



Climate change fingerprints in recent European plant phenology

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Abstract

A paper published in *Global Change Biology* in 2006 revealed that phenological responses in 1971–2000 matched the warming pattern in Europe, but a lack of chilling and adaptation in farming may have reversed these findings. Therefore, for 1951–2018 in a corresponding data set, we determined changes as linear trends and analysed their variation by plant traits/groups, across season and time as well as their attribution to warming following IPCC methodology. Although spring and summer phases in wild plants advanced less (maximum advances in 1978–2007), more (~90%) and more significant (~60%) negative trends were present, being stronger in early spring, at higher elevations, but smaller for nonwoody insect-pollinated species. These trends were strongly attributable to winter and spring warming. Findings for crop spring phases were similar, but were less pronounced. There were clearer and attributable signs for a delayed senescence in response to winter and spring warming. These changes resulted in a longer growing season, but a constant generative period in wild plants and a shortened one in agricultural crops. Phenology determined by farmers' decisions differed noticeably from the purely climatic driven phases with smaller percentages of advancing (~75%) trends, but farmers' spring activities were the only group with reinforced advancement, suggesting adaptation. Trends in farmers' spring and summer activities were very likely/likely associated with the warming pattern. In contrast, the advance in autumn farming phases was significantly associated with below average summer warming. Thus, under ongoing climate change with decreased chilling the advancing phenology in spring and summer is still attributable to warming; even the farmers' activities in these seasons mirror, to a lesser extent, the warming. Our findings point to adaptation to climate change in agriculture and reveal diverse implications for terrestrial ecosystems; the strong attribution supports the necessary mediation of warming impacts to the general public.

KEYWORDS

attribution, climate change impacts, crops, farmers' activities, flowering, fruiting, leaf colouring, leaf unfolding, natural vegetation

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1 | INTRODUCTION

Although plant phenology is one of the oldest forms of environmental monitoring, with phenological observations taken by ancient civilizations (Koch et al., 2007; Schwartz, 2003), it was only in the 1990s that its renaissance started with key publications on detection of climate change impacts on global vegetation. Keeling, Chin, and Whorf (1996) were the first to report a 7 day earlier start of the growing season based on long-term measurements of atmospheric CO₂ concentration, which Myneni, Keeling, Tucker, Asrar, and Nemani (1997) confirmed using normalized difference vegetation index satellite data from the Northern Hemisphere. Menzel and Fabian (1999) then provided the necessary ground truth by their analyses of long-term European phenological data. Many other papers, summarized in well-cited reviews and relevant chapters in IPCC reports (e.g. Rosenzweig et al., 2007; Walther et al., 2002), confirmed the extraordinary role of phenology as a bio-indicator of climate change. While research initially focused purely on the identification of changes, it then extended to communication of climate change to the general public (e.g. Van Vliet et al., 2003) as well as on various ecological consequences of these changes (Morissette et al., 2009; Thackeray et al., 2010). Nevertheless, at the beginning of this renewed research there was a latent accusation of a publication bias, or cherry picking, in the sense that only the most advancing records or extraordinary changes found their way into popular scientific journals. Therefore, the COST725 initiative collected all available European phenological data (later developed as the PEP725 database, Templ et al., 2018) and analysed more than 100,000 time series for climate change-driven changes (Menzel, Sparks, Estrella, Koch, et al., 2006, hereafter referred as GCB2006). The GCB2006 study concluded that there was indeed a strong response in European phenology to climate change and that these changes matched the warming pattern. With more than 1,500 citations in the Web of Science Core Collection, this study has a high relevance for the scientific discourse on climate change impacts on the biosphere. It was also the backbone of the corresponding assessment of observed changes and responses in natural and managed systems of AR4 WGII of the IPCC (Rosenzweig et al., 2007) as well as of the subsequent paper of attribution of global impacts in nature to anthropogenic warming (Rosenzweig et al., 2008).

Thus, the well-accepted role of phenology as a climate change indicator is based on the formal attribution of shifted phenological onset dates to anthropogenic-induced warming (Rosenzweig et al., 2007, 2008), demonstrating at the same time that the phenological trends are not just natural variability, for example, as shown by Guan (2014) for two phenophases which unequivocally corresponded to the respective winter/spring warming trends. Most studies, however, rely on proof of the sensitivity of phenological phases to temperature as the fundamental prerequisite of climate change detection and attribution, and have linked phenological changes to temperature increases (e.g. Cook et al., 2012; Thackeray et al., 2016). Since there is thorough evidence that spring phenological development is also partially triggered by fulfilment of winter chilling and by photoperiod

(e.g. Laube et al., 2014; Tang et al., 2016; Vitasse & Basler, 2013), it is debated whether phenological changes still mirror the recent ongoing warming, or mirror it to the same extent as before. Therefore, an update of the assessment of phenological changes across Europe and their attribution to climate change is necessary. In contrast to the GCB2006 publication, this update will uniquely concentrate on plant phenology.

Major factors that may impact on the results of this update are different changes in (apparent) temperature sensitivity (e.g. Fu, Piao, et al., 2015; Fu, Zhao, et al., 2015). Species-specific increases in heat requirements related to a decrease in chilling have been especially identified as the main reason (Fu, Piao, et al., 2015). However, there are also contrasting opinions for example, by Wang et al. (2017). Gusewell, Furrer, Gehrig, and Pietragalla (2017) showed that for Switzerland there are still no indications of a lack of chilling leading to altered temperature sensitivities. Changes in temperature sensitivities are reported as not uniform over time (Chen et al., 2019) and, in particular, a weakened temperature response was observed since 2000 (Fu et al., 2014). Spatial variations in temperature sensitivity have been linked to mean annual temperature and to seasonal temperature range (Lapenis, Henry, Vuille, & Mower, 2014; Menzel, Sparks, Estrella, & Roy, 2006; Wang et al., 2014). Both major backup systems to prevent a premature spring development (chilling, photoperiod) may finally lead to nonlinear responses of phenological onset dates to forcing temperatures (Jochner, Sparks, Laube, & Menzel, 2016).

Temperature sensitivity has also been shown to vary with specific plant traits, such as evolutionary relatedness, and to support invasions and plant performance (e.g. Wolkovich, Cook, & Davies, 2014). For wheat and maize in agriculture there are hints of geographic differences among cultivars in sensitivity to vernalization, day length and temperature (Van Bussel, Stehfest, Siebert, Müller, & Ewert, 2015). However, there are still major knowledge gaps concerning the so-called 'false' phenological phases, such as sowing or harvesting in agriculture, whose timings are decided by farmers. The GCB2006 study and follow-up publications provided the first evidence that the phenological signal in agriculture was weaker than the signal for wild growing plant species (Bock, Sparks, Estrella, & Menzel, 2013; Estrella, Sparks, & Menzel, 2007; Menzel, Sparks, Estrella, Koch, et al., 2006; Menzel, Vopelius, Estrella, Schleip, & Dose, 2006). However, it can be anticipated that, sooner or later, agricultural management and/or choice of cultivars will also be adapted to the new potential growing seasons. The drivers of autumn phenology, such as leaf colouring and leaf fall, are still far from being completely understood (Estrella & Menzel, 2006; Gallinat, Primack, & Wagner, 2016; Gill et al., 2015; Wu et al., 2018).

The aim of the current paper is to update the previous study on climate change fingerprints in European phenology and include as many plant species/phenophases as are available. Recent publications have exclusively focused on a few prominent spring leaf unfolding phases and results of those may be strongly related to the choice of analysed species, having different sensitivities and covering different seasons. Phenology is controlled by seasonal patterns in the warming signal (Lapenis et al., 2014) and these will vary by location (spatial differences

in the climate signal) and study period (temporal differences in the climate signal, e.g. Rutishauser et al., 2009). Consequently, this update is more than timely since the climate signal has not been stable, but temporal variations or trends in climate change have been reported, especially related to the so called hiatus or standstill period (Zang, Jochner-Oette, Cortés, Rammig, & Menzel, 2019). A publication has already indicated that there were no trends in spring and autumn phenology during this warming hiatus period (Wang et al., 2019). Another phenological regime shift in the mid-1980s was also related to discontinuous temperature changes (Reid et al., 2016).

Thus, this update study will focus on the following research questions by analysing the complete picture of plant phenological changes in Europe:

1. We expect that there is an inherent variation of trends and will thus concentrate on how do phenological onset dates/trends vary overtime and by season and what drives the strength of recent trends.
2. An important result of the GCB2006 paper was that farmers' activities exhibited weaker trends and that there was an unclear change pattern in autumn. We will therefore study recent differences in climate change signals among wild plants, fruit trees, agricultural crops and farmers' activities and expect 'false' farming and agricultural crop phenology to be more similar to wild species and fruit trees now, but leaf colouring and fall still unchanged.
3. Addressing the discussion on lack of chilling, altered warming patterns and differential responses in farming we ask whether, and for which phenological groups, there is still an attributable fingerprint of climate change in phenology.

2 | MATERIALS AND METHODS

2.1 | Phenological data

Complete original plant phenological observation data were retrieved individually from the European Meteorological Services of Germany (DWD), Austria (ZAMG) and Switzerland (MeteoSwiss). Data of these countries account for 96.3% of the PEP database (Templ et al., 2018), thus our results are comparable to any other based on PEP725 data. However, these national phenological databases are richer in sites, species and phenophases; therefore, although having a smaller spatial extent, are preferred for this study (see map in Figure S1a).

Unfortunately, it was not possible to directly update the GCB2006 data set due to a lack of access to the recent phenological data of specific countries. However, data from Germany, Austria

and Switzerland constituted around 96.7% of the GCB2006 data set. Thus, it is justified to consider the new data set as comparable.

Out of the complete phenological data from these countries, we took observational data between 1951 and 2018 with time series (series per species/phase/station) longer than 29 years and ending in or after 2000. Duplicates were removed by averaging the respective DOYs (onset dates as day of the year) in the same year. Very early phenological events (e.g. hazel or snowdrop flowering in December) were allocated to the correct reference year by negative DOYs.

For data correction (following e.g. Chen et al., 2018, 2019; Ma, Huang, Hänninen, & Berninger, 2019; Vitasse, Signarbieux, & Fu, 2018), we filtered out in each series those observations outside the range median $\pm 3.5 \times$ MAD (median absolute deviation), which is definitely a more than conservative approach (see Leys, Ley, Klein, Bernard, & Licata, 2013; Miller, 1991), since only the extreme values considered absolutely wrong were excluded (in our case less than 0.7% of the data).

This data set, hereafter called Update, comprised more than 4.2 million observational records and almost 97,000 time series (Table 1). For the specific species and phases observed in the different networks we refer the reader to Kaspar, Zimmermann, and Polte-Rudolf (2014), ZAMG (2013), and Gusewell, Pietragalla, Gehrig, and Furrer (2018).

It is important to notice that a direct comparison between GCB2006 and the updated results is not straightforward since some differences in phenophases and data selection procedure exist. Thus a GCB2006s (s = simulated) data set was defined as a subset of Update containing identical species/phases/stations, but restricted to the GCB2006 period and series length (1971–2000, 15+ years). This simulation of GCB2006 conditions in Update allowed studying the effects of ongoing climate change post-2000 as well as methodological aspects (15+ vs. 30+ year series), when comparing Update and GCB2006s results. In contrast, GCB2006 results are only reported and discussed with respect to possible effects due to some different sites/phenophases in GCB2006s.

In the previous GCB2006 study comprising ~100,000 series in the period 1971–2000 plant phenological series were categorized into four groups (see Table 2). For Update and GCB2006s, we further refined this categorization into nine clusters, taking into account BBCH coding of phases (Meier, 1997) as well as farming activities, and additionally defined four periods/seasons, different from those in GCB2006.

2.2 | Climatic and other auxiliary data

The E-OBS v19.0HOM gridded data set with a 0.25 degree regular grid (Cornes, Schrier, Besselaar, & Jones, 2018), which is the homogenized

TABLE 1 Statistics of the phenological data set with 30+ year series in the period 1951–2018 ending ≥ 2000

	Observations	Series	Species	Phases	Stations
Germany	4,085,218	93,171	53	22	1,628
Austria	51,951	1,340	37	20	53
Switzerland	115,098	2,485	21	8	127

TABLE 2 Categorization of phenophases in Update comprising nine clusters and four phenological periods/seasons as compared to GCB2006

GCB2006—four phenogroups		Update—nine clusters		Update—four periods/seasons	
b0	Farmers' activities	F _{sp}	<u>F</u> armer <u>s</u> pring Sowing of spring cereals/crops (b0) and the first follow-up BBCH scale (germination, leaf development, part of b1 GCB2006)	FS	<u>F</u> arming Season Time period of farmers' activities from earliest phenophase in F _{sp} to the latest phenophase in F _{au} available at each station
		F _{au}	<u>F</u> armer <u>a</u> utumn Sowing of autumn cereals (b0) and the first follow-up BBCH scale before winter (germination, leaf development, part of b1 GCB2006)		
b1	Leaf unfolding, flowering	Cv _{sp}	<u>C</u> rop <u>v</u> egetative <u>s</u> pring All BBCH macrostages from 1 (leaf development, if not in F _{sp}), 2 (tillering), 3 (stem elongation) to 4 (booting) in agricultural crops		
		Cg _{sp}	<u>C</u> rop <u>g</u> enerative <u>s</u> pring All BBCH macrostages from 5 (inflorescence emergence, heading) to 6 (flowering, anthesis) in agricultural crops		
		FWv _{sp}	<u>F</u> ruit trees & <u>w</u> ild plant species <u>v</u> egetative <u>s</u> pring All BBCH macrostages from 0 (bud sprouting), 1 (leaf development) to 3 (shoot development) in fruit trees and wild plant species		
		FWg _{sp}	<u>F</u> ruit trees & <u>w</u> ild plant species <u>g</u> enerative <u>s</u> pring All BBCH macrostages from 5 (inflorescence emergence) to 6 (flowering) in fruit trees and wild plant species		
b2	Fruit ripening	F _{su}	<u>F</u> armer <u>s</u> ummer (ripeness, harvest) All BBCH macro stages from 7 (development of fruit) to 8 (ripening) in agricultural crops plus harvest dates (part of b0 GCB2006)	CgP	<u>C</u> rop <u>g</u> enerative <u>P</u> eriod Period from beginning of flowering in Cg _{sp} to fruit maturity stages in F _{su}
		FWg _{su}	<u>F</u> ruit trees & <u>w</u> ild plant species <u>g</u> enerative <u>s</u> ummer All BBCH macrostages from 7 (development of fruit) to 8 (ripening, maturity of fruit and seed) in fruit trees and wild plant species	FWgP	<u>F</u> ruit trees & <u>w</u> ild plant species <u>g</u> enerative <u>P</u> eriod Period from (beginning of, full) flowering (FWg _{sp}) to fruit maturity/first ripe fruits in FWg _{su}
b3	Leaf colouring	FWv _{au}	<u>F</u> ruit trees & <u>w</u> ild plant species <u>v</u> egetative <u>a</u> utumn Phenophases related to senescence such as leaf colouring and leaf fall	GS	<u>G</u> rowing <u>S</u> eason Period from leaf unfolding (FWv _{sp}) to leaf colouring (FWv _{au})

version of E-OBS v19.0e and thus more suitable to derive long-term trends, was used for extracting the daily mean temperature for all stations during 1951–2018. It was additionally adjusted for station-specific elevation by using the elevation difference between the station and the average of the climatic grid cell derived from the global raster Digital Elevation Model, the Global 30 Arc-Second Elevation Data Set (GTOPO30) together with E-OBS v19.0HOM, based on a temperature lapse rate of 6.4°C/km (see also Ma et al., 2019; Olsson & Jönsson, 2014).

Phenological traits (woodiness—woody vs. nonwoody, and pollination mode—insect vs. wind pollination) for all species were extracted from the LEDA database (Kleyer et al., 2008).

2.3 | Analyses of trends

Phenological changes were determined as linear regressions of onset days (DOY) against year for all series (i.e. 30+ years in Update). For GCB2006s (1971–2000), similar to GCB2006, all 15+ year series were considered. *p* values of the linear regression slopes were adjusted for multiple comparisons using the false-discovery-rate (FDR; Benjamini & Hochberg, 1995). Proportions of (significant) negative/(significant) positive trends and mean slopes (Tr_{mean}) were determined for the different categories described in Table 2. The uncertainty range of Tr_{mean} is the 95% confidence interval for estimating the mean (of the slopes), and not the 95% interval of the underlying data. Thus, the range is

equivalent to the 95% CI of a one-sample t test. Trends were also determined for moving 30 year blocks over the whole study period where 15+ years of valid data existed. The mean slope per category and 30 year block was then calculated to assess the varying trend strength over time. Daily mean temperature (T_{mean}) was extracted and processed into annual and seasonal averages (DJF winter, MAM spring, JJA summer, SON autumn) in order to calculate the respective linear annual and seasonal temperature trends over the entire 1951–2018 time period for Update based on the geographical coordinates of each phenological station.

Furthermore, the overall mean onset dates (DOY_{mean}) and mean temperature (T_{mean}) over the whole time period (1951–2018) for each phenological series (per species/phase/station) were calculated and aggregated in weeks to study the phenological anomalies from the average. Every 10 year time block (1950s, 1960s and so on) was selected and the corresponding DOY_{mean} and T_{mean} were again calculated for the corresponding weeks of the year. The deviations of DOY_{mean} and T_{mean} from the overall mean were considered as the phenological anomalies and 95% confidence intervals for each week in each time block were calculated. For each decade we used loess smoothing of the temperature anomalies and inverted the y -axis for better visual comparison with the phenological anomalies.

2.4 | Trend modelling

In order to understand what the partial contribution of explanatory factors to the observed phenological trend was, we followed a modelling approach. Explanatory factors/variables were the nine clusters (cluster9, see Table 2), topography (longitude, latitude and elevation), traits (woodiness, pollination mode), start year of records and number of recorded years. A symbolic description of the generalized additive model (composed of linear, nonlinear/smooth and factorial terms) is

$$\begin{aligned} \text{Phenological trend} &= \text{cluster9} + \text{woodiness} + \text{pollination mode} + \text{longitude} + \text{latitude} \\ &+ \text{elevation} + s(\text{start year}) + s(\text{number years}) + \text{woodiness} \\ &* \text{pollination mode} + \text{cluster9} * \text{longitude} + \text{cluster9} * \text{latitude} \\ &+ \text{cluster9} * \text{elevation}, \end{aligned}$$

where cluster9, woodiness and pollination mode are factorial variables (encoded as dummies in the model) with levels indicated as above (cluster9), woody or nonwoody (woodiness), wind or insect (pollination mode); all other variables are numeric; start year and number years were included as smooth functions (denoted with prefix s ; using penalized splines); all other numeric variables were included with linear coefficients; interaction terms are denoted by $*$.

In the results section, the model coefficients are visualized using so-called effect plots, which plot the predicted effect of each explanatory variable on the outcome. This makes comparisons easier with respect to the different units and range of the explanatory variables, and allows the identification of interaction terms and smooth terms.

The effect of each variable is calculated by holding all other variables constant (except for interactions). The models were fitted in R statistical software version 3.6 using the mgcv-package (Wood, 2017), effects were calculated using the emmeans-package (Lenth, 2019), and results were visualized using the ggplot2-package (Wickham, 2016).

2.5 | Attribution of the phenological change pattern to temperature changes

Attribution followed the methods proposed by Rosenzweig et al. (2007, 2008). First, based on statistically significant trends only, the percentage of significant trends (out of all significant trends) matching the direction expected from climate warming was determined, both for the phenological groups of GCB2006 and of Update. According to IPCC likelihood terminology, >66% probability corresponds to 'likely', >90% to 'very likely', and >95% to 'extremely likely'.

Second, we applied a spatial approach based on all sites for which we tested the effect of the corresponding temperature trends on all phenological trends. For this we divided all (significant as well as non-significant) temperature trends in terciles (below, average, above) on a seasonal basis and the phenological trends by sign and significance (negative significant, negative nonsignificant, positive nonsignificant, positive significant). A frequency analysis was performed on this cross tabulation using Chi-square tests and p -values were adjusted for multiple comparisons using the FDR. Pearson (standardized) residuals for each cell were determined to assess their relative contribution to the total Chi-square score.

All calculations were done in R statistical software (R Core Team, 2019).

3 | RESULTS

3.1 | Phenological changes

For leaf unfolding and flowering, fruiting and farmers' activities, the percentage of negative trends slightly increased, for example from 87% (GCB2006s) to 89% advanced for leaf unfolding and flowering (Table 3). The percentage of expected, delayed trends for leaf colouring increased from 49% (GCB2006s) to 57%. Longer (30+ years) series led to considerably higher proportions of significantly advancing trends (e.g. 54% of leaf unfolding and flowering series compared to 30% in GCB2006s). While GCB2006 as well as GCB2006s indicated a less clear pattern for both farmers' activities and leaf colouring, the direction of changes was more obvious in Update with farmers' activities being mostly advanced (72%) and leaf colouring predominantly delayed (57%). Though the phenological change signal in terms of the proportion of significant trends increased, the mean advance in days per year was considerably weaker than in GCB2006s. For example, the mean slope for leaf unfolding and flowering was -0.394 ± 0.003 days/year (95% confidence intervals) in GCB2006s and only -0.240 ± 0.002 days/year in Update.

TABLE 3 Summary of phenological trends in Update compared to GCB2006s and GCB2006

	n	Negative_all			Positive_all			Positive_sig.			Tr _{mean} (days/year)					
		GCB 2006	GCB 2006s	Update	GCB 2006	GCB 2006s	Update	GCB 2006	GCB 2006s	Update	GCB 2006	GCB 2006s	Update			
Farmers' activities	22,338	11,273	12,285	0.57	0.68	0.72	0.13	0.15	0.34	0.43	0.32	0.28	0.07	-0.041	-0.149 ± 0.008	-0.126 ± 0.004
Leaf unfold., flowering	64,027	58,099	63,667	0.78	0.87	0.89	0.31	0.30	0.54	0.22	0.13	0.11	0.02	-0.250	-0.394 ± 0.003	-0.240 ± 0.002
Fruit ripening	11,191	13,854	15,073	0.75	0.82	0.84	0.25	0.32	0.52	0.25	0.18	0.16	0.03	-0.237	-0.405 ± 0.008	-0.256 ± 0.005
Leaf colouring	5,643	5,249	5,971	0.48	0.51	0.43	0.12	0.11	0.15	0.52	0.49	0.57	0.26	0.017	-0.015 ± 0.013	0.036 ± 0.007

Note: Update refers to quality controlled series of 30+ years in the 1951–2018 period, ending in 2000 or later, of the DWD/ZAMG/METEOSWISS data sets. GCB2006 refers to quality controlled series of 15+ years in the 1971–2000 period in a European phenological data set including COST725 data (Menzel, Sparks, Estrella, Koch, et al., 2006; see Section 2). GCB2006s simulates GCB2006 results by subsetting 15+ year series in the 1971–2000 period from the Update data set. n: number of series, Negative_all/Positive_all: proportions of negative and positive trends, Negative_sig./Positive_sig.: proportions of significantly negative and positive trends ($p < .05$), p -values adjusted by FDR for multiple testing, Tr_{mean}: mean slopes (days/year), with 95% confidence intervals for Update and GCB2006s.

For the nine clusters, trends in terms of sign, proportions of significant trends and mean slope are summarized in Figure 1 (corresponding numbers are given in Table S1a,b). Except for FWV_{au} which comprises leaf colouring and fall in fruit trees and wild species in autumn, the overall change pattern in all other clusters was advancing. All spring and summer clusters had higher percentages of negative and significant negative trends in Update than in GCB2006s (Figure 1a), for example, ~90% of the four climate-driven spring categories (Cv_{sp}, Cg_{sp}, FWv_{sp}, FWg_{sp}) advanced (86%, 90%, 92% and 91%, respectively), up to 60% significantly. Interestingly, for ripening in fruit trees and wild species in summer (FWg_{su}), the percentage was slightly smaller with 81% (46% significantly) advanced, although this pattern also intensified from GCB2006s to Update. In contrast, the mean slopes of the spring and summer phenological groups (Cv_{sp}, Cg_{sp}, FWv_{sp}, FWg_{sp} and FWg_{su}) very clearly indicated throughout smaller advances in Update than in GCB2006s. This decrease in trend strength was also quite large, for example, -0.428 ± 0.004 days/year for FWg_{sp} in GCB2006s compared to only -0.254 ± 0.002 days/year in Update (Figure 1c; Table S1a).

The percentage of delayed leaf colouring and leaf fall increased to 57% (26% significant) compared to GCB2006s (49% and 11%, respectively). The mean slope was $+0.036 \pm 0.007$ days/year versus -0.015 ± 0.013 days/year in GCB2006s, thus more clearly indicating a later ending of the growing season.

Undoubtedly ~3/4 of the farmers' spring and summer activities (F_{sp} sowing of spring cereals, F_{su} harvest) were advancing (74% and 84%, respectively) and the percentages of significant advances clearly increased from GCB2006s to Update (14%–31% and 24%–53%, respectively). For farmers' sowing of autumn crops (F_{au}), more advanced than delayed series were observed; however, the picture was still similar to GCB2006s except that more trends (both advances and delays) were significant (Figure 1a; Table S1a). Surprisingly, mean slopes became less negative, except for F_{sp} which advanced more strongly in Update than in GCB2006s (-0.116 ± 0.005 vs. -0.075 ± 0.011 days/year).

About 84% of the series indicated a lengthening of the growing season (GS, from leaf unfolding to colouring) and 48% were significantly longer (Figure 1b). The mean trend was $+0.261 \pm 0.008$ days/year. The farming season (FS, period of farmers' activities from spring to autumn) shortened by -0.149 ± 0.022 days/year with two-thirds of the trends being negative. Although the generative period for agricultural crops (CgP, from flowering to ripeness) was definitively shortened (-0.205 ± 0.019 days/year, 78% negative), there was no clear change pattern for fruit trees and wild plants (FWgP, from flowering to ripeness; see Table S1b). The average trend was almost zero with roughly equal numbers of the series showing a shortening or lengthening of the generative period.

3.2 | Variation of phenological changes across different periods

The approach of calculating trends over moving 30 year windows across the whole study period 1951–2018 clearly indicated

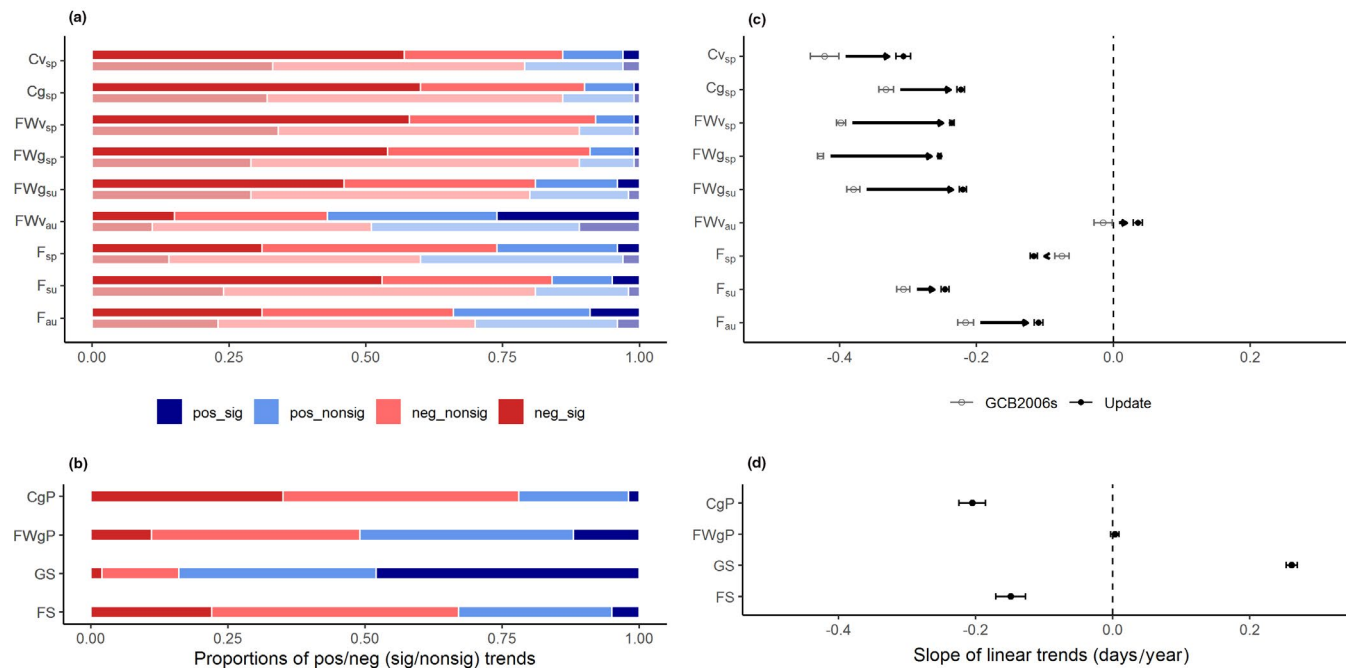


FIGURE 1 Phenological trends in Update for the nine clusters (a, c) and four periods (b, d) as defined in Table 2. CgP, Crop generative Period; Cg_{sp}, Crop generative spring; C_v_{sp}, Crop vegetative spring; F_{au}, Farmer autumn; FS, Farming season; F_{sp}, Farmer spring; F_{su}, Farmer summer; FWgP, Fruit trees & wild plant species generative Period; FWg_{sp}, Fruit trees & wild plant species generative spring; FWg_{su}, Fruit trees & wild plant species generative summer; FWV_{au}, Fruit trees & wild plant species vegetative autumn; FWV_{sp}, Fruit trees & wild plant species vegetative spring; GS, Growing Season. (a, b) Proportions of positive/negative (significant after FDR adjustment $p < .05$ /nonsignificant) trends. Paler lower bars in (a) indicate the respective proportions for GCB2006s. (c, d) mean slopes of linear trends (days/year) with 95% confidence intervals, open circles in (c) indicate the respective mean slopes for GCB2006s [Colour figure can be viewed at wileyonlinelibrary.com]

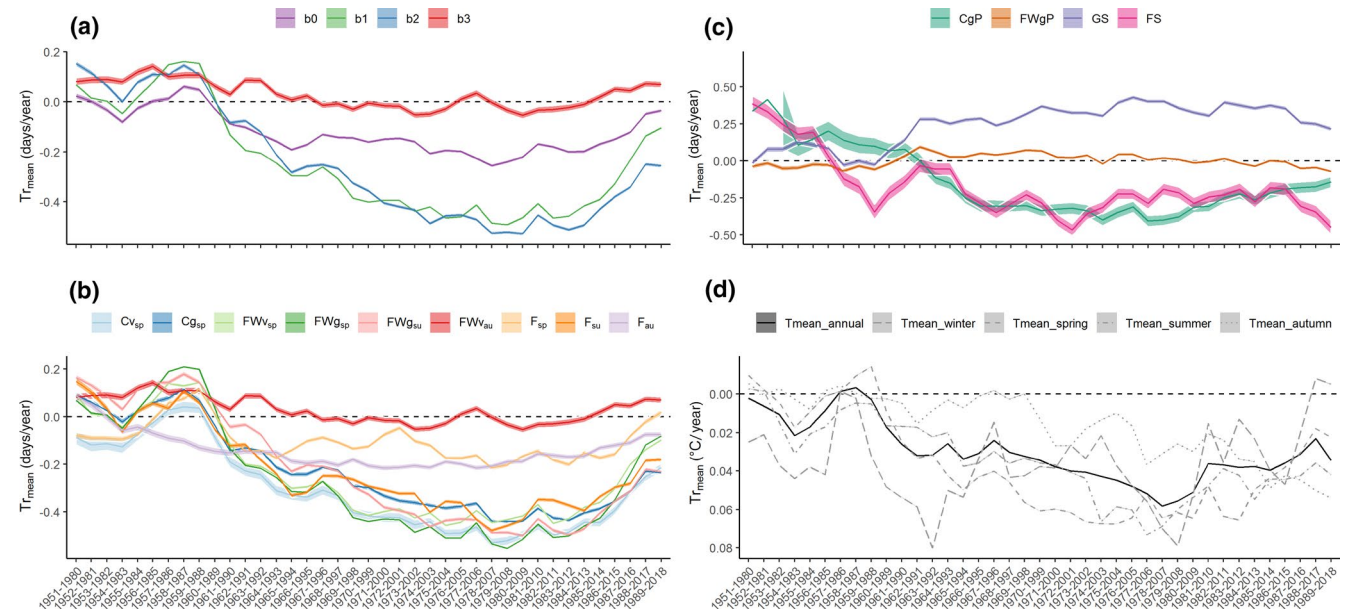


FIGURE 2 Mean slopes of linear trends (Tr_{mean}) calculated for all 15+ year phenological series in respective 30 year moving window blocks within 1951–2018 for the Update data set. Shading indicates 95% confidence intervals in all subplots. Phenophase groups according to (a) GCB2006, (b) nine clusters, and (c) four periods as defined in Table 2, (d) mean slopes of annual and seasonal mean temperature trends with inverted y-axis for all sites and time blocks [Colour figure can be viewed at wileyonlinelibrary.com]

time-varying changes in onset dates (Figure 2). Until the end year of 1988 slopes were stable and positive for most phenogroups (Figure 2a) and clusters (Figure 2b) indicating delayed onsets.

Advancing onsets were only determined for some phenophases related to agriculture (C_v_{sp}, F_{sp}, F_{au}, i.e. development of crops in spring, sowing of spring crops and winter cereals). After the end

year of 1989, slopes for leaf colouring and leaf fall (b3 in Figure 2a, FWv_{au} in Figure 2b) oscillated around zero, whereas for all other groups/clusters the trends were becoming more and more negative. The minimum slopes (i.e. strongest advancing trends) were reached around 1979–2008 and the most pronounced advancing mean trend of -0.553 ± 0.004 days/year was recorded for flowering phases of fruit trees and wild plant species in spring (FWg_{sp}). Afterwards, trends became weaker again, especially for spring leaf unfolding and flowering of fruit trees and wild plant species (FWv_{sp} , FWg_{sp}). Finally, for the most recent 30 year period (1989–2018) they were all less than half of their maximum in the 1980s to 2010s although still negative (Cv_{sp} -0.214 ± 0.018 , Cg_{sp} -0.237 ± 0.010 , FWv_{sp} -0.098 ± 0.007 , FWg_{sp} -0.080 ± 0.005 , FWg_{su} -0.232 ± 0.010 , F_{su} -0.179 ± 0.009 , F_{au} -0.075 ± 0.012 days/year) except for F_{sp} ($+0.018 \pm 0.013$ days/year).

The recorded changes of the four periods (GS, FWgP, FS, CgP) differed substantially (Figure 2c). The growing season (GS) was clearly prolonged for all 30 year periods ending after 1989, exhibiting a maximum slope of $+0.428 \pm 0.016$ days/year for the period 1976–2005 and a considerably smaller one of $+0.215 \pm 0.017$ days/year for the final 30 year block. The generative period of fruit trees and wild plant species (FWgP) showed almost no changes in any direction, thus was stable across the study period. The FS, defined as the period between first and last farmers' activities, and the crop generative period (CgP) were predominantly shortened for the 30 year periods ending after 1989, both reaching mean slopes of -0.449 ± 0.048 and -0.143 ± 0.038 days/year, respectively, in the final 30 year period.

Quite clearly, these changes in the intensity of phenological changes overtime were related to temperature changes. Slopes of mean annual temperature warming increased in time till 1978–2007 ($+0.0582 \pm 0.0004^\circ\text{C}/\text{year}$), and for the last block (1989–2018) they only reached $+0.0344 \pm 0.0004^\circ\text{C}/\text{year}$ (Figure 2d). This picture was also true for all single seasons except autumn.

3.3 | Variation of phenological changes and decadal anomalies across seasons

Plotting mean trends over weeks of the year (Figure 3) clearly exhibits systematic variations with season. Only weeks covered by less data points at the beginning or end of record had wider confidence intervals of the mean trends. In autumn, trends of delayed leaf colouring and leaf fall (b3 in Figure 3a, FWv_{au} in Figure 3b) increased from week 36 to 47, suggesting that sites or species with later senescence were delayed more. During the first 3 months of the year (week 4–12), advance in flowering of first fruit trees and wild plant species (FWg_{sp} in Figure 3b) decreased distinctly, indicating that strongest advances in spring phenology were observed for early flowering species and/or very warm sites. The more detailed clusters show that the advance of leaf unfolding of fruit trees and wild plant species (FWv_{sp} in Figure 3b) was stable across the weeks 11–23, matching those of FWg_{sp} . Consequently, when adjusted for

identical weeks in spring, there were no differences in trends between generative and vegetative phases.

Respective spring phases for crops (Cv_{sp} , Cg_{sp}) advanced more strongly than for fruit trees and wild plant species before week 20 and less strongly afterwards. In summer, from week 28 onwards, fruit ripening in fruit trees and wild plant species (FWg_{su}), as well as ripening of crops and harvest dates in agriculture (F_{su}), exhibited similar advancing trends. However, before that, in early summer (week 22 to 28), farmers' activities were more strongly advancing than contemporaneous ripening phases in FWg_{su} . Farmers' activities in early autumn from mid-August to end of September were almost unchanged, whereas in October a clear advancing response to warming was visible.

Mean decadal phenological anomalies across weeks of the year (Figures S2 and S3a) allow deeper insights into the trend structure. The spring and summer clusters (uppermost five panels in Figure S3a) provide a text book example of climate change-driven changes in phenology: In the last four decades the weekly mean anomalies gradually decreased, whereas respective decadal anomalies of weekly mean temperatures increased. Interestingly, during week 10–13 the anomalies of leaf unfolding and flowering of fruit trees and wild plant species in spring (FWv_{sp} , FWg_{sp}) displayed a reverse order of the last three decades: 1991–2000 had the earliest mean onset dates, 2011–2018 the least early ones.

This reverse order was equally apparent in mean weekly temperature anomalies (Figure S3b) where the 1991–2000 decade exhibited the warmest weekly temperatures and the 2011–2018 decade the coldest ones, but from week 4 to 8, thus 6 weeks prior to the leafing/flowering phenological response. In general anomalies in T_{mean} varied more strongly from week to week mirroring the more fluctuating weather/temperature (Figure S3b). For leaf colouring and fall (FWv_{au}) the 1951–1960 decade had the earliest onset dates, thus, it is likely that the inclusion of this decade in Update (1951–2018) triggered the now delaying autumn trends. Farmers' activities in spring and summer (F_{sp} , F_{su}) only exhibited earlier than average starting dates in the last and the two last decades respectively.

3.4 | Modelling of the slopes of the phenological trends

Since phenological trends varied with phenological group (Table 3) and cluster (Figure 1), year (Figure 2), season (Figure 3) and length of the series (Table 3), these variables, as well as geographical coordinates and species traits, were used in the generalized additive model. The following reported values are model estimates, and their uncertainty relates to the uncertainty in estimating the model (i.e. confidence intervals do not cover the variability of the data, but the uncertainty in estimating the mean values). The results (Figure 4) indicate that all phenological clusters except leaf colouring and leaf fall (FWv_{au}) exhibited negative trends of on average -0.224 days/year. Only farmers' activities had smaller

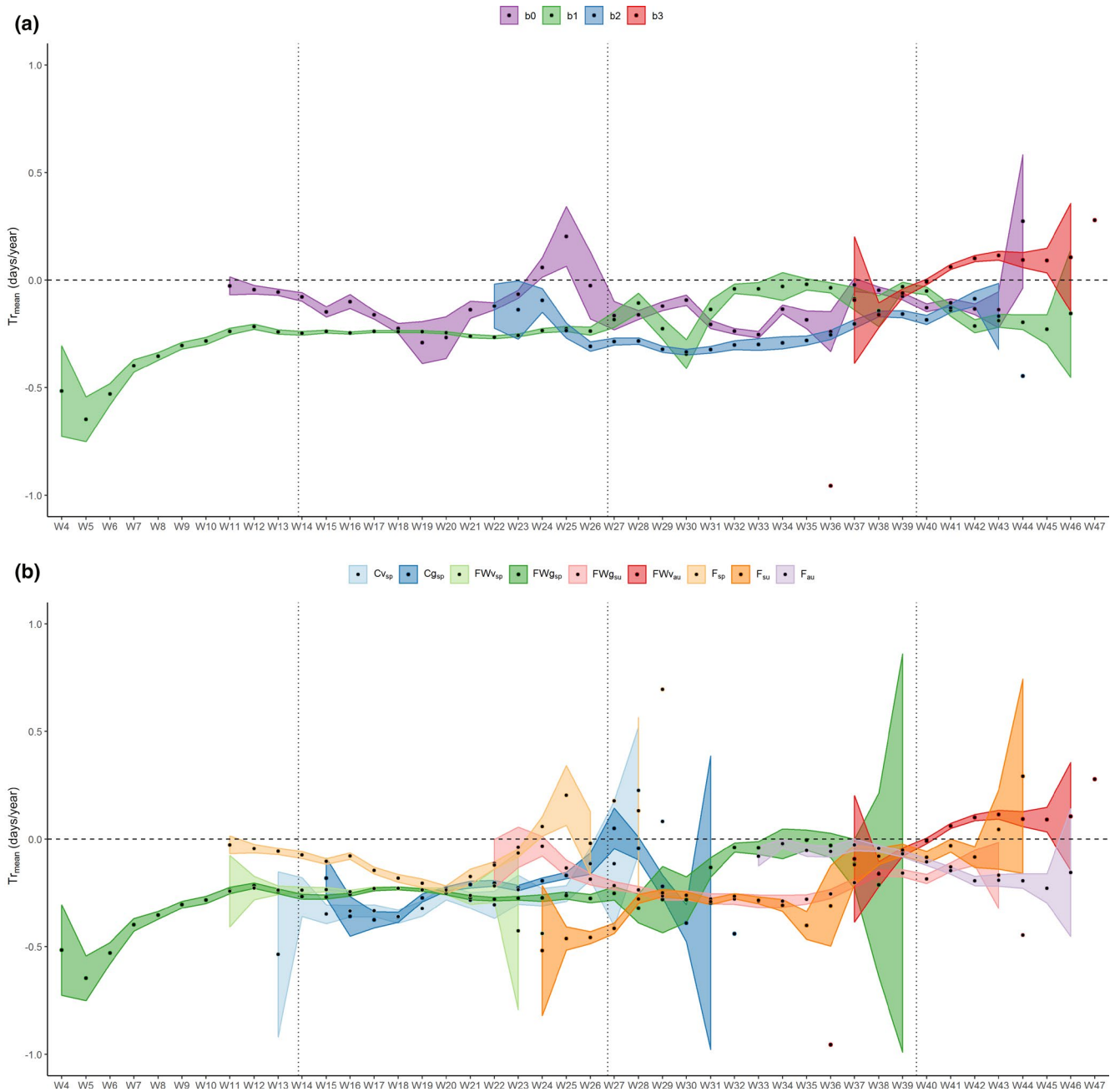


FIGURE 3 Mean slopes of linear trends per week of the year (W4–W47) calculated for all series in Update. Phenophase groups according to (a) GCB2006, and (b) nine clusters. Mean values indicated by solid black circles, vertical division at 90 day intervals. Shading indicates 95% confidence intervals (CI). CIs exceeding the y-axis range are not shown by default [Colour figure can be viewed at wileyonlinelibrary.com]

negative trends: in spring -0.126 days/year (95% CI: -0.136 , -0.116) and autumn -0.128 days/year (-0.138 , -0.118). Flowering of fruit trees and wild plant species in spring, FWg_{sp} , -0.277 days/year (-0.284 , -0.270), and vegetative development of agricultural crops in spring, Cv_{sp} , -0.317 days/year (-0.328 , -0.306), had stronger trends. For species traits, the models showed that nonwoody insect-pollinated species had smaller trends with -0.150 days/year (-0.159 , -0.142) than the other three combinations (on average -0.210 days/year). There was no obvious effect of the length of the phenological series on trends. However,

the start of the series mattered: Series starting at the end of the 1970s were linked to the strongest advancing trends, while earlier and later starting series were associated to less strong advancing trends. For many clusters there was a mixed effect of longitude on trends, and clear negative effects of latitude and elevation; however, the largest impacts were seen for elevation. The average effect on phenological trends of latitude was -0.010 days/year per degree latitude and for elevation -0.140 days/year per km elevation, thus higher elevations were consistently associated with stronger advancing trends.

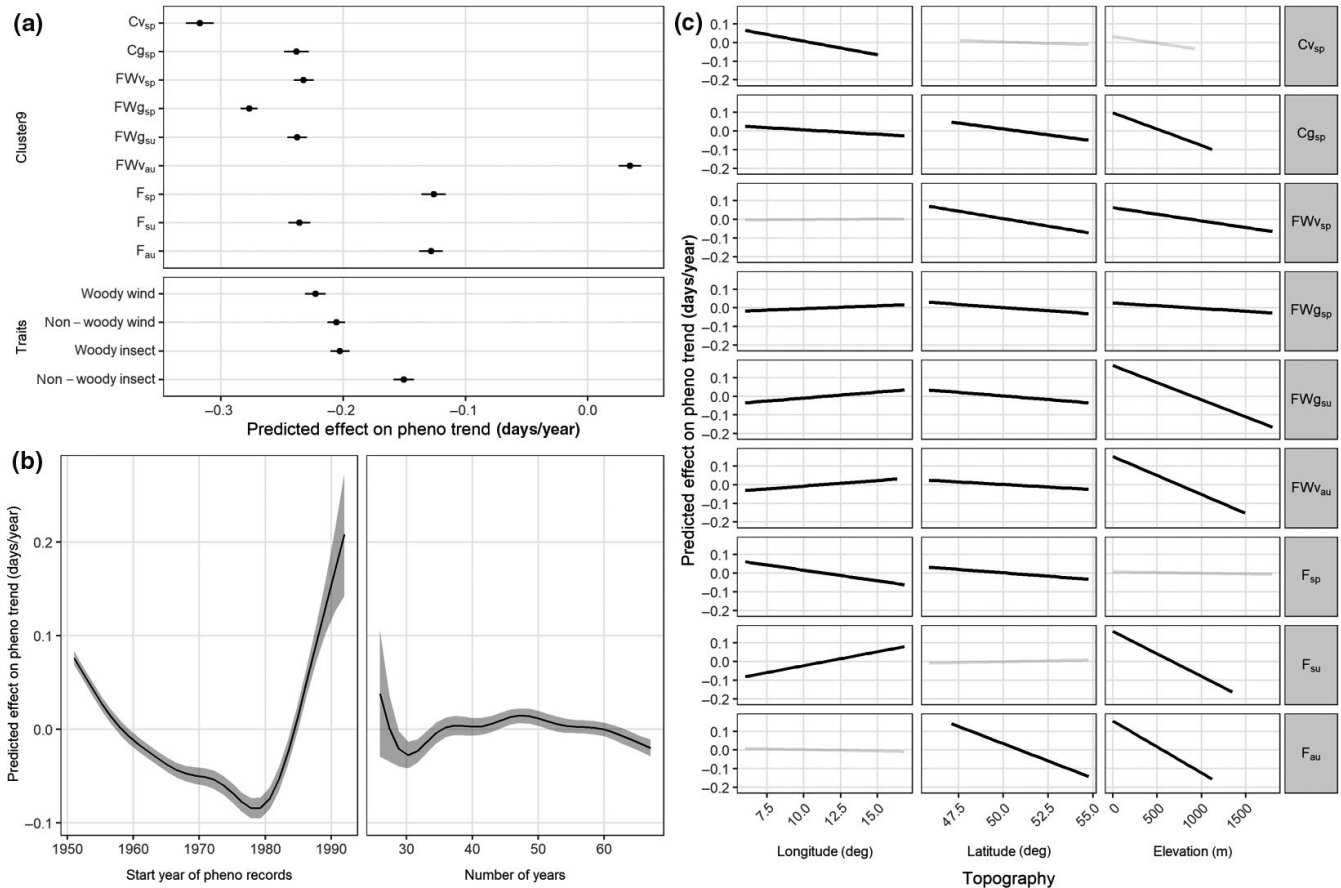


FIGURE 4 Effect plots of the generalized additive model showing the predicted effect of each explanatory variable on the slope of phenological trends in Update. (a) Factorial variables of nine clusters and of selected plant species traits with 95% confidence intervals, (b) start year and number of years as smooth functions with penalized splines with 95% confidence intervals, (c) topographical variables interacting with phenological clusters

3.5 | Attribution of phenological changes to warming

About 96% and 95% of the significant changes of leaf unfolding and flowering (b1) and fruit ripening (b2), respectively, were negative, thus indicating advancing onset dates with warming (see Table 3). For farmers' activities, 83% of the significant trends were negative. Significant leaf colouring and leaf fall trends (b3 in Table 3, FWV_{au} in Table S1a) were 63% positive, hinting to delayed autumn with warming. This pattern is confirmed by the corresponding analysis for the spring and summer clusters (data from Table S1a): 95%, 98%, 98%, 98%, 92% and 91% of their significant trends (CV_{sp} , CG_{sp} , FWV_{sp} , FWg_{sp} , FWg_{su} , F_{su}) were negative and matched the warming signal. Only 89% and 78% of the significant trends of farming activities in spring and autumn were advancing. Thus, advancing farming activities are likely, phenological phases in summer are very likely and phenological phases in spring, such as leaf unfolding and flowering, are even extremely likely to be attributable to increasing temperatures.

Concerning the spatial match of temperature trends to all phenological trends, results of the Chi-square tests indicated

that for all phenological clusters, except crop vegetative development in spring (CV_{sp}) as well as ripening phases of fruit trees and wild plant species in summer (FWg_{su}), there was at least one significant association of phenological trends with seasonal warming patterns in winter/spring/summer (Figure 5; Figure S4). Crop generative development in spring (CG_{sp}) was significantly associated with winter and spring warming patterns, and the respective spring phases in fruit trees and wild plant species (FWV_{sp} , FWg_{sp}) even displayed a stronger positive association (see Figure S4). For the latter two, counterintuitively average and above average summer temperature trends were associated with delayed (subsequent) spring phenophases. Above average warming in winter and spring was significantly associated with delayed leaf colouring and leaf fall (FWV_{au}). For farmers' activities, the Chi-square tests indicated that advancing spring activities (F_{sp}) were significantly linked with above average warming in winter, but below average warming in summer. For farmers' summer activities, above average warming in summer and autumn was associated with advancing summer trends (F_{su}). In contrast, below average warming in summer was connected to advancing autumn activities (F_{au}).

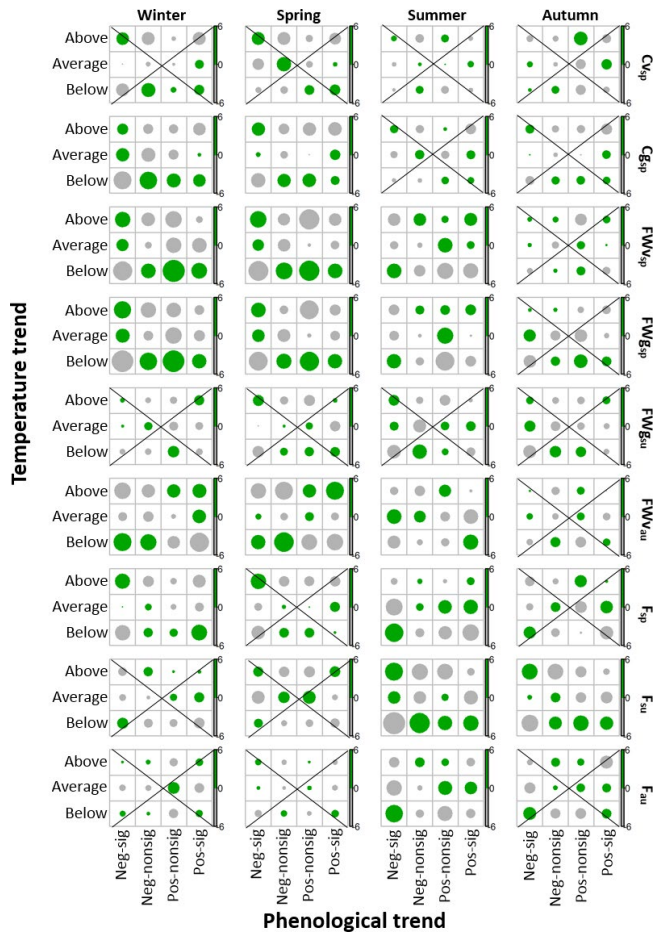


FIGURE 5 Attribution of phenological trends for the nine clusters (see Table 2) to trends in seasonal temperatures by Chi-squared test (absolute numbers are given in Figure S4). Pearson residuals indicate the relative contribution of a cell to the total Chi-square. Crossed out combinations were not significant (p -values adjusted for multiple comparisons of $4 \times 9 = 36$ tests by FDR). The size of the circle is proportional to the amount of the contribution, green indicates positive residuals, which specify a positive association between phenological and temperature trends, and light grey implies a repulsion or negative association [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

The update of the GCB2006 study almost two decades later has clearly revealed that there is still a significant climate change pattern in European plant phenology. Since a direct comparison of the almost 97,000 Update series to the GCB2006 ones was not possible, we simulated GCB2006s results based on Update to study the effects of ongoing climate change after 2000 as well as of longer series (15+ vs. 30+ years). Differences in the trend structure of GCB2006 and GCB2006s suggested that any results of trends analyses may also partly be driven by the set of species and phenophases included. In our case a considerable adjustment in the observational programme of the DWD in 1991 has led to a substantial reduction in the number of (agricultural) species/

phases when series were selected to end in 2000 or later. ZAMG data selection mirrors a similar decrease of observations in the last two decades (see Figure S1b).

In the following the results will be discussed with respect to the three guiding research questions. There is still a clear picture of phenological advance except for autumn. For the vegetative and generative phases of crops, fruit trees and wild plants, longer time series (30+ years in Update) led to $\geq 90\%$ advancing trends in spring ($C_{g_{sp}}$, FW_{sp} , $FW_{g_{sp}}$), $\geq 81\%$ for $C_{v_{sp}}$ and $FW_{g_{su}}$, and $\sim 75\%$ for the farmers' activities in these seasons (F_{sp} , F_{su}). Accordingly, at least 30+ year series are needed for robust trend estimations (Dose & Menzel, 2004; Rosenzweig et al., 2007) as also confirmed by our trend modelling. Longer series were also linked to a higher percentage of significant trends, but assuming comparable variability and change rates, greater statistical power would be expected to lead to an increase in significance.

Although the proportion of trends that was significant increased, mean advances of spring and summer phases decreased in the extended period beyond 2000, especially for fruit trees and wild plants, but also to a lesser degree for crops. This confirms findings of a review by Piao et al. (2019) of decelerated or even reversed trends in recent years. Only farmers' spring activities exhibited a stronger advance (-0.116 ± 0.005 days/year) in Update which is well explained by considerably earlier dates in 2011–2018 as shown in the anomaly plots. It was not the aim of our paper to disentangle the contribution of the obvious reasons for this result, but the moving window approach clearly showed that spring and winter warming trends exhibited very similar variation over-time, that is, the strongest trends in the 1980–2010 period. Thus, it is more likely that a reduction in forcing conditions has driven the decrease in the advance of spring and summer phenology (as reported by Güsewell et al., 2017 for Switzerland) than a lack of chilling (e.g. Fu, Zhao, et al., 2015). Nevertheless, there are differences in this decreased sensitivity of warming with leaf unfolding and flowering of fruit trees and wild plant species exhibiting the strongest decline in trend strength.

In autumn, leaf colouring and fall trends now predominantly (57%) indicated delayed onset dates with a mean positive trend. However since 1951–1960 was characterized by earlier mean onset dates, it has to be checked whether a prolongation of the records into the past (1951–1970) might have driven this result. In contrast, farmers' activities in autumn were still advancing, but to a lesser degree, although the percentage of advancing trends slightly decreased. To conclude, any changes in leaf colouring and fall dates are still not well understood. With ongoing climate warming, more heat and drought extremes, such as in 2003, 2015 and 2018, in conjunction with biotic disturbances might lead to premature leaf senescence interfering with correct observation of autumn phenophases.

There was still a lengthening of the growing season of ~ 0.26 days/year and this lengthening only marginally decreased in the most recent decade confirming many other studies (e.g. Kolářová, Nekovář, & Adamík, 2014). In this respect our paper disagrees with the findings

of Chen et al. (2019), likely because species other than trees were also incorporated in our spring signal. In contrast, the FS was shortened by -0.15 days/year due to a smaller advancing trend in farmers' spring activities than in the development of wild plant species, matching the previous findings of Estrella et al. (2007). In principle, farmers themselves should profit from this earlier start of the (abiotic) growing season, also by using more cold tolerant cultivars of maize and summer cereals, but according to Parker, Shonkwiler, and Aurbacher (2017) this advance is buffered by still severe minimum temperatures. Equally, crop ripening and harvest (F_{su}) may also be partially triggered by the choice of early versus late-maturing cultivars (Peltonen-Sainio & Jauhiainen, 2014), explaining the shortened crop generative period.

The control of phenology by seasonal warming patterns (Lapenis et al., 2014) leads to a variation in the phenological signal over time, with time of the year, site and elevation. Our results, for nearly all phases, match findings of stronger advancing trends at higher elevations (e.g. Ziello, Estrella, Kostova, Koch, & Menzel, 2009) resulting, for example, in a more uniform spring across elevations (Vitasse et al., 2018). Across the seasons the strongest advances in spring phenology were observed for early flowering species and/or very warm sites. Modelling clearly confirmed differential advances: Farmers' activities in spring and autumn only advanced at half of the rate, whereas ripening phases and especially crop vegetative phases in spring advanced more than the mean rate of ~ 0.22 days/year. It is important to notice that spring development of winter cereals is (at least) comparable to that of fruit trees and wild species. Nonwoody and insect-pollinated plant species advanced less than wind-pollinated species, which was also found in the western Mediterranean (Gordo & Sanz, 2009). Advancing trends reached their maximum rates when starting at ~ 1978 , a finding which corresponds to the reported 1980s regime shift (Reid et al., 2016).

Although the change pattern varied over time, the (still) advancing trends could be attributed to warming. More specifically, based on percentages of significant trends matching the warming, advancing farming activities are likely, ripening phases in summer are very likely and phenological spring phases, such as leaf unfolding and flowering, are very or extremely likely to mirror the increasing temperatures. The spatial approach confirmed this attribution, however, to a lesser degree. Seasonal warming was significantly associated with spring phases' advance in fruit trees and wild plant species, generative phases in crops as well as farmers' activities mirroring winter and spring warming (descending order, F_{sp} not with spring warming). Advancing farmers' summer activities clearly mirrored summer and autumn warming patterns. The association in autumn was reversed with below average warming in winter and spring being linked to advanced leaf colouring and fall (see equally Estrella & Menzel, 2006; Zohner & Renner, 2019) and less warming in summer being linked to advanced farmers' autumn activities. Most interestingly, what has been described as carry-over effects (Sparks, Buras, Estrella, & Menzel, 2020; Zohner & Renner, 2019), is depicted by this attribution analysis, where below average warming in summer was linked to advancing phenological trends in spring ($FW_{v_{sp}}$, $FW_{g_{sp}}$, F_{sp}). Thus, formal attribution of phenological trends does not only shape a

formal fingerprint in nature, but additionally fosters a deeper understanding of the drivers.

The results of the updated study are relevant in a number of ways. A stronger advance of early spring wind-pollinated species leads to an earlier start of the allergenic pollen season. Citizen scientists can still observe climate change in their backyard and these spring advances including a lengthening of the growing season are to a large extent attributable to warming, although our refined analysis on nine clusters showed the superiority of fruit trees and wild species in this respect. A tricky question to be investigated in the future is why summer ripening phases of fruit trees and wild species do not mirror any warming pattern, whereas summer harvesting in agriculture does.

Our results clearly underline that farmers' decisions (weaker trends and smaller trend changes in spring and autumn) may be driven by other factors as well, although farmers seem to respond/adapt since their activities in spring were the only phase to exhibit stronger advancing trends in Update. A shortening of the crop generative period may have undesired consequences for yield, but will allow more intercropping or earlier sowing of winter cereals.

Results of our comprehensive analysis of the complete plant phenological data set in these three Central European countries underline that the ecological consequences of these changes are challenging to be assessed due to inherent variation of changes over time, season, with topography and plant traits, but this variation does not hamper climate change attribution.

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DATA AVAILABILITY STATEMENT

Phenological data are available through the PEP725 database (<http://www.pep725.eu/>) as well as the complete data through the meteorological services themselves.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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