

Farmers' annual activities are not tracking the speed of climate change

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ABSTRACT: Global climate change impacts are already tracked in many physical and biological systems and they reveal a consistent picture of changes, e.g. an earlier onset of spring events in mid and higher latitudes and a lengthening of the plant growing season. However, available results are mainly based on the study of wild plants, whereas only a few studies have hinted at an earlier spring onset for agricultural plants. So far, no comprehensive study has compared phenological shifts between agricultural crops, fruit trees and wild plants. We analysed phenological time series of 93 phases in Germany (1951–2004) employing Bayesian nonparametric function estimation, and found that events related to the production of annual crops clearly differ from spring and summer events in wild plants and fruit trees. While non-farmer driven agricultural events and spring and summer growth stages of wild plants and fruit trees advanced (i.e. occurred earlier) by 4.4 to 7.1 d decade⁻¹, farming indicators, such as sowing and subsequent emergence of spring and winter crops, as well as harvesting, advanced by only 2.1 d decade⁻¹. The estimated functional behaviour and emergence of discontinuous changes are clearly different between the 2 groups. We conclude that phenological responses to temperature changes are only reflected in data of wild plants, fruit trees and those spring growth stages of winter crops and later growth stages of spring crops which are exclusively triggered by climate, while other changes due to agricultural production are subject to management practice alterations.

KEY WORDS: Response · Climate change impact · Temperature · Adaptation · Agriculture · Phenology · Germany · Climate change

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1. INTRODUCTION

Studies examining the impacts of global warming on terrestrial ecosystems reveal a consistent pattern of change; the response of phenological change to warming across the northern hemisphere seems to be especially well documented (IPCC 2001, Sparks & Menzel 2002, Walther et al. 2002, Parmesan & Yohe 2003, Root et al. 2003). Studies have focused on identifying changes (detection) and relating them to changing regional climates (attribution). In general, phenological shifts are detected by ground observations (e.g. Menzel & Fabian 1999, Walther et al. 2002) and by analysis of the CO₂ signal (Keeling et al. 1996) and of Normalised Difference Vegetation Index (NDVI) satellite data (Myneni et al. 1997, Zhou et al. 2001). The latter 2 provide a spatially-

and species-averaged signal, integrating agricultural and more natural areas. In contrast, phenological observations are mainly focused on wild plants. Numerous research papers have examined the response of wild plant species, including comparison of annuals and perennials (e.g. Fitter & Fitter 2002). Meta-analyses by Parmesan & Yohe (2003) and Root et al. (2003) have summarised the global 'fingerprint' of climate change, finding mean spring advances (i.e. occurrences at an earlier date) of 2.3 and 5.1 d decade⁻¹, respectively (discrepancies in these figures being mainly due to different methods). The mean advance of spring in Europe is estimated to be 2.5 d decade⁻¹ (Menzel et al. 2006). Annually recurring events in wild plant species are called true phases, because their onset is exclusively triggered by environmental factors, predominantly climate. Events in agricul-

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tural species, which are driven by farmers' activities such as tilling and harvesting, are known as false phases (Schnelle 1955). However, the phase subsequent to a false phase (e.g. emergence after sowing), although strictly defined as a true phase, is strongly related to its preceding false phase. In consequence, results of time series analyses of emergence dates are similar to the preceding false phase (Menzel 2000).

The few studies that have examined these changes in detail have also found a temporal advance in farmers' activities in Central Europe (Chmielewski et al. 2004, De La Torre & Benoit 2004, Hildén et al. 2005). In France, for example, sowing of maize and wheat is, on average, up to 1 mo earlier compared to 30 yr ago (De La Torre & Benoit 2004). In Finland, sowing dates of potato have advanced by ~5 d over the last 35 yr, whereas the sowing dates of spring cereals have not changed much despite the observed warming. Hildén et al. (2005) assumed that the latter observation may be due to special risks connected with late spring frosts. In Germany, phenological stages have advanced moderately since 1961 for annual crops such as maize, winter rye and sugar beet (Chmielewski et al. 2004). Most of these reported trends are determined by linear regression methods, which do not allow for further comparisons of trends and functional behaviours (see Dose & Menzel 2004).

The Intergovernmental Panel on Climate Change (IPCC), Working Group II on Impacts, Adaptation and Vulnerability will, in its next report (AR4), assess observed changes in natural and managed systems (www.ipcc.ch/activity/wg2outlines.pdf). In the present study the entirety of phenological changes in natural terrestrial ecosystems and managed agricultural systems has to be considered. However, especially in agriculture, the analysis of evidence of change and its attribution is more complicated because farmers adapt to those climatic changes and concurrently alter their crop production.

In our study, we focused on the question of whether observed phenological shifts in agriculture and wild plants differ, and if so, how? To address these questions we analysed long-term records of annual crops (both farmer and non-farmer driven events), fruit trees and wild plants using Bayesian time series analysis. Special attention was paid to the comparison of different indicators of change such as model types, periods of discontinuous change and trends or rates of change.

2. DATA AND METHODS

2.1. Phenological data

A comprehensive phenological data set for Germany, collected by the German Meteorological Ser-

vice, was analysed. The data covered the period 1951–2004 and included data from more than 1600 stations. Only a few phases started later in the 1950s and ended earlier in the 2000s. The data set was comprised of data describing 93 different seasonal events (phenophases) for 3 plant types: agricultural annual crops (39 phenophases), fruit trees (23 phenophases) and wild plants (31 phenophases). The data encompassed the whole seasonal cycle and included false phases. After assigning all species to plant types (agriculture, fruit trees & wild plants) and classifying their phases across the seasonal cycle to growth stages (e.g. flowering), we defined 12 groups of phenophases (G0–G11) (Table 1).

For all phenophases, the annual mean anomalies for Germany were determined by employing the Menzel (2003) procedure: (1) anomalies were calculated as the deviations of each annual date from the corresponding station mean (1971–1986 station) but only if >11 yr out of 16 yr of observation were available; (2) annual mean anomalies (1951–2004) were computed for Germany. The period 1971–1986 was selected because, within the phenological database, this period is characterised by the greatest number of stations and highest data densities. Due to the way in which the national mean annual anomalies were calculated, further adjustment for missing values at single stations was not necessary.

2.2. Methods

The Bayesian approach to analysing the functional behaviour of the 93 anomaly time series and their trends follows the methodology introduced by Dose & Menzel (2004) to which we refer for computational details. The analysis and description of the phenological time series employed 3 different models. Model I represents the hypothesis of no change at all. It assumes a functional behaviour constant in time with associated zero rate of change/trend and will be called the constant model henceforth. Model II, the linear model, assumes a time-linear change of the observed phenomenon with associated constant rate of change/trend. Model III allows for a time-varying trend. Model III is referred to hereafter as the change-point model. The change-point model is more complicated than the other models. It begins with a triangular function, hence 2 linear segments, which match at a particular change-point. Since the change-point probability distribution is extended over several years, it does not make sense to select the maximum-likelihood triangular function for the time series model. Instead we employed the Bayesian marginalization rule to eliminate the change-point variable from the model function. The result of this marginalization was a super-

Table 1. Results of Bayesian function estimation of annual anomalies in Germany (1951–2004) averaged by groups of plant types and phenophases (mean \pm SD). Column headings—G: Group; Type: (A = agricultural plants, W = wild plants, F = fruit trees); Phenophases: observed phases in plant species; n: number of species \times phases; Onset: group mean onset date of species \times phases in Germany (1951–2004); Probability of the change-point, linear and constant models; trend in 2002–2004 resulting from all 3 models; year with max. change-point probability in the change-point model. D of Y: day of year

G	Type	Phenophase	n	Onset (D of Y)	Probability change-point-model	Probability linear model	Probability constant model	Trend 2002–2004 (d yr ⁻¹)	Year with max. change-point prob.
0	A	Spring sowing ⁰	4	104.8	0.35 \pm 0.09	0.44 \pm 0.17	0.22 \pm 0.24	-0.18 \pm 0.08	1978.0 \pm 26.6
1	A	Emergence ^{1a} , closed stand ^{1b} , shooting ^{1c} , heading ^{1d} , flowering ^{1e}	15	138.4	0.77 \pm 0.22	0.19 \pm 0.19	0.04 \pm 0.10	-0.41 \pm 0.16	1982.5 \pm 9.1
2	W	Leaf unfolding/mayshoot ²	7	119.8	0.82 \pm 0.20	0.17 \pm 0.19	0.01 \pm 0.01	-0.48 \pm 0.16	1982.3 \pm 2.9
3	F	First flowers ^{3a} , full flowering ^{3b} , end of flowering ^{3c}	14	123.2	0.78 \pm 0.15	0.16 \pm 0.09	0.06 \pm 0.07	-0.44 \pm 0.15	1982.4 \pm 2.2
4	W	Start of flowering ^{4a} , full flowering ^{4b}	18	114.1	0.81 \pm 0.17	0.18 \pm 0.15	0.02 \pm 0.03	-0.71 \pm 0.27	1984.4 \pm 3.7
5	A	Beginning of yellow ripeness ⁵	4	205.2	0.91 \pm 0.12	0.09 \pm 0.12	0.00 \pm 0.01	-0.57 \pm 0.03	1966.5 \pm 9.0
6	F	Fruit ripe for picking ⁶	9	218.5	0.91 \pm 0.21	0.06 \pm 0.13	0.03 \pm 0.03	-0.54 \pm 0.25	1980.3 \pm 10.0
7	W	Fruit ripening ⁷	2	255.7	0.94 \pm 0.07	0.05 \pm 0.06	0.02 \pm 0.02	-0.65 \pm 0.37	1984.5 \pm 0.7
8	W	Leaf colouring ⁸	4	281.5	0.43 \pm 0.03	0.46 \pm 0.10	0.11 \pm 0.11	0.04 \pm 0.12	1967.0 \pm 16.4
9	A	First silage cutting ^{9a} , harvest ^{9b}	8	230.4	0.75 \pm 0.22	0.23 \pm 0.22	0.02 \pm 0.03	-0.23 \pm 0.25	1970.1 \pm 12.5
10	A	Autumn sowing ¹⁰	4	265.5	1.0 \pm 0.01	0.00 \pm 0.01	0.00 \pm 0.00	-0.18 \pm 0.10	1962.2 \pm 8.5
11	A	Autumn emergence ¹¹	4	278.2	0.97 \pm 0.03	0.03 \pm 0.03	0.00 \pm 0.00	-0.21 \pm 0.13	1963.5 \pm 6.6

0 Sugar beet, fodder beet, oat, maize; ^{1a} Oat, sugar beet, fodder beet, maize; ^{1b} Sugar beet, fodder beet; ^{1c} Oat, winter barley, winter rye, winter wheat; ^{1d} Oat, winter barley, winter rye, winter wheat; ^{1e} Winter rape; ² Horse chestnut, birch, beech, oak, larch, ash, spruce; ^{3a} Red currant, gooseberry, sweet cherry, sour cherry, pear, apple; ^{3b} Sweet cherry, sour cherry, pear, apple; ^{3c} Sweet cherry, sour cherry, pear, apple; ^{4a} Hazel, snowdrops, coltsfoot, goat willow, Norway maple, forsythia, horse chestnut, blackthorn, lilac, elder, big leaf linden, common alder, dandelion, wood anemone, ash, robinia; ^{4b} Meadow foxtail, orchard grass; ⁵ Winter barley, winter rye, winter wheat, oat; ⁶ Red currant, gooseberry, sweet cherry [2 varieties], sour cherry, pear (2 varieties), apple (2 varieties); ⁷ Horse chestnut, elder; ⁸ Horse chestnut, birch, beech, oak; ^{9a} Permanent grassland; ^{9b} Sugar beet, fodder beet, winter rape, winter barley, winter wheat, oat, maize; ^{10/11} Winter barley, winter rye, winter wheat, winter rape

position of all possible triangular functions, hence the change-points 1952 to 2003 for the present data were weighted by their respective change-point probability. An analogous procedure was applied to the trend estimation.

An important feature of Bayesian probability theory is that it allows the calculation of the probability of the 3 models given time series data. If any 1 of the 3 exhibits a considerably higher probability, then it constitutes the optimal solution for description of the time series. If on the other hand the probabilities of the 3 models are comparable, we eliminate the variable 'model' from the calculation using a further marginalization step. This consists of superposing the 3 answers for functional behaviour and trend, and weighting them by their respective model probabilities. It is worth noting that the latter averaging process does not alter the shape of the trend derived from the change-point model. It does, however, add an offset due to the constant contribution from the linear model and a reduction of the amplitude by the amount of model probability obtained for the change-point model.

Using linear regression against mean onset dates we studied: (1) the probabilities of the 3 models, (2) the years with maximum change-point probability in the change-point model and (3) whether the trends at the end of the time series (2002–2004) changed with the

different phenophases. Differences between groups (agricultural, wild, fruit) across seasons are determined by analysis of variance followed by Tukey's HSD.

3. RESULTS

3.1. Model probabilities

For the 93 time series analysed, we found that the model of a constant onset of events over time (1951–2004) is the least likely one, with an average model probability of 0.04 (Fig. 1c). For 3 phases (sowing of oats and fodder beets as well as the emergence of oats), the constant model was superior to the linear and change-point model, which means that their onset dates were more or less constant over time. The average model probabilities for the 12 groups are given in Table 1. Except for leaf colouring (G8) and spring sowing (G0), the probability for the constant 'no change' model remains negligible. There were significant differences between groups ($p < 0.0046$), however, only spring sowing differed pair-wise (all comparisons were significant at the 5% level) from the other groups (except G7 and G8).

The linear model stands for changes which are constant over time; it achieved on average 0.17 probability

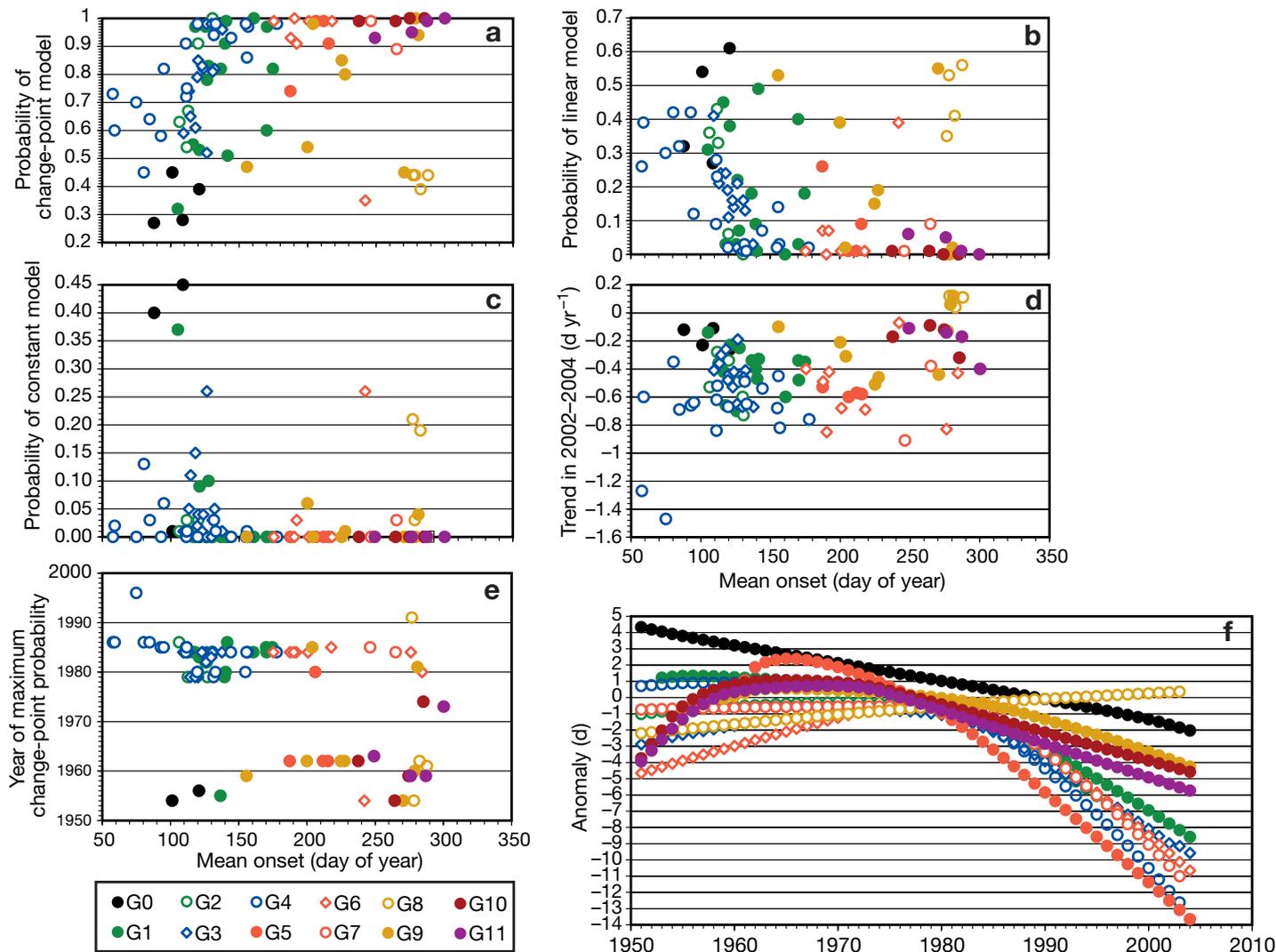


Fig. 1. Results of Bayesian nonparametric function estimation for 93 phenological anomalies in Germany (1951–2004): (a) probabilities of the change-point model against respective national mean onset dates, (b) probabilities of the linear model against mean onset dates, (c) probabilities of the constant model against mean onset dates, (d) trend (d yr⁻¹) in ending year (2002–2004) against mean onset dates, (e) year with the maximum change-point probability (only if probability of the change-point model > 0.33) against mean onset dates, (f) Bayesian non-parametric function estimates of anomalies in Germany (1951–2004) averaged by groups of plant types and phenophases. Code numbers for groups of species and phases correspond to Table 1. Colours and symbols: black: farmers' tilling in spring, green: leaf unfolding, blue: flowering, red: fruit ripening, yellow: harvest/leaf colouring, brown: farmers' tilling in autumn, pink: leaf unfolding of winter crops, filled dots: agricultural crops, open diamonds: fruit trees, open circles: wild plants

with significant differences between groups ($p < 0.001$) (Table 1). Pair-wise differences existed between spring sowing (G0 mean = 0.44) and 3 other groups (G6, G10 and G11) as well as between leaf colouring (G8 mean = 0.46) and 6 other groups (G3–G6, G10 and G11). For some phases in G0 (spring sowing), all in G8 (leaf colouring of 4 deciduous tree species) and a few in G1, G2 and G3, the linear model is the preferred model (probability > 0.33) for explaining the observed data (Fig. 1b, which displays the probabilities of the linear model for all phenophases against their respective mean onset dates in Germany). The preference for the

linear model decreases with increasing mean date for leaf unfolding (G2 linear regression coefficient $r = -0.02$, $p = 0.0024$), flowering of fruit trees (G3 $r = -0.01$, $p = 0.0012$) and flowering of wild plants (G4 $r = -0.003$, $p = 0.0001$).

By far the most favoured model describing the data is the change-point model with a range of substantial change-point probabilities over several years indicating generally non-linear change over time. For all time series, this model reached a mean probability of 0.79; for 34 time series the probability was 0.95 or higher, which is a satisfactory description of the data (Fig. 1a).

This important result implies that the traditional method of change detection in phenological time series, the maximum likelihood linear regression approach, would not be appropriate in the majority of cases (phenological time series). As for the change-point model, there are also significant differences in mean probabilities between groups ($p < 0.001$); spring sowing (G0 mean = 0.35) differed pair-wise from the other groups (except G8 mean = 0.43) and leaf colouring itself differed pair-wise from the other groups (except spring sowing, harvest). The preference for the change-point model increases with increasing mean date for leaf unfolding (G2 linear regression coefficient $r = 0.02$, $p = 0.0020$), flowering of fruit trees (G3 $r = 0.01$, $p = 0.0232$) and flowering of wild plants (G4 $r = 0.004$, $p = 0.0001$).

3.2. Years with the maximum change point probability

When comparing records of wild plants, fruit trees and agricultural plants preferentially explained by the change-point model, the most striking feature was found in the years with the maximum change-point probability (Fig. 1d). The differences among groups were significant ($p < 0.0001$). All spring and summer phases of wild plants, fruit trees (G2–G4, G6 and G7, Fig. 1d) as well as spring events in agricultural plants (G1) reveal discontinuous changes at the beginning of the 1980s or few phases at the end of the 1970s. This finding is in accordance with an observed accelerated temperature increase in the spring and summer instrumental records in the mid 1980s (Dose & Menzel 2006). By contrast, leaf colouring of wild plants (G8) as well as all other events in agriculture (G0 spring sowing, G5 yellow ripeness, G9 harvest, G10/11 autumn sowing and emergence) experienced such discontinuous changes mainly in the 1950s and at the beginning of the 1960s. Pairwise comparisons of G1–G4 with G9–11 and G4 with G5 and G8 were significant.

We assume that these changes, especially in autumn (G9–G11), reflect less the adaptation by farmers to altered climate conditions than the introduction of new cultivars, generally improved management practices in plant production, and technological changes which alter, for example, soil trafficability and thus suitable days for working in the fields.

3.3. Trends

The modelled average rate of change in the final years of the data set (2002–2004, depending on the phenophase) was assessed by the trends which were

estimated by the marginalization of the 3 model types (see 'Methods'). Nearly all records exhibited negative trends, indicating advancing onset. Only leaf colouring of 3 tree species and 2 harvest records (sugar and fodder beet) were delayed (see Table 1, Fig. 1e). In particular, flowering of wild plants (G4) and all 3 fruit ripening groups (G5–G7) exhibited strong advancing trends ranging from -0.54 to -0.71 d yr⁻¹. Other spring events (G1–G3) range from -0.41 to -0.48 d yr⁻¹. Smaller advancing trends were identified for spring and autumn sowing (G0 and G10, both -0.18 d yr⁻¹), harvest (G9 -0.23 d yr⁻¹) and autumn emergence (G11 -0.21 d yr⁻¹). The mean trend of emergence of spring sown crops (only part of G1 phenophases) was -0.24 d yr⁻¹, much lesser than for all crops (G1 -0.41 d yr⁻¹) and almost equivalent to spring sowing trends. This indicates that first emergence, through strong temporal coherence, is indirectly triggered by farmers' activities. In contrast to G1 (spring emergence and following spring events), G11 comprises solely autumn emergence dates and is thus taken as false phase, mirroring autumn sowing dates.

In total, there were significant differences among groups ($p < 0.0001$). Delayed leaf colouring (G8 mean = 0.04) differed pair-wise from other spring and summer phases (G1–G7). The strongest advancing of flowering of wild plants (G4 mean = -0.71) differed pair-wise from autumn groups (G8–G11) and agricultural phases in spring (G0, G1 and G3).

3.4. Mean anomalies (1951–2004)

Our main findings are summarized in Fig. 1f, which displays (averaged by group) the estimated functional behaviour of anomalies that results from all 3 model functions weighted with the respective model probabilities. This figure shows that all onset dates have been advancing in the last 1 to 2 decades, however false agricultural phases (G0 and G9–11) exhibit smaller trends, whereas true agricultural phases (G1 and G5 and all agricultural phases; filled circles in Fig. 1) compare with wild plants and fruit trees (G2–4, G6 and G7; open circles in Fig. 1).

Leaf colouring of deciduous trees (G8) clearly behaves differently. It is delayed compared to its 1971–1986 mean onset and the delay is more gradual, as its functional behaviour is described best by the linear or change-point model with the highest change-point probability in the 1950s.

A second group of activities that differs markedly from the others are farmers' spring activities (G0), such as sowing of oats, maize, sugar and fodder beet. This group has the highest mean probabilities for the constant model (0.22), the smallest for the change-point

model (0.35), and thus reveals the smallest advancing trends. This means that sowing dates have been somewhat adjusted to warmer spring conditions over the last 5 decades, however not synchronously with the advance of spring and summer phases. Other false agricultural phases, such as harvest (G9), sowing (G10), related emergence of winter crops (G11), and yellow ripeness (G5), have advanced since the mid 1960s. By contrast, spring emergence and all spring and summer events in fruit trees and wild plants have been advancing sharply since 1980. Before that, their onset dates were mostly constant or slightly delayed.

A clear ranking is apparent in the anomalies reached in the 2000s: False agricultural phases, triggered by farmers' activities in autumn (harvest, sowing and the subsequent emergence of winter crops), advance by between -1 and -4 d, whereas true agricultural phases (G1 spring emergence and subsequent events, G5 yellow ripeness) as well as all wild plant species and fruit trees advance by -8 to -14 d on average.

4. DISCUSSION

Summarizing these findings and putting them into the context of published results on spring phenological changes of wild plants, we conclude that: (1) delayed leaf colouring in autumn is clearly different from other events in autumn, such as fruit ripening or harvest and sowing of winter crops; and (2) there is apparent evidence that recent warming has clearly advanced a significant part of the agricultural calendar. Thus, any study on observed climate change impacts should clearly differentiate between different autumn phases (i.e. leaf colouring to fruit ripening), between annual crops and wild plants/perennial crops, and, within agriculture, between false and true phases.

We observed a clear signal of advancing spring, summer and autumn phenology across all plant types studied. This appears to be a quantitative indicator for climate change impacts, since observed advances in spring and summer match the pattern of warming (Menzel et al. 2006). Our results also agree with studies on single plant types, both on wild plants (for a review see e.g. Walther et al. 2002) and the few that exist on agricultural crops (Chmielewski et al. 2004, De La Torre & Benoit 2004, Hildén et al. 2005).

However, our time series analyses by Bayesian non-parametric function estimation reveal that the estimated functional behaviour is clearly different: (1) between wild plants/fruit trees and annual crops and (2), within crop production, among farmers' activities, such as seed drilling, tilling, harvesting (false phases), and climate triggered true phases (partly emergence but especially shooting, flowering and ripening).

Growth stages of wild plants and fruit trees as perennial crops have strongly advanced since the beginning of the 1980s and were, together with true agricultural phases, 1 to 2 wk earlier in the 2000s. This discontinuous shift is well in accordance with previous results of an earlier onset of spring in recent years, mainly since 1988, when a clear shift in spring appearance occurred (e.g. Studer et al. 2005).

False agricultural phases, which have either gradually advanced or have initially been delayed (until the mid 1960s) before advancing, seem to respond to a lesser degree to climate, but reflect plant-production and crop-management practices. There are various possible reasons why agricultural phenophases do not follow climate warming to the same extent as wild plants: general technological progress in machinery (including altered harvesting techniques and improved soil trafficability), timing of field work restricted to prefixed dates in the case of contractors or organised machine cooperatives, growing of new cultivars or varieties, chemical plant-protection measures, and manure application, delaying maturity.

Similar to our study, De La Torre & Benoit (2004) found that sowing dates of maize and wheat in France were up to 1 mo earlier (clearly exceeding our mean values for Germany), and also found that harvesting dates of sunflower had advanced. It is interesting that they also report a general preference for more retarding varieties of crop seeds. Further analyses of annual crops are required to properly distinguish between pure phenological changes and those that result from changes in management practices by farmers.

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