate Research* 53: 245-262

412  
413 Eccel E, Rea R., Caffarra A, Crisci A (2009) Risk of spring frost to apple production under future climate scenarios: the  
414 role of phenological acclimation. *International journal of biometeorology* 53: 273-286

415  
416 Emberlin J, Detandt M, Gehrig R, Jaeger R, Bolard N, Rantio-Lehtimäki A (2002) Responses in the start of *Betula*  
417 (birch) pollen seasons to recent changes in spring temperatures across Europe. *Int J Biometeorol* 46(4) 159-70

418  
419 Gleeson E, Donnelly A, Ní Bhroin A, O'Neill BF, Semmler T, McGrath R (2013) A comparison of spring tree  
420 phenology with a range of meteorological parameters. *Biology and Environment; Proceedings of the Royal Irish*  
421 *Academy*

422  
423 Grolemond G, Wickham H (2011). Dates and Times Made Easy with lubridate. *Journal of Statistical Software*, 40(3):  
424 1-25. URL <http://www.jstatsoft.org/v40/i03/>.

425  
426 Gu L, Hanson P, Mac Post W, Kaiser DP, Yang B, Nemani R, Pallardy S, Meyers T (2008) The 2007 Eastern US  
427 spring freeze: increased cold damage in a warming world? *Bioscience* 58: 253-262

428  
429  
430 Haylock MR, Hofstra N, Tank AMGK, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded  
431 dataset of surface temperature and precipitation. *Journal Geophysical Research (Atmospheres)*. doi:  
432 10.1029/2008JD10201

433  
434 Hewitt CD, Griggs DJ (2004) Ensembles-based predictions of climate change and their impacts. *EOS* 85:566

435  
436 Hijmans RJ, van Etten J (2013). raster: Geographic data analysis and modeling. R package version 2.1-16  
437 <http://CRAN.R-project.org/package=raster>

438  
439 Hijmans RJ, Williams E, Vennes C (2012) geosphere: Spherical Trigonometry. R package version 1.2-28.  
440 <http://CRAN.R-project.org/package=geosphere>

441  
442 IPCC (2007) Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the  
443 Fourth Assessment Report of the Intergovernmental Panel on Climate Change. EDS. Parry ML, Canziani OF, Palutikof  
444 JP, van der Linden PJ, Hanson CE. Cambridge University Press

445  
446 Kurz WA, Dymond CC, Stinson G., Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L (2008) Mountain pine  
447 beetle and forest carbon feedback to climate change. *Nature* 452:987–990

448  
449 Morin X, Viner D, Chuine I (2008), Tree species range shifts at a continental scale: new predictive insights from a  
450 process-based model. *Journal of Ecology* 96: 784–794

451  
452 Myking T, Heide OM (1995). Dormancy release and chilling requirement of buds of  
453 latitudinal ecotypes of *Betula pendula* and *Betula pubescens*. *Tree Physiology* 15: 697-704

454

455 Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S et al. (2000). Special report on emissions  
456 scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change (No. PNNL-  
457 SA-39650). Pacific Northwest National Laboratory, Richland, WA (US), Environmental Molecular Sciences  
458 Laboratory (US).

459

460 Newnham RM, Sparks TH, Skjøth CA, Head K, Adams-Groom B, Smith M (2013) Is the timing of birch pollen re-  
461 lease in the UK approaching its limit? *International Journal of Biometeorology* 57: 391-400

462

463 O'Connor B, Dwyer E, Cawkwell F, Eklund L (2012) Spatio-temporal patterns in vegetation start of season across the  
464 island of Ireland using the MERIS Global Vegetation Index. *ISPRS Journal of Photogrammetry and Remote Sensing*  
465 68:79-94.

466

467 Pagel, J, Schurr FM (2012), Forecasting species ranges by statistical estimation of ecological niches and spatial  
468 population dynamics. *Global Ecology and Biogeography*, 21: 293–304.

469

470 Pearson, R. G. and Dawson, T. P. (2003), Predicting the impacts of climate change on the distribution of species: are  
471 bioclimate envelope models useful?. *Global Ecology and Biogeography*, 12: 361–371.

472

473 R Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical  
474 Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org/>.

475

476 Richardson DS (2001) Measures of skill and value of ensemble prediction systems, their interrelationship and the  
477 effect of ensemble size. *Q. J. R. Meteorol. Soc.* 127: 2473-2489.

478

479 Smiddy P, O'Sullivan O (1998) The status of Little Egret *Egretta garzetta* in Ireland. *Irish Birds* 6 (2): 201-206.

480

481 Toth Z, Kalnay E (1993) Ensemble forecasting at nmc: the generation of perturbations. *Bull. Amer. Meteor. Soc.* 74:  
482 2317–2330

483

484 Van Der Linden P, Mitchell J.F.B. (eds) (2009). ENSEMBLES: Climate Change and its Impacts: Summary of  
485 Research and Results from the ENSEMBLES Project. Met Office Hadley Centre, Fitzroy Road, Exeter EX1 3PB , UK

486

487 Walsh S (2012) Met Eireann Climatological Note No.14: A Summary of Climate Averages for Ireland 1981-2010

488

489 Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O Bairlein F  
490 (2002) Ecological responses to recent climate change. *Nature* 416:389-395

491

492 Zhang H, Pu Z., (2010) Beating the Uncertainties: Ensemble Forecasting and Ensemble-Based Data Assimilation in  
493 Modern Numerical Weather Prediction. *Advances in Meteorology*.doi:10.1155/2010/432160

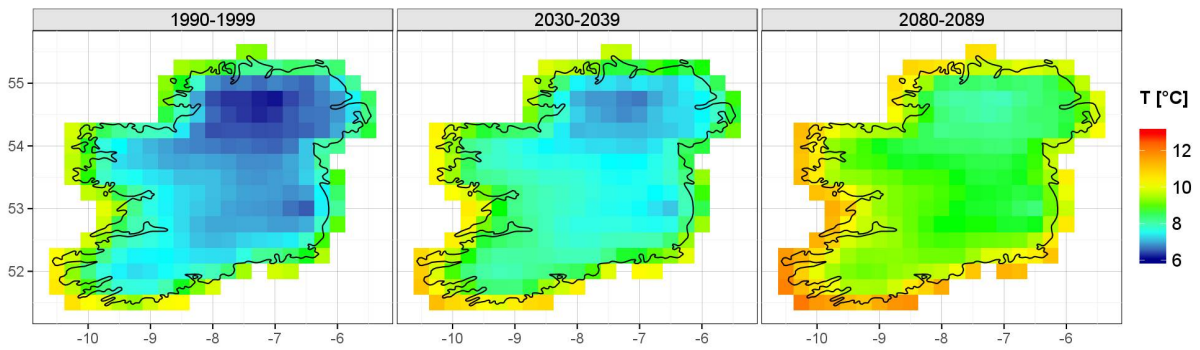
494

495 Ziello C, Sparks TH, Estrella N, Belmonte J, Bergmann KC, et al (2012) Changes to Airborne Pollen Counts across  
496 Europe. *PLoS ONE* 7(4): e34076.

497

498

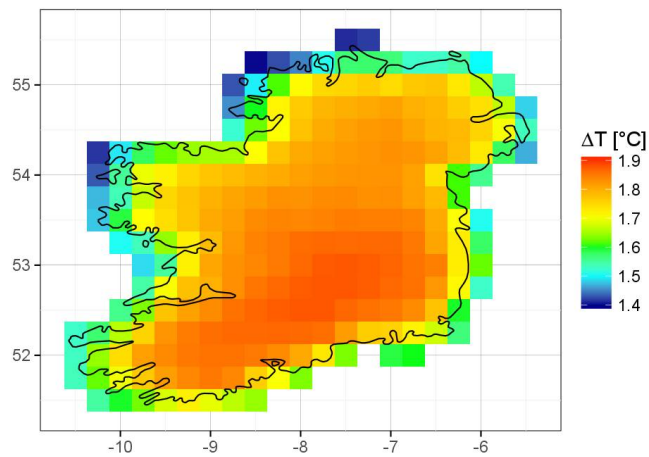
499 **Figures**



500

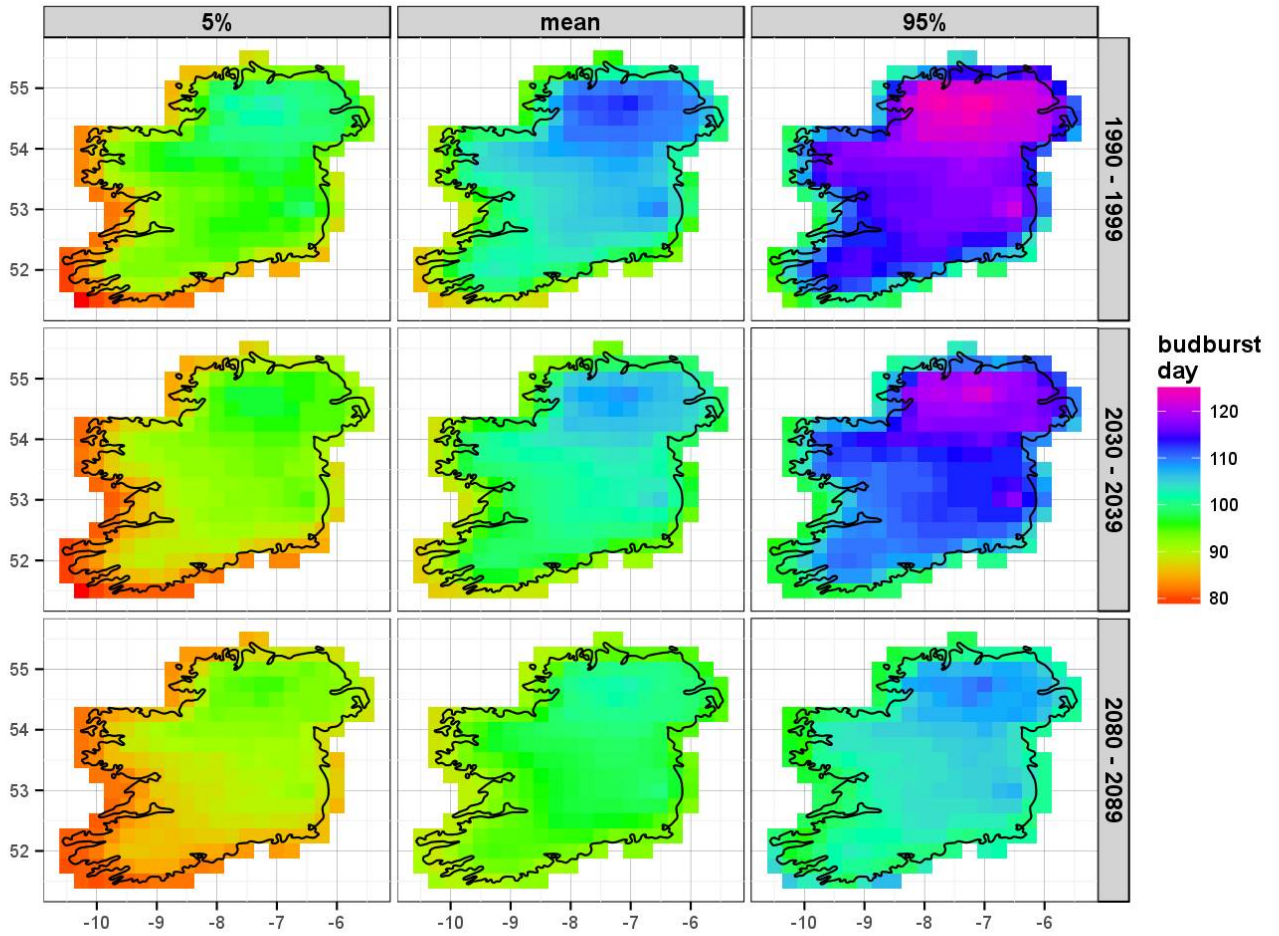
501 Figure 1. Mean autumn-winter temperatures (from September to March) over Ireland, for (a) 1990-1999 (recent past)  
502 (b) 2030-3039 (near future) and (c) 2080-2089 (far future). See Table 2 for the details on the models used to calculate  
503 these maps.

504



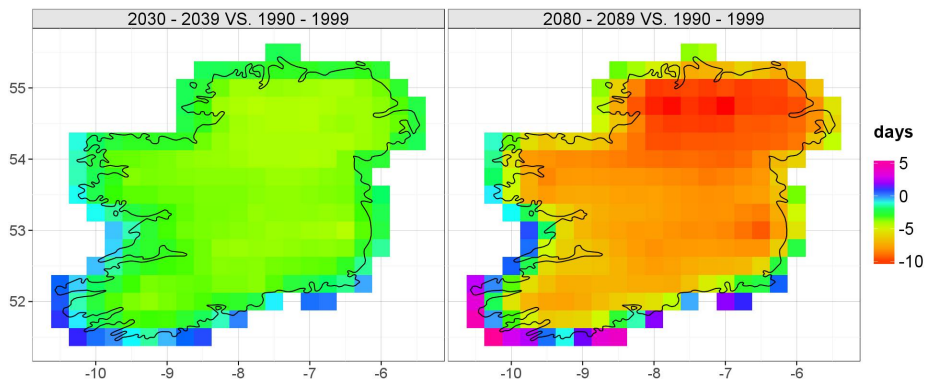
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506 Figure 2. The change in autumn-winter temperatures (from September to March) between the baseline decade  
507 (1990-1999) and the far future (2080-2089)



508

509 Figure 3. Ensemble mean, 5<sup>th</sup> and 95<sup>th</sup> percentiles of budburst day over Ireland, for (a) 1990-1999 (recent past,  
 510 calculated using 19 model members) (b) 2030-2039 (near future, calculated using 19 model members) and (c)  
 511 2080-2089 (far future, calculated using 11 model members).

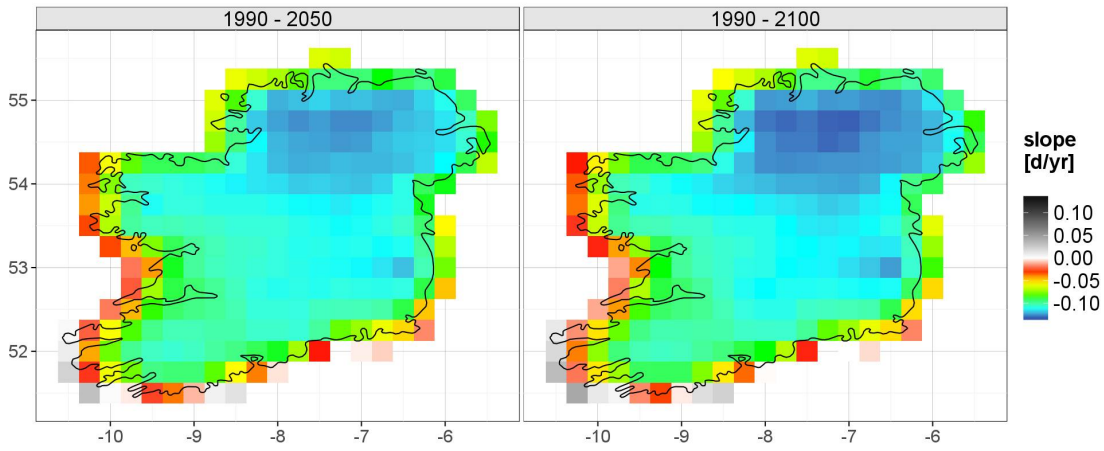


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513 Figure 4. Simulated changes in birch budburst date relative to the period 1990-1999 for the following future decades (a)



514 2030-2039 and (b) 2080-2089.

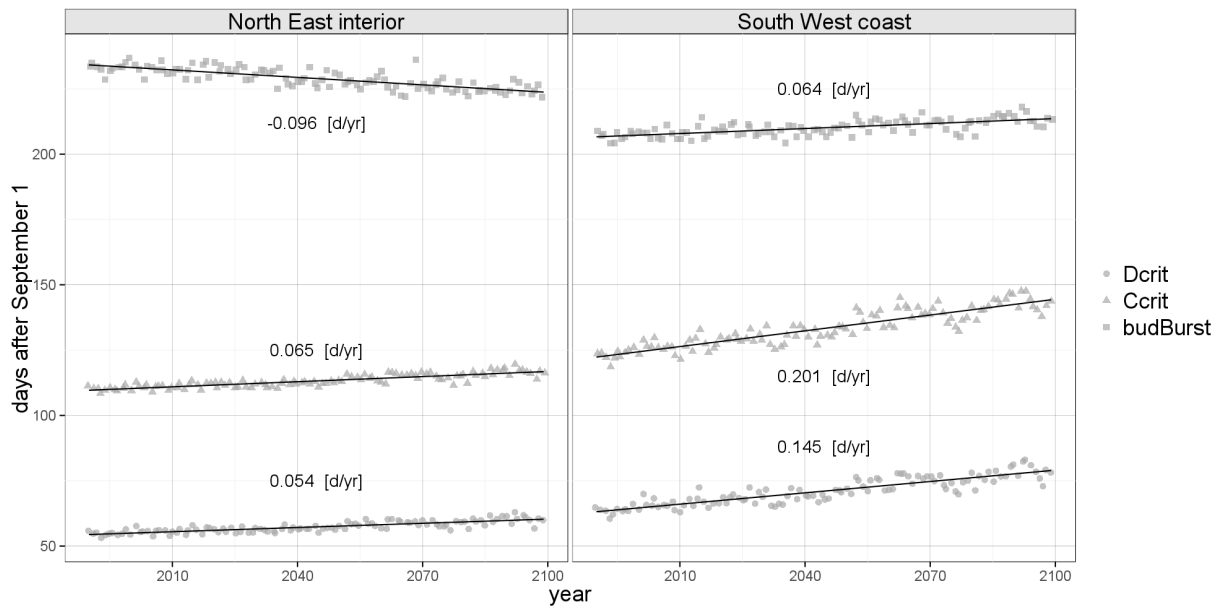


515

516 Figure 5. Regression coefficients (slope, days/year) of the linear relationship between budburst timing and years for  
517 two time spans: (a)1990 – 2050 and (b)1990 – 2100

518

519



520

521

522 Figure 6. Temporal trends in the timing of attainment of intermediate dormancy phenophases, i.e. dormancy induction  
523 (Dcrit) and chilling fulfillment (Ccrit) for the two sites with extreme changes over the projected period (northeast  
524 interior at 54.75 N, 7 W, with the maximum advance, and southwest coast at 51.50 N, 10.25 W with the maximum  
525 delay)

526

527

528

529

530 Figure 7. Temporal trends in the timing of attainment of budburst for the two sites with extreme changes over the  
531 projected period (northeast interior at 54.75 N, 7 W, with the maximum advance, and southwest coast at 51.50 N,  
532 10.25 W with the maximum delay) (left), compared with the temporal trends of the average September-March  
533 temperature

534