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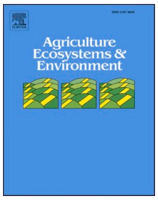

Climate induced phenological shifts in pears – A crop of economic importance in the UK

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ABSTRACT

Phenological advancements in flowering have been well documented in many food crop, ornamental, and native plant species. However, there is lack of information on how flowering times in crop species, especially fruit trees will react to future climate scenarios. This is important as changes in phenology could have significant implications for ecosystem services and function, biological interactions and agronomic outputs. Using 60 years of data from pear (*Pyrus communis* L.) orchards in two research organisations in Kent, UK we explored temporal changes in flowering phenology, identified the weather variables driving this change, and predicted how flowering times may be altered by 2080 with respect to future emissions scenarios. We show pear flowering (1990–2020) in the last 30 years has advanced 11.44 days compared to historical data (1960–1989). Furthermore, we highlight this advancement is apparent in all twelve pear cultivars and the four phenological stages analysed, including Conference, the most common UK pear cultivar. Our results indicate that this advancement in flowering began after 1982; that air temperature and frost days significantly impact pear flowering; and this change in flowering phenology is likely to continue under future climate scenarios. Four Representative Concentration Pathways from the UK Climate Projections 2018 report were used to model the impact of future climate, including low, medium, medium-high and high emission scenarios. Under all scenarios a phenological advancement in flowering time was predicted by 2080 with the greatest advancement in flowering time observed under the high emission scenario. Earlier flowering and budburst could result in phenological mismatches between plant and pollinators, alter agricultural spraying regimes, increase risk of frost exposure and exacerbate impacts of pest populations within an agroecosystem, thus it is vital to monitor advancements in flowering phenology.

1. Introduction

Global climate is predicted to change significantly over the next 80 years, with temperatures estimated to rise between 2.6 and 4.8 °C (Scott et al., 2016) and CO_2 levels predicted to increase above 900 ppm (Collins et al., 2013). The UK Climate Projections 2018 report (UKCP18) projects that all areas of the UK will be warmer by the end of 2100 (Met Office, 2019). The UK is likely to experience wetter winters and hotter drier summers (Murphy et al., 2018), with a higher frequency of extreme weather events such as flooding and heatwaves (Kennedy-Asser et al., 2020). Furthermore, climatic variability may increase within the UK alongside climate mean, with more variable interannual rainfall and temperature (Arnell, 2003).

Changes in weather variables could impact community structure (Kardol et al., 2011; Yang et al., 2011), biodiversity including species richness (Gitay et al., 2002; Iverson and Prasad, 2001), phenological events (Amano et al., 2010; Fitter and Fitter, 2002), and ecosystem services (Mooney et al., 2009; Scholes, 2016). One central phenological event for plants is flowering time; the timing of this event can alter the probability of successful pollination, impacting fruit set and yield (Fitter

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and Fitter, 2002; Rafferty and Ives, 2012). Alongside this, earlier flowering may increase the risk of exposure to spring frost, although spring frosts risk may be decreasing due to climatic warming (Cannell and Smith, 1986; Eccel et al., 2009). Finally earlier budburst and flowering may provide more shelter for pests earlier in the year, with denser plant canopies providing shelter from agrochemical sprays (Derksen et al., 2007), weather conditions (frost, wind, rainfall, and temperature extremes), and natural enemies (Norris, 2005). Furthermore, pests such as pear sucker (*Cacopsylla pyri*) nymphs are often found inside buds, flowers or rolled leaves (Solomon et al., 1989), which could provide more protection if available earlier in the year, altering pest populations within an agroecosystem.

There is significant evidence to suggest that flowering times of angiosperms are advancing (becoming earlier) globally and within the UK (Amano et al., 2010; Büntgen et al., 2022; Fitter and Fitter, 2002). Büntgen et al. (2022), compared flowering times of 406 plant species before and after 1986. The study found a shift in UK flowering times, with flowering becoming 26 days earlier for current (1987–2019) compared to historical time periods (1753–1986). Rapid advancements in flowering phenology may be occurring in crop species in addition to other angiosperms- research indicates that flowering phenology of fruit trees are advancing in Europe, with studies showing earlier flowering in apple, sweet cherry, pear, and plum (Cosmulescu et al., 2010; Sparks et al., 2005; Unterberger et al., 2018). This is cause for concern within the agricultural sector, as there are potential impacts on pollination, yield and ultimately food security (Craufurd and Wheeler, 2009).

Change point analyses, examining the point or points in time where a significant change has occurred (Taylor, 2000), have indicated that this advancement in flowering phenology began during the late 1980 s (Drepper et al., 2020; Guédon and Legave, 2008; Kunz and Blanke, 2014). A phenological changepoint during the late 1980 s may therefore correspond to the rapid temperature increase during this decade (Drepper et al., 2020; Hansen et al., 2006). Many studies focus on temperature as the driving factor influencing flowering phenology (Atkinson et al., 2004; Drepper et al., 2020; Fitter et al., 1995; Sparks et al., 2005); as a large proportion of fruit crops are influenced by chilling and forcing times including blackcurrant, pear, apple, sweet cherry, plum and peach (Atkinson et al., 2013, 2004). These crops go into a dormancy phase over winter, a period of restricted growth that protects them from cold temperatures and frost damage. Chilling periods for pear are often between October–December, whilst forcing times are from January-April (Drepper et al., 2020), although these time periods can vary depending on cultivar. Other weather variables also influence flowering phenology and budburst including frost days, rainfall, relative humidity, and solar radiation (Lesica and Kittelson, 2010; Mortensen, 1986; Nagy et al., 2013; Peñuelas et al., 2004; Westwood and Bjornstad, 1978).

Although, many studies have used temperature to explore phenology (Chitu and Paltineanu, 2020; Legave et al., 2015; Sparks et al., 2005), few have considered other factors or attempted to project based on future emission scenarios (Hoffmann and Rath, 2013; Mateescu et al., 2009). Furthermore, there is a gap within the scientific literature on how flowering phenology of crop species is advancing in the UK. Currently Sparks et al. (2005) is the main UK study concentrating on phenological advancement in agriculture; the study focuses on how flowering dates have become earlier over time and that flowering phenology is influenced by January-March temperatures in multiple crop species.

This study uses pear as a model system and the methods employed could be easily transferable to other crops. Pear is the fifth most produced fruit; with over 23 million tonnes grown per year globally and top producers including China, Europe and the U.S. (Silva et al., 2014). Pears are also an economically important crop within the UK, contributing to 4.0 % of total fruit production; with a planted area of over 1500 ha and an economic value of £ 22.8 million in 2019 (DEFRA, 2020), therefore an advancement in pear flowering time or reduction in yield would have significant economic implications.

This study aims to analyse whether pear flowering phenology is advancing over time within the UK, if this advancement differs depending on cultivar and which weather variables are driving this advancement. Furthermore, this study aims to predict how future Representative Concentration Pathways (RCP) emissions scenarios may impact flowering phenology in the future. We specifically tested three hypotheses 1) Pear flowering phenology is advancing over time in the UK and some cultivars are more sensitive than others, 2) Advancements in flowering due to climate change are driven by changes in weather variables including air temperature, frost days and rainfall, and 3) Flowering phenology will continue to advance in the future and be greatest under high emission scenarios.

2. Materials and methods

Historical data on pear flowering times was collated from two sites in Kent, UK, comparing historical (1960–1989) and current (1990–2020) time periods and how flowering phenology changed depending on year. Flowering was also compared against several climate variables from local weather stations, to highlight which weather variables were most influential for phenological change. Finally, temperatures were predicted under four future Representative Concentration Pathways (RCPs), which are concentrations of released greenhouse gases that will result in radioactive forcing (the change in energy going in and out of the upper atmosphere) increasing by a specific amount by 2100 (Lowe et al., 2018; Van Vuuren et al., 2011) to explore how project how flowering would change by 2080.

2.1. Flowering data

Phenological data on pear flowering were collected for the following metrics (see Fig. S1):

- first (first flower opens on a tree or flower's anthers are visible),
- ten percent (when 10 % of flowers are open on the tree),
- full (when 50 % of flowers have opened on the tree), and
- last (90 % of petals have fallen)

These data were collected at two sites (Fig. S2); from 1960 to 2020 at NIAB EMR (formerly East Malling Research, 51.2885° N, 0.4383° E) and 1960–2019 at the Brogdale Collection (51.3007° N, 0.8762° E). Records of 1991 flowering were missing for all cultivars at Brogdale (Table S1). Full and last flowering was recorded at both sites in the South-East of England, first flowering was only recorded in East Malling for 2 cultivars, whilst ten percent flowering was recorded at Brogdale for all cultivars. Both sites are valuable resources for pear production; Brogdale is part of the National Fruit Collection, with approximately 560 varieties of pear (Fernández-Fernández, 2010), whilst NIAB EMR is involved in developing best practice guides for the UK pear industry (Gregory, 2014). Phenological data was collated for twelve standard pear cultivars (cv.) including: Beurre Hardy LA (BH), Beurre Superfin (BS), Clapp's Favourite (CF), Conference (Con), Doyenne du Comice (DC), Durondeau LA (Du), Glou Morceau LA (GM), Louise Bonne of Jersey (LB), Nouveau Poiteau LA (NP), Packham's Triumph (PT), Precoce de Trevoux (PdT) and Williams' Bon-Chretien (WB).

2.2. Weather data

To analyse flowering phenology weather data (1959–2020) from the East Malling weather station (51.288° N, 0.448° E) in Kent were used for pear data from NIAM EMR. For Brogdale flowering phenology, Faversham (51.297° N, 0.878° E) weather data were used. The following weather data were collated from Met Office MIDAS data base (MetOffice, 2021): daily maximum and minimum temperature data and daily rainfall from East Malling. Daily maximum and minimum temperature data and daily rainfall from Faversham (Table S2). Mean temperatures were calculated from an average of maximum and minimum temperatures. Frost days were calculated by summing the number of days where the daily minimum temperature was below zero. Monthly mean, maximum and minimum temperatures, Frost days for each month (Oct-Dec and Jan-May) were calculated and total rainfall for each month were calculated, for use within the PCA analysis.

2.3. *Future emissions scenarios*

For historical temperature data, mean January to April temperatures were calculated from 1960 to 2020, using data from East Malling (51.288° N, 0.448° E) and Faversham (51.297° N, 0.878° E); Jan-Apr temperatures were chosen as these months were shown to be particularly important for influencing pear flowering in Drepper et al. (2020) and had lowest AIC during the model selection process. To calculate future temperature scenarios for 2080, data was extracted using the UK Climate Projections User Interface (UKCP, 2021). A 2080 scenario was chosen as this year is commonly used in papers predicting future phenological events (Chung et al., 2011; Mateescu et al., 2009; Stöckle et al., 2010), thus the results of this paper can be easily compared to others. The predicted increase in mean air temperature at 1.5 m for 2080 was calculated for January to April (baseline scenario 1981–2000) for a 25 km-by-25 km region in Kent, surrounding East Malling (562500.00, 162500.00), these temperatures were calculated for each of the four RCP scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5.) and added to the average 1981–2000 January-April temperature (6.30°C).

For historical frost day data, total frost days from January to April were calculated from 1960 to 2020, using data from East Malling (51.288° N, 0.448° E) and Faversham (51.297° N, 0.878° E). Frost days were calculated by totalling the number of days where the daily minimum temperature was below 0 °C. Jan-Apr temperatures were chosen as this model had lowest AIC during the model selection process. Future frost day scenarios were calculated for 2080 for RCP2.6 (low emissions) and RCP8.5 (high emissions) scenarios. Daily minimum temperature data for 2080 was extracted using the UK Climate Projections User Interface for a 60 km-by-60 km region in Kent. Frost days were calculated by summing the number of days where the minimum temperature was below 0 °C. RCP4.5 and RCP6.0 future frost day scenarios could not be calculated as minimum daily temperatures for these two scenarios were not available from the UK Climate Projections User Interface.

3. Data analyses

3.1. *Changes in flowering phenology over time*

To test the hypothesis that flowering phenology has advanced over time (from 1960 to 2020), generalised additive models (GAM) were applied with model selection using AIC (Anderson and Burnham, 2002; Thomas et al., 2013; Zuur, 2012). GAMs with flowering time (in Julian days) as a dependent variable, year as a smoother and cultivar as a factor (with 12 levels) were selected. Site (Brogdale or East Malling) was removed from the model during the AIC selection process, this variable was not significant and did not improve model fit. The data were normally distributed and the residuals were also tested for normality and homogeneity. Separate models were plotted for first, ten percent, full and last flowering times, using the R package 'mgcv' (Wood and Wood, 2015) and 'ggplot2′ (Wickham et al., 2016). The late 1980 s was identified as the changepoint in flowering times in previous phenological studies (Drepper et al., 2020; Kunz and Blanke, 2014), so the two flowering time periods 1960–1989 (historical) and 1990–2020 (current) and the impact of cultivar were tested using a 2-way ANOVA.

3.2. *Impact of weather variables*

Weather variables were condensed into TempPC1, RainPC1 and FrostPC1, using principal component analyses (PCA) in R (Thomas et al., 2013), using the 'stats' package, version 4.2.0 (R, 2022). TempPCA used minimum, maximum and mean temperatures from May – Dec (previous year) and Jan – Apr (current year), RainPCA used total monthly rainfall from May – Dec (previous year) and Jan – Apr (current year) and FrostPCA total frost days from May and Oct – Dec (previous year) and Jan – Apr (current year), data from 1959 to 2020 were used. To test which weather variables were influencing flowering phenology linear mixed models (LMM) were applied; model selection using AIC was used as before. The PC1 from each weather variable (TempPC1, RainPC1, FrostPC1) was extracted from the PCA analyses and used within the LMM as fixed effects and cultivar as the random effect. LMMs with flowering time as a dependent variable, TempPC1 and FrostPC1 as fixed effects and cultivar as a random effect were selected for first, ten percent, full, and last flowering. Residuals were tested for normality and homogeneity. Separate models were plotted for first, ten percent, full and last flowering times, using the R package 'nlme' (Pinheiro et al., 2017).

3.3. *Predicting the effect of future emissions scenarios*

For future temperature scenarios LMMs with flowering time as a dependent variable, mean Jan-Apr temperature (°C) as a fixed effect and cultivar as a random effect (with 12 levels), were chosen for first, ten percent, full and last flowering. January – April temperature ranges from the four RCP scenarios were used to predict flowering dates under the four future climate scenarios, alongside historical (1960–1989) and current (1990–2020) temperature scenarios, using the predict function using the 'stats' package version 4.2.0 (R, 2022). These RCP scenarios were RCP2.6 (low emissions scenario), RCP4.5 (medium emissions scenario), RCP6.0 (medium-high emissions scenario) and RCP8.5 (high emissions scenario).

For future frost day scenarios LMMs with flowering time as a dependent variable, total Jan-Apr frost days as a fixed effect and cultivar as a random effect (with 12 levels), were chosen for first, ten percent, full and last flowering. Total January – April frost days from RCP2.6 and RCP8.5 scenarios were used to predict flowering dates under future climate scenarios, alongside historical (1960–1989) and current (1990–2020) temperature scenarios, using the predict function using the 'stats' package version 4.2.0 (R, 2022). Only RCP2.6 and RCP8.5 gave daily temperature values, allowing us to predict future frost day scenarios.

The temperature ranges, frost days and standard deviations for each RCP scenario are specified in Table 4. AIC selection was used to choose the optimal model and residuals were tested for normality and homogeneity. Separate models were analysed and plotted for first, ten percent, full and last flowering times, using the R package 'nlme' (Pinheiro et al., 2017) and 'gglpot2′ (Wickham et al., 2016).

4. Results

4.1. *Flowering phenology for historical and current time periods*

On average, full flowering time has advanced considerably over the past few decades; becoming 11.44 days (± 14.16, SD) earlier in 1990–2020 compared to the 1960–1989 time-period. Similar trends are also apparent for first (7.91 days earlier ± 14.43, SD), ten percent (9.82 days earlier ± 15.24, SD) and last (11.22 days earlier ± 13.13, SD) flowering times (Fig. 1, Table S3-S6). Significant differences in flowering time between the two time periods were found within 2-way ANOVAs; with flowering being significantly earlier in 1990–2020 compared to 1960–1989, for all four phenological stages. For first flowering time there was a significant difference in flowering time depending on time period ($F_{(1)} = 41.18$, $p < 0.001$) and cultivar ($F_{(1)} = 19.94$, $p < 0.001$), however the interaction between time-period and cultivar was non-significant ($F_{(1,1)} = 0.343$, $p = 0.559$). For ten percent flowering, there was also a significant difference in flowering time

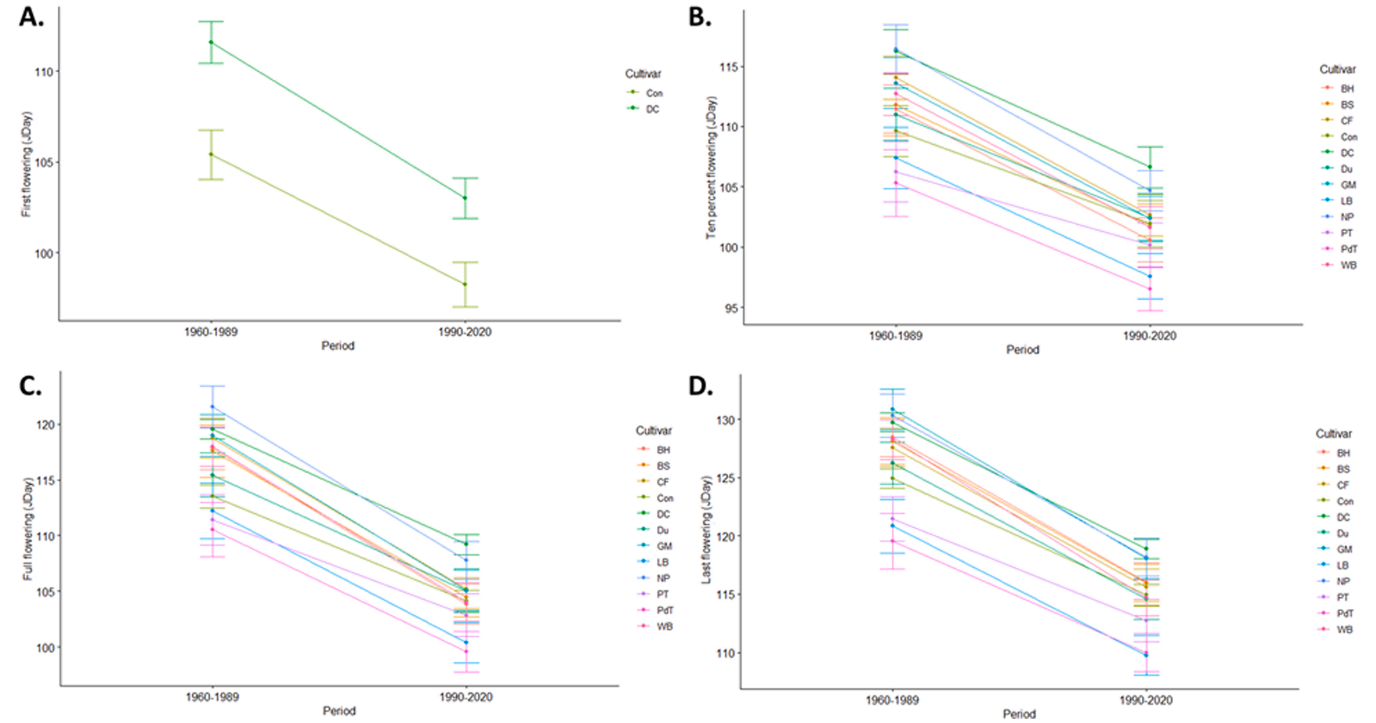

Fig. 1. **:** Flowering times (Julian Days) in pear (*Pyrus communis* L.) for first (A.), ten percent (B.), full (C.) and last (D.) flowering, comparing two different time periods 1960–1989 and 1990–2020. For first flowering two cultivars (Conference and Doyenne du Comice) were recorded, for ten percent, full and last flowering 12 cultivars were recorded. These included Beurre Hardy LA (BH), Beurre Superfin (BS), Clapp's Favourite (CF), Conference (Con), Doyenne du Comice (DC), Durondeau LA (Du), Glou Morceau LA (GM), Louise Bonne of Jersey (LB), Nouveau Poiteau LA (NP), Packham's Triumph (PT), Precoce de Trevoux (PdT) and Williams' Bon-Chretien (WB).

depending on time period ($F_{(1)} = 144.33$, $p < 0.001$) and cultivar ($F_{(11)} = 4.676$, $p < 0.001$), however the interaction between time-period and cultivar was non-significant ($F_{(1,11)} = 0.349$, $p = 0.974$). For full flowering, there was a significant difference in flowering time depending on time period ($F_{(1)} = 320.9$, $p < 0.001$) and cultivar ($F_{(11)} = 7.297$, $p < 0.001$) but no significant difference depending between sites ($F_{(1)} = 1.23$, $p = 0.268$). The interaction between time-period and cultivar was also non-significant ($F_{(1,11)} = 0.794$, $p = 0.646$). For last flowering, there was a significant difference in flowering time depending on time period ($F_{(1)} = 366.5$, $p < 0.001$) and cultivar ($F_{(11)} = 9.460$, $p < 0.001$) but no significant difference depending on site ($F_{(1)} = 0.572$, $p = 0.450$). The interaction between time-period and cultivar was also non-significant ($F_{(1,11)} = 0.419$, $p = 0.948$). As there were no significant differences in flowering time between the two sites (Fig. S3), data were combined for subsequent analyses.

All pear cultivars showed a much earlier average flowering for first, ten percent, full, and last flowering stages in 1990–2020 (current) compared to 1960–1989 (historical) (Fig. 1).

4.2. *Changes in flowering phenology depending on year*

The models on first, ten percent, full, and last flowering phenology, year had a significant effect on flowering time (Table 1). Cultivar also had a significant effect on flowering phenology (p and F values stated in Table 1), with Louise Bonne of Jersey and Precoce de Trevoux showing earlier ten percent, full, and last flowering times than other cultivars, whilst Nouveau Poiteau LA had later flowering (Fig. S4). However, all twelve cultivars responded similarly to year, with an advancement of 16.67 days per decade between 1983 and 1993 in full flowering time (Fig. 2). Deviance explained by the models ranged from 25.3 % to 38.3 % (Table 1). Models for first, ten percent, full, and last flowering all seem to indicate an advancement in flowering time between 1982 and 1994/1995, indicated by the highlighted blue areas in Fig. 2. Furthermore, there seems to be the start of a second advancement in flowering phenology from 2014 onwards.

Table 1
Results of models for flowering times of first, ten percent, full and last pear (Pyrus communis L.) flowering depending on year and cultivar, for 12 varieties of pear (2 varieties for first flowering). With flowering time (in Julian days) as a dependent variable, year as a smoother and cultivar as a factor. Reporting P-values, F-values, R2 values and an estimate of the intercept, significant P-values are in bold.

Response variable	Fixed effects	Estimate	F-value	p-value
First flowering	**R^2 (adj) = 22.7 %, Deviance explained** = 25.3 %, **e.d.f. value** = 7.82			
	Year	101.96	6.86	**< 0.001**
	Cultivar		21.67	**< 0.001**
Ten-percent flowering	**R^2 (adj) = 25.5 %, Deviance explained** = 27.7 %, **e.d.f. value** = 8.11			
	Year	105.87	21.01	**< 0.001**
	Cultivar		4.88	**< 0.001**
Full flowering	**R^2 (adj) = 22.7 %, Deviance explained** = 25.3 %, **e.d.f. value** = 7.82			
	Year	110.71	43.89	**< 0.001**
	Cultivar		7.72	**< 0.001**
Last flowering	**R^2 (adj) = 22.7 %, Deviance explained** = 25.3 %, **e.d.f. value** = 7.82			
	Year	122.20	49.19	**< 0.001**
	Cultivar		9.80	**< 0.001**

4.3. *Effect of temperature, frost, and rainfall*

TempPC1 explained the largest amount of variation for first (24.5 %), ten percent (30.3 %), full (28.5 %) and last flowering (28.5 %). Whilst FrostPC1 explained the second largest amount of variation in the dataset for first (20.8 %), ten percent (23.0 %), full (22.1 %) and last (22.1 %) flowering. RainPC1 explained the least amount of variation in

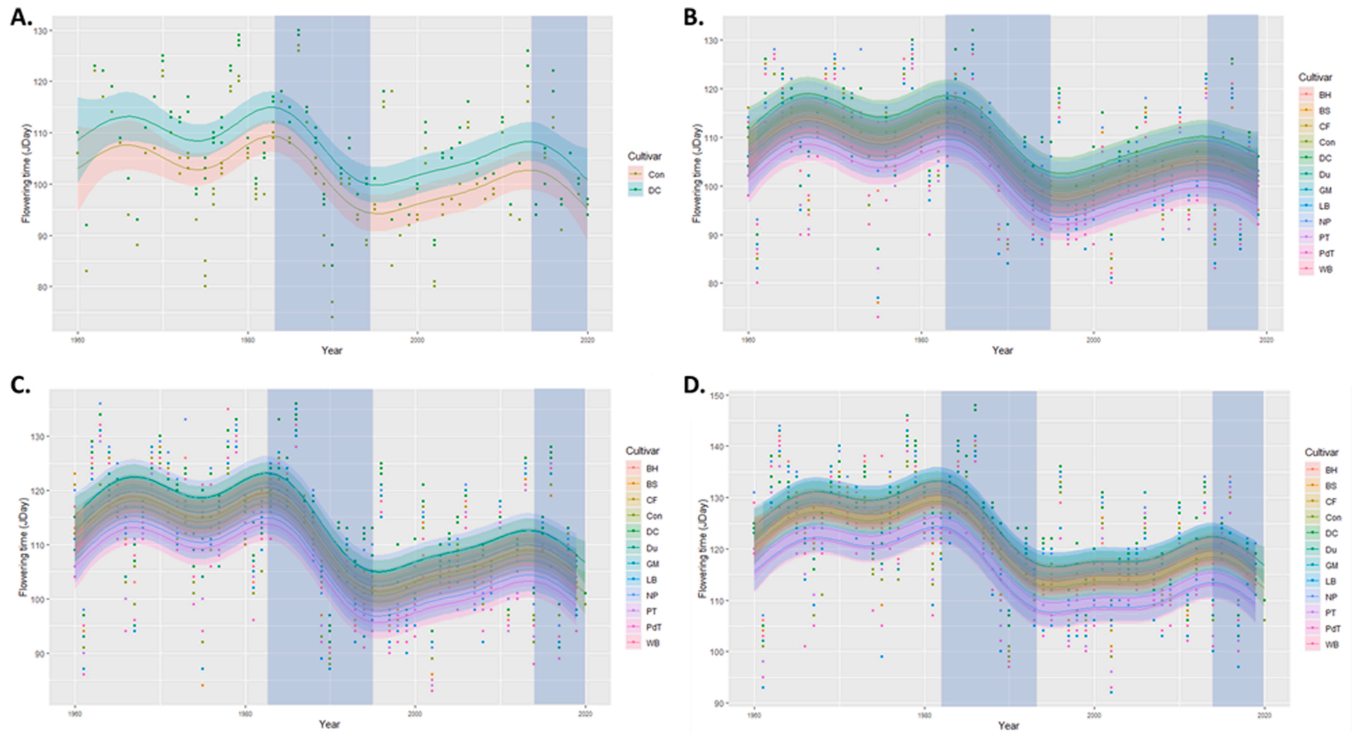

Fig. 2. : Flowering times for A. first, B. ten percent, C. full and D. last pear (*Pyrus communis* L.) flowering Observed values indicated as points with lines representing predicted values with 95 % confidence intervals, for x varieties of pear denoted by different colours, blue shaded areas represent rapid advancements in flowering. For first flowering two cultivars (Conference and Doyenne du Comice) were recorded, for ten percent, full and last flowering 12 cultivars were recorded. Including: Beurre Hardy LA (BH), Beurre Superfin (BS), Clapp's Favourite (CF), Conference (Con), Doyenne du Comice (DC), Durondeau LA (Du), Glou Morceau LA (GM), Louise Bonne of Jersey (LB), Nouveau Poiteau LA (NP), Packham's Triumph (PT), Precoce de Trevoux (PdT) and Williams' Bon-Chretien (WB.

the dataset for first (16.0 %), ten percent (16.2 %), full (16.0 %) and last (16.0 %) flowering. Loadings for PC1 and PC2 for temperature, frost and rainfall for each month are shown in biplots (Fig. S5-S8). More information on the biplots and PCAs can be found in the Supplementary material.

First, ten percent, full, and last flowering models were significant for both TempPC1 and FrostPC1 (Table 2), with marginal R^2 values that ranged from 41.80 % to 44.43 % and conditional R^2 values that ranged from 47.92 % to 56.08 % (Table 2). There was a strong negative relationship between TempPC1 and flowering time for all phenological stages (first, ten percent, full and last), with higher TempPC1 values (representing higher min, max and mean monthly temperatures) resulting in earlier flowering (Fig. 3). A similar negative relationship occurred between FrostPC1 and flowering time; with higher FrostPC1 values (representing less frost during Dec-Apr) resulting in earlier flowering. Therefore, higher monthly temperatures and reduced frost days from December to April are likely to result in earlier flowering.

Table 2
Results of models for flowering times of first, ten percent, full and last pear (Pyrus communis L.) flowering, depending on TempPC1 and FrostPC1, for 12 varieties of pear (2 varieties for first flowering). Reporting P-values, F-values, R2 values and an estimate of the intercept. With flowering time (in Julian days) as a dependent variable, TempPC1 and FrostPC1 as fixed effects and cultivar as a random effect selected. Significant P-values are in bold.

Response variable	Fixed effects	Estimate	F-value	p-value
First flowering	**R^2 (marginal)** = 44.12 %, **R^2 (conditional)** = 56.08 %, **intercept** = 104.74			
	TempPC1	-0.994	150.36	**< 0.001**
	FrostPC1	-4.341	107.87	**< 0.001**
Ten-percent flowering	**R^2 (marginal)** = 44.12 %, **R^2 (conditional)** = 56.08 %, **intercept** = 106.34			
	TempPC1	-0.543	312.32	**< 0.001**
	FrostPC1	-4.721	216.43	**< 0.001**
Full flowering	**R^2 (marginal)** = 44.12 %, **R^2 (conditional)** = 56.08 %, **intercept** = 110.24			
	TempPC1	-1.018	581.76	**< 0.001**
	FrostPC1	-3.958	239.66	**< 0.001**
Last flowering	**R^2 (marginal)** = 44.12 %, **R^2 (conditional)** = 56.08 %, **intercept** = 120.63			
	TempPC1	-1.170	609.39	**< 0.001**
	FrostPC1	-3.104	165.55	**< 0.001**

4.4. *Effect of future emission scenarios*

Even the lowest emissions scenario (RCP2.6) projecting future temperatures predicted a significant advancement in full flowering time by 2080; 5.11 days (± 40.06, SD) earlier compared to current values (1990–2020). Similar observations were seen in first (4.90 days ± 63.81, SD), ten percent (5.07 days ± 34.55, SD) and last (4.68 days ± 43.96, SD) flowering times. However, for the RCP8.5 scenario, this advancement in flowering time by 2080 was far greater, for first (17.76 days ± 65.47, SD), ten percent (18.25 days ± 37.58, SD), full (18.52 days ± 42.39, SD) and last (16.99 ± 45.95, SD) flowering compared to current values (1990–2020). Flowering times for first and ten percent flowering were quite similar (Table 4), suggesting there was little time difference from when the first and ten percent of flowers opened. There was a significant advancement in flowering time depending on January-April temperature for all flowering stages, with higher temperatures resulting in earlier flowering (Table 3). For first, ten percent, full and last flowering models (LMMs) there was a significant negative relationship between January - April temperatures and flowering times (Fig. 4). With marginal R^2 values ranging from 58.35 % to 66.64 % and conditional R^2 values ranging from 70.27 % to 73.72 %. R^2 values explained a large proportion of the variance for all phenological stages.

There was also a significant advancement in flowering time, with respect to future frost day projections. Earlier flowering was predicted for all phenological stages and emissions scenarios by 2080 (Table 4).

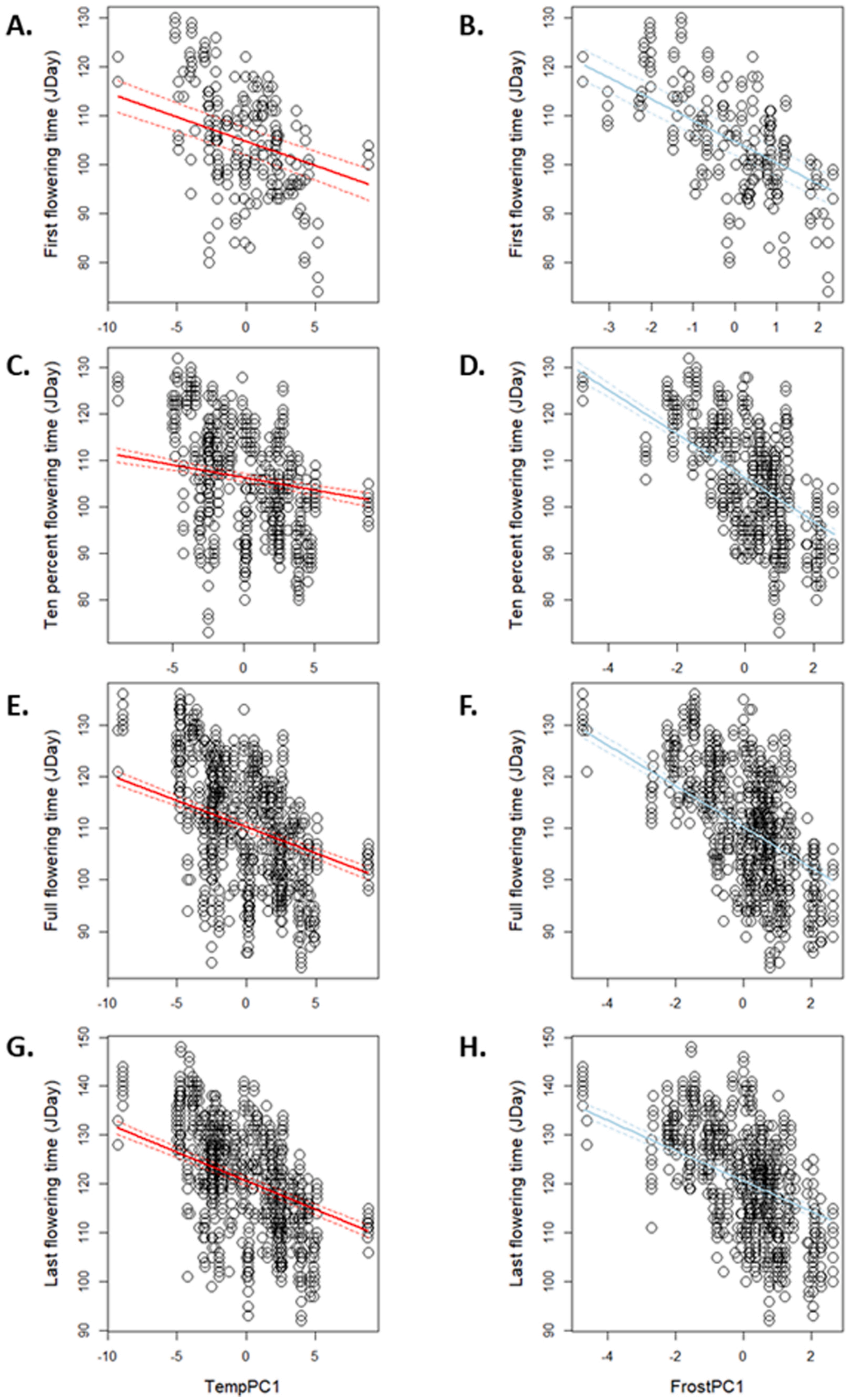

Fig. 3. : Flowering times for first (A, B), ten percent (C, D), full (E, F) and last (G, H) pear (*Pyrus communis* L.) flowering, based on temperature and frost. Lines represent Julian day values with 95 % confidence intervals predicted from TempPC1 based on average FrostPC1 values (A, C, E, G) and FrostPC1 based on average TempPC1 values (B, D, F, H), points represent observed values. With flowering time as a dependent variable, TempPC1 and FrostPC1 as fixed variables and cultivar as a random factor. Year and RainPC1 were not used in the models, due to AIC selection.

Table 3
Results of models for flowering times of first, ten percent, full and last pear (Pyrus communis L.) flowering, depending on January – April temperatures (T) and frost days (F), for 12 varieties of pear (2 varieties for first flowering). Reporting P-values, F-values, R2 values and an estimate of the intercept. With flowering time (in Julian days) as a dependent variable, January – April mean temperature/ frost days as fixed effects and cultivar as a random effect selected. Significant P-values are in bold.

Model	F-value (Jan-Apr temp/frost)	P-value (Jan-Apr temp/frost)	Estimate (intercept)	R^2 (marginal)	R^2 (conditional)	d.f.
First (T)	504.41	**< 0.001**	153.77	58.35 %	70.27 %	255
Ten percent (T)	1427.09	**< 0.001**	155.66	63.87 %	70.54 %	647
Full (T)	2314.61	**< 0.001**	160.35	66.64 %	73.72 %	903
Last (T)	2081.96	**< 0.001**	166.64	62.73 %	72.44 %	905
First (F)	1398.71	**< 0.001**	85.55	43.46 %	55.38 %	255
Ten percent (F)	13176.07	**< 0.001**	88.70	44.16 %	50.57 %	647
Full (F)	15644.49	**< 0.001**	92.60	43.49 %	49.65 %	903
Last (F)	15211.43	**< 0.001**	104.84	38.89 %	47.65 %	905

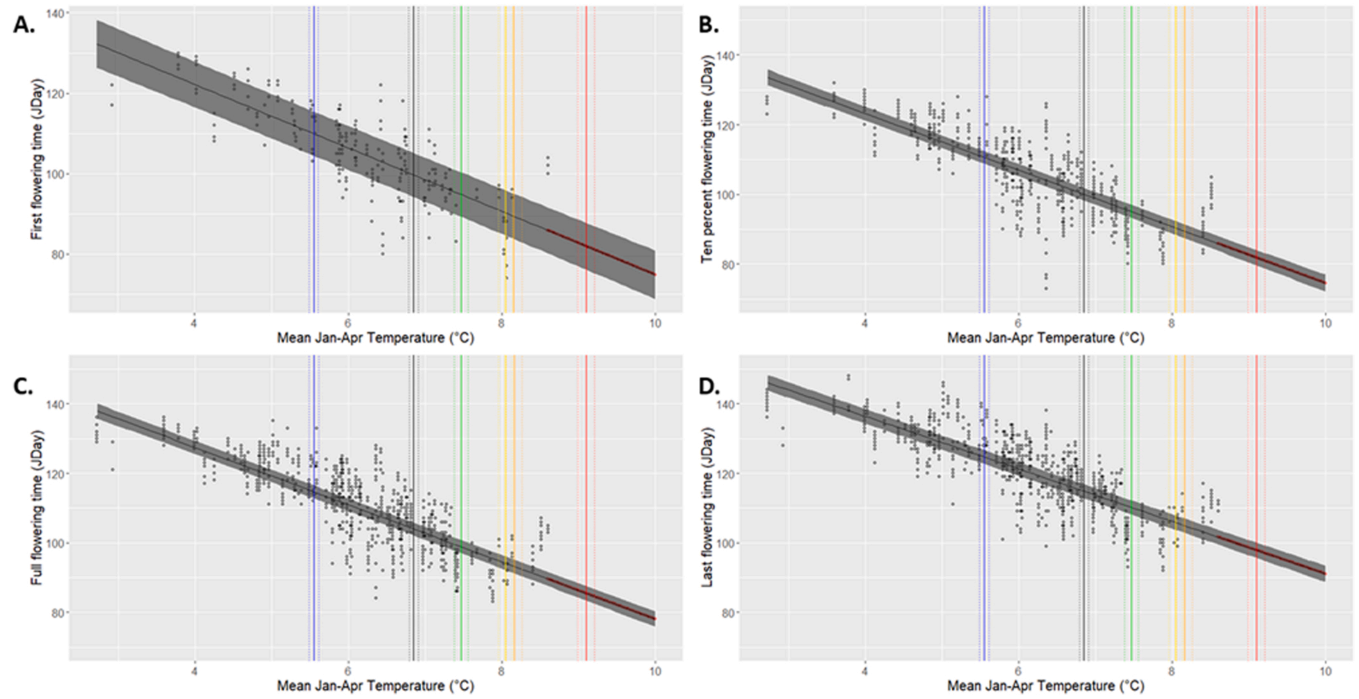

Fig. 4. **:** Flowering times for first (**A**), ten percent (**B**), full (**C**) and last (**D**) pear (*Pyrus communis* L.) flowering, based on January-April mean temperature. The diagonal line represents Julian day values with 95 % confidence intervals predicted from January-April mean temperature, black circles represent observed values, red circles represent values beyond previously observed temperatures. With flowering time as a dependent variable, January-April mean temperature as a fixed variable and cultivar as a random factor. Coloured lines represent different time periods and emissions scenarios, with dotted lines as ± SE: blue (1960–1989), black (1990–2020), green (RCP2.6), yellow (RCP4.5), orange (RCP6.0) and red (RCP8.5). For first flowering two cultivars (Conference and Doyenne du Comice) were recorded, for ten percent, full and last flowering 12 cultivars were recorded.

Table 4
Predicted first, ten percent, full and last pear (*Pyrus communis* L.) flowering times (Julian days ± SE) by 2080 depending on January - April temperatures (**T**) and frost days (**F**). Based on different time periods and emissions scenarios; these include 1960–1989 (before changepoint), 1990–2020 (after changepoint), RCP2.6 scenario, RCP4.5 scenario, RCP6.0 scenario and RCP8.5 scenario. With flowering time (in Julian days) as a dependent variable, Jan-Apr temperature/ frost days as fixed effects and cultivar as a random effect. Frost days not available for RCP 4.5 and 6.0.

Flowering	1960–1989	1990–2020	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Jan-Apr temp (°C)	5.55 ± 0.06	6.85 ± 0.06	7.47 ± 0.09	8.05 ± 0.09	8.16 ± 0.10	9.10 ± 0.11
First (T)	109.98 ± 2.80	99.73 ± 2.80	94.83 ± 2.82	90.26 ± 2.86	89.39 ± 2.87	81.97 ± 2.97
Ten percent (T)	110.65 ± 0.93	100.12 ± 0.94	95.09 ± 0.97	90.39 ± 1.01	89.49 ± 1.02	81.87 ± 1.13
Full (T)	114.69 ± 0.92	104.00 ± 0.93	98.89 ± 0.95	94.12 ± 0.98	93.22 ± 0.98	85.48 ± 1.05
Last (T)	124.71 ± 1.01	114.88 ± 1.02	110.20 ± 1.03	105.82 ± 1.06	104.99 ± 1.07	97.89 ± 1.13
Jan-Apr total frost days	31.93 ± 2.13	23.74 ± 1.51	6.73 ± 1.49	~	~	1.47 ± 0.43
First (F)	107.92 ± 2.81	102.19 ± 2.81	90.26 ± 2.95	~	~	86.58 ± 3.03
Ten percent (F)	110.05 ± 0.94	104.57 ± 0.93	93.20 ± 1.07	~	~	89.68 ± 1.15
Full (F)	113.77 ± 0.89	108.34 ± 0.88	97.06 ± 1.00	~	~	93.57 ± 1.06
Last (F)	123.78 ± 0.99	118.92 ± 0.98	108.83 ± 1.08	~	~	105.71 ± 1.13

The lowest emission scenario (RCP2.6) predicted full flowering times to become 11.28 days (± 40.32, SD) earlier by 2080, whilst the highest emission scenario predicted a 14.77 day (± 41.79, SD) advancement in flowering time compared to current values (1990–2020). Similar advancements were seen for first, ten percent and last flowering times under both future frost day scenarios (Table 4). There was a significant advancement in flowering time depending on total January-April frost days for all flowering stages, with lower numbers of frost days resulting in earlier flowering (Table 3). For first, ten percent, full and last flowering models (LMMs) there was a significant positive relationship between total January - April frost days and flowering times (Fig. 5). With marginal R^2 values ranging from 38.89 % to 44.16 % and conditional R^2 values ranging from 47.65 % to 55.38 %. R^2 values explained a reasonable proportion of the variance for all phenological stages, however January-April temperature explained a higher proportion.

5. Discussion

5.1. Advancements in flowering phenology over time

This study tested three hypotheses: 1. whether pear flowering phenology is advancing over time, 2. if advancements in flowering are driven by changes in weather variables frost and temperature and 3. if flowering phenology will continue to advance under future emission scenarios. The results demonstrated that pear (*Pyrus communis* L.) flowering phenology has advanced in several cultivars and phenological stages within UK orchards (Fig. 2). In addition, these studies showed that both temperature and frost days impacted flowering time, although there may be a correlation between the two variables and that flowering time is predicted to advance under all future climate emissions scenarios by 2080, for both temperature and frost. Current full flowering times (1990–2020) have advanced by an average of 11.44 days (± 14.16, SD) compared to historical conditions (1960–1989), with similar results in all twelve tested pear cultivars and four flowering phenological stages analysed (Table S3-S6). There were also significant differences in flowering time depending on pear cultivar, for example Louise Bonne of Jersey and Precoce de Trevoux had earlier ten percent, full, and last flowering times compared to other cultivars, whilst Nouveau Poiteau LA indicated later flowering (Fig. S4). However, all twelve pear cultivars responded similarly to year, temperature and frost days.

Results from this study indicate that advancement in pear flowering occurred after 1982, which although slightly earlier than some other changepoints (Drepper et al., 2020; Guédon and Legave, 2008; Kunz and Blanke, 2014), is within the range of other studies (Dose and Menzel, 2006; Menzel and Dose, 2005). For example, sweet cherry (*Prunus avium* L.), and lime (*Tilia platyphyllos* L.), changepoints were between 1980 and 1990 (Dose and Menzel, 2006), while multiple flowering records in Germany revealed a maximum change point probability in the mid-1980 s for most of the species analysed (Menzel and Dose, 2005). Therefore, perhaps this rapid advancement in flowering time begins earlier than the late-1980 s changepoint that Guédon and Legave (2008) use for their study on pear and apple flowering phenology.

5.2. Impacts of weather variables

The models that looked at effects of weather variables within our study, indicate that both temperature and frost may influence flowering phenology, while no significant effect of rainfall was detected. Much of the scientific literature focuses solely on how temperature impacts flowering time (Atkinson et al., 2004; Drepper et al., 2020; Fitter et al., 1995; Sparks et al., 2005). For example, Sparks et al. (2005) indicated that for every 1°C of warming for January-March temperatures, pear flowering was 7.2 days earlier, supporting the hypothesis that higher temperatures result in earlier flowering phenology. However, our study highlights that the impact of other variables like frost days need to be studied as well. Although there is a large amount of information in

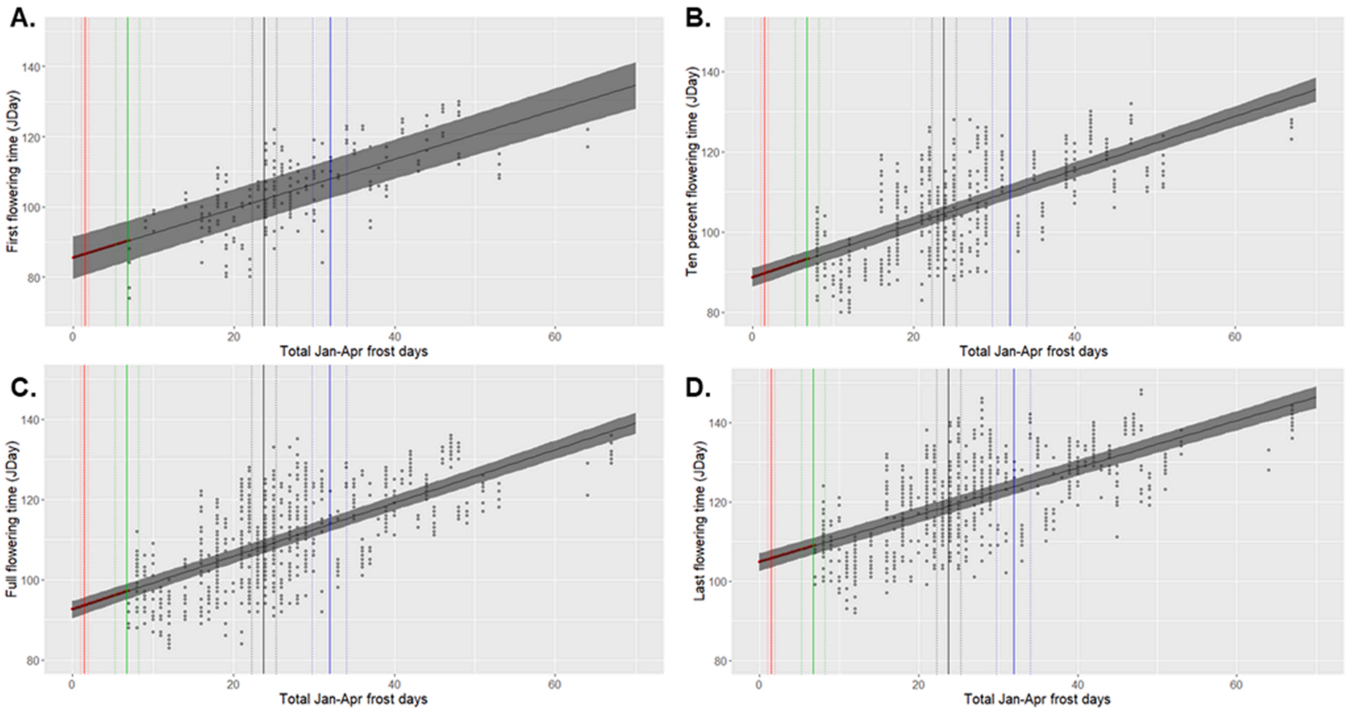

Fig. 5. : Flowering times for first (**A**), ten percent (**B**), full (**C**) and last (**D**) pear (*Pyrus communis* L.) flowering, based on January-April total frost days. The diagonal line represents Julian day values with 95 % confidence intervals predicted from January-April total frost days, black circles represent observed values, red circles represent values beyond previously observed temperatures. With flowering time as a dependent variable, January-April total frost days as a fixed variable and cultivar as a random factor. Coloured lines represent different time periods and emissions scenarios, with dotted lines as ± SE: blue (1960–1989), black (1990–2020), green (RCP2.6) and red (RCP8.5), RCP4.5 and RCP6.0 scenarios were unavailable for calculating future frost days. For first flowering two cultivars (Conference and Doyenne du Comice) were recorded, for ten percent, full and last flowering 12 cultivars were recorded.

papers about frost damaging flower buds or resulting in floral abscission (Anderson and Seeley, 1993; Guo et al., 2019; Rodrigo, 2000), there is a lack of information on frost directly impact flowering time. This may be due to the fact it is difficult to isolate the impacts of frost from low temperatures, indicating the need for further research.

5.3. Future advancements in flowering phenology

Results indicate that flowering times are likely to continue to advance in the future, with respect to the four RCP scenarios. These findings are supported by other studies (Babálová et al., 2018; Chung et al., 2011; Mateescu et al., 2009; Schmidt et al., 2010), for example, an analysis on multiple fruit tree species in Romania (apricot, plum, pear and apple) predicted an intermediate emissions scenario (2°C increase from 1961 to 2004 baseline), could advance pear full flowering times from 106 Julian days (current flowering times) to 96 Julian days by 2080 (10 days) (Mateescu et al., 2009), closely corresponding to our RCP4.5 scenario (Table 4). Mateescu et al. (2009) also used a 1°C increase in air temperature from baseline scenario (1961–2004) where pear flowering advances by 5 days, comparable to the low emissions temperature scenario (RCP2.6) used in this study (5.11 day advancement).

Although, there are a lack of European fruit tree studies that concentrate on phenological changes under high emissions scenarios (Funes et al., 2016; Mateescu et al., 2009). A European study on multiple deciduous tree species found leaf unfurling dates were predicted to advance 14–18 days by 2070–2100 in the RCP8.5 scenario, compared to the 1980–2012 baseline scenario, whilst in the RCP2.6 scenario flowering was predicted to advance by around 4 days (Zhao et al., 2021) although this study focussed on woodland tree species rather than fruit crops. The latter studies are similar to our scenarios.

However, it is important to highlight the potential issues with using the RCP8.5 scenario. Recent articles by Hausfather and Peters (2020a; 2020b) described the RCP8.5 scenario as misleading because it does not account for potential reductions in coal usage and drop in renewable energy costs. This description has been highly contested by Schwalm et al. (2020) who speculated the RCP8.5 was the optimal scenario at tracking CO_2 emissions until 2050, and even by 2100 RCP8.5 was feasible. Therefore, the RCP8.5 scenario has been included in this paper but should be used with some discretion. In addition, the standard deviations for all RCPs scenarios should also be considered, these are quite large especially for the models on first flowering phenology, suggesting a high coefficient of variation. Although a high coefficient of variation is expected due to the large sample size and number of years covered, there is still some uncertainty for scenarios with smaller time differences.

5.4. Potential impacts of earlier flowering in an agroecosystem

Earlier flowering times could have consequences for ecosystem function and services; impacting pollination, pest populations and crop yield. Firstly, earlier flowering and budburst could impact pesticide application (Paltineanu and Chitu, 2020). Kaolin a foliar spray used to control pear psyllid, is recommended for pre-bloom application (February-April) to control, however, when budburst and flowering occurs poor spray coverage of particle films is likely (Nottingham and Orpet, 2020). Therefore, spraying regimes should shift to earlier in the year, which may not be optimal for controlling pest populations, depending on pest emergence. Recent surveys suggest that pear psyllid, *Cacopsylla pyri* (L.), most common pest in UK pear orchards, is estimated to cost the UK pear industry £ 5 million per annum due to crop damage and control costs (AHDB, 2012). Pear psylla also cause considerable economic damage across Europe (Lethmayer et al., 2011; Sanchez et al., 2021), North America (Bartlett, 1978), and Asia (Burckhardt, 1994). Psyllid nymphs produce honeydew; a sugary secretion that encourages the growth of black sooty mould, reducing the economic value of fruit and photosynthesis of leaves (Daniel et al., 2005; Montanari et al., 2015; Salvianti et al., 2008), adults are also a vector of pear decline phytoplasma; which can reduce growth and lead to tree death (Carraro et al., 2001; Kucerová et al., 2007; Süle et al., 2007), thus impacts on psyllid populations may have considerable impacts on global pear production. Earlier budburst and flowering could provide more shelter for pests earlier in the year; plant canopies may provide shelter from agrochemical sprays (Derksen et al., 2007), weather variables (frost, wind, rainfall and temperature extremes), and natural enemies (Norris, 2005). Furthermore, pear pests such as psyllid nymphs are often found sheltering inside buds, flowers or rolled leaves (Solomon et al., 1989), which could provide more protection if available earlier in the year.

Earlier flowering may also result in mismatches between pollinators, if flowering occurs earlier in the year but pollinator emergence does not. This could potentially reduce pollination and impact crop yield (Hegland et al., 2009; Memmott et al., 2007; Vanbergen and Initiative, 2013). Pollinators are vital in the role of pear production; a reduction in pollination services can significantly impact yield quality, quantity and variability (Belien et al., 2021; Fountain et al., 2019; Hünicken et al., 2021, 2020). Hünicken et al. (2021) found a 50 % reduction in pear fruit set during pollinator exclusion experiments. Whilst another study found that higher quality pears were positively associated with proximity to mason bee (*Osmia* spp.) nesting boxes (Belien et al., 2021). An experiment highlighting the impact of plant-pollinator phenological mismatches looked at advancing flowering in apple (*Malus x domestica*), where flowering was 2 ½ weeks earlier (17th-19th of April) than control trees (Kőrösi et al., 2018). Findings suggested that the pollinator community visiting advanced trees differed from the control; with more wild bees, with lower abundances of honey bees and hoverflies. However, there are few plant-pollinator mismatch studies on pear which, as an earlier flowering crop than apple, could experience more pronounced plant-pollinator mismatches. A reduction in pollination due to phenological mismatches, could potentially impact pear yield and quality, highlighting the need for plant-pollinator shift experiments.

Finally, there is also the potential for increased frost damage; a shift to earlier flowering could increase the risk of exposure of pear flowers to spring frost. Spring frost can have a significant impact on fruit yield; one study on pear flowering found that early spring frosts damaged 64 % of flowers in Conference pear, reducing yield by 2 kg per tree and resulting in an economic loss of €1200 ha^{-1}, compared to those that were protected from frost damage using gibberellin (Yarushnykov and Blanke, 2005). However, spring frost risk is also decreasing with respect to climate change (Atkinson et al., 2004; Eccel et al., 2009). Sunley et al. (2006) found that spring frost severity had decreased by 50.4 % at East Malling compared to historical levels (1969 – 1979), thus despite earlier flowering, there may be less risk of damage.

6. Conclusions

Flowering phenology has advanced considerably since the early 1980 s and this study indicates a continued advancement in the future. Earlier pear flowering times are likely for all phenological stages analysed in the study (first, ten percent, full and last flowering times) and for all RCP scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). Models for flowering times based on January-April mean temperatures, explained a large proportion of the variance for all phenological stages, with total January-April frost days also explaining a considerable proportion, suggesting that these variables could be important to consider with respect to flowering. Our data suggests that air temperature, followed by frost days have the greatest influence flowering, with less influence from monthly average rainfall. Earlier flowering and budburst could alter pollination and yield, frost damage risk and potentially enhance pest populations, by influencing canopy microclimate; providing shelter from adverse weather conditions, agrochemical sprays and natural enemies earlier in the year. However, these impacts also depend on the shift in pest and natural enemy populations within the ecosystem; if psyllid nymphs emerge earlier in the year compared to budburst, or if natural enemies do not shift their emergence or migration times, there is the potential for trophic mismatches. Thus, it is vital to consider the responses of all three trophic levels; the primary producer (pear tree), the primary consumer (pear psyllid) and secondary consumer (natural enemy) when predicting responses to climate change. The methods used within this study could be easily applied to other crops, making broader predictions about the impact of climate change on multiple fruit tree and crop species, highlighting the need for long-term phenological data within agriculture.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Dataset accessible from the University of Reading Research Data Archive: https://doi.org/10.17864/1947.000404.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108109.

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