ORIGINAL PAPER

Bayesian analysis of the species-specific lengthening of the growing season in two European countries and the influence of an insect pest

Annette Menzel · Nicole Estrella · Werner Heitland · Andreja Susnik · Christoph Schleip · Volker Dose

Abstract A recent lengthening of the growing season in mid and higher latitudes of the northern hemisphere is reported as a clear indicator for climate change impacts. Using data from Germany (1951–2003) and Slovenia (1961–2004), we study whether changes in the start, end, and length of the growing season differ among four deciduous broad-leaved tree species and countries, how the changes are related to temperature changes, and what might be the confounding effects of an insect attack. The functional behaviour of the phenological and climatological time series and their trends are not analysed by linear regression, but by a new Bayesian approach taking into account different models for the functional description (one change-point, linear, constant models). We find advanced leaf unfolding in both countries with the same species order (oak > horse chestnut, beech, and birch). However, this advance is non linear over time and more apparent in Germany with clear change-points in the late 1970s, followed by marked advances (on average 3.67 days decade^{-1} in the 2000s). In Slovenia, we find a more gradual advance of onset dates (on average 0.8 days decade^{-1} in the 2000s). Leaf colouring of birch, beech, and oak has been slightly delayed in the last 3 decades, especially in Germany, however with no clear functional behaviour. Abrupt changes in leaf colouring dates of horse chestnut with recent advancing onset dates can be linked across countries to damage by a newly emerging pest, the horse chestnut leaf-miner (*Cameraria ohridella*). The lengthening of the growing season, more distinct in Germany than in Slovenia (on average 4.2 and 1.0 days decade^{-1} in the 2000s, respectively), exhibits the same species order in both countries (oak > birch > beech). Damage by horse chestnut leaf-miner leads to reduced lengthening (Germany) and drastic shortening (Slovenia) of the horse chestnut growing season (-12 days decade^{-1} in the 2000s). Advanced spring leaf unfolding and lengthening of the growing season of oak, beech and birch are highly significantly related to increasing March temperatures in both countries. Only beech and oak leaf unfolding in Germany, which is generally observed later in the year than that of the other two species, is more closely correlated with April temperatures, which comparably exhibit marked change-points at the end of the 1970s.

A. Menzel · N. Estrella · C. Schleip
Chair of Ecoclimatology, Technical University Munich,
Am Hochanger 13,
D-85354 Freising, Germany

W. Heitland
Chair of Animal Ecology, Technical University Munich,
Am Hochanger 13,
D-85354 Freising, Germany

A. Susnik
Agrometeorological Department, Environmental Agency
of the Republic of Slovenia,
Vojkova 1b,
1001 Ljubljana, Slovenia

V. Dose
Max-Planck-Institut für Plasmaphysik,
Boltzmannstrasse 2,
D-85748 Garching, Germany

A. Menzel (✉)
Department of Ecology, Technical University Munich,
Am Hochanger 13,
85 354 Freising, Germany
e-mail: menzel@forst.tu-muenchen.de

Introduction

Since the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2001), there has been increasing evidence of a coherent signal of climate change across systems and sectors, especially in terrestrial ecosystems (see reviews by Sparks and Menzel 2002; Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003). A quite frequently reported phenomenon is the lengthening of the growing season in mid and higher latitudes of the northern hemisphere, revealed by analyses of time series of remote sensed data, e.g. AVHRR NDVI data (Myneni et al. 1997; Zhou et al. 2001), of atmospheric CO_2-concentrations (Keeling et al. 1996), of the Bowen ratio (e.g. Fitzjarrald et al. 2001) and of phenological observations (e.g. Defila and Clot 2005; Menzel and Fabian 1999). However, even the simple question whether this lengthening is mostly due to spring advance, autumn delay, or both is difficult to answer.

For example, in Japan, the lengthening of the growing season of *Gingko biloba* by 2.6 days decade^{-1} is predominantly caused by a later leaf fall (Matsumoto et al. 2003). In Germany, the observed expansion of broad-leaved tree species' growing season is more a consequence of advancing leaf unfolding, and rather less due to later leaf colouring, whereas in other European countries these effects may be equally important (Menzel et al. 2006). Variations in the reported lengthening of the growing season across countries may be due to differences in regional warming, to varying time periods analysed, or to different definitions of the start and the end of the growing season.

Satellite data and CO_2 measures provide species and regional averaged information; in contrast, phenological observations are species- and site-specific. So far, there is some evidence that the lengthening of the growing season differs across species. For example, in Central Europe, European Beech (*Fagus sylvatica* L.) experiences smaller advances in leaf unfolding (Menzel et al. 2001; Kramer 1995) and exhibits a lower temperature response (e.g. Menzel et al. 2006). Another likely disturbance, which has to be taken into account, is a species-specific insect pest, the horse chestnut leaf-miner *Cameraria ohridella* (Lep., Gracillariidae), causing premature defoliation on white flowering horse chestnut (*Aesculus hippocastanum* L.) (Salleo et al. 2003). As the damage to leaves can be associated with leaf colouring, observed leaf colouring dates may be influenced by horse chestnut leaf-miner damage (Menzel 2003). After the first detection of the horse chestnut leaf-miner near Lake Ohrid in Macedonia in 1984 (Simova-Tošić and Filev 1985) and its description as a new species in 1985 (Deschka and Dimic 1986), this species has expanded its area by about 50–100 km year^{-1}.

Totally unexpected, *C. ohridella* appeared in Austria in 1989 in the region of Linz and rapidly spread east, north, and west so that, by 2000, it had colonised major parts of Central and Eastern Europe (Heitland and Freise 2001). It can now be observed as far north as England (2002), Denmark, and Sweden (Heitland et al. 2005). Therefore, Germany and Slovenia are suitable countries to study the above-mentioned questions, as their phenological networks both offer long-term records of four deciduous tree species, both countries being affected by the insect pest, and allowing a comparison of phenological impacts under both Central European and Mediterranean climates.

In this paper, we study by Bayesian non-parametric function estimation for the two European countries, Germany and Slovenia, (1) whether changes in the length of the growing season are related to trends in leaf unfolding and/or leaf colouring dates, (2) what is the variation among different broad-leaved species, (3) what might be the confounding effects of an insect attack, and (4) how these changes are related to recent temperature changes.

In contrast to traditional analyses of phenological change by linear regression techniques, we apply here the method of Bayesian non-parametric function estimation, which allows a comparison of models to describe the time series (e.g. change point, linear and constant models). Annual estimates of functional behaviour as well as rates of change (trends) with their respective variances and standard deviations can be given either for all models separately or averaged by the respective model probabilities.

Materials and methods

Phenological data

From the phenological network data of the German (1951–2003) and the Slovenian meteorological service (1961–2004), we selected four deciduous tree species: horse chestnut (*Aesculus hippocastanum* L.), silver birch (*Betula pendula* L.), common oak (*Quercus robur* L.), and European beech (*Fagus sylvatica* L.). The length of the growing season was determined by (1) the onset of leaf unfolding, defined as the stage when the first leaf stalks are visible, and by (2) leaf colouring, defined as the date when 50% of all leaves (still on the tree or already fallen to the ground) show autumnal colouring. In both national networks, these phases have been recorded by volunteers interested in nature and by a few employees of the respective weather services, following similar observation rules and standards (DWD 1991; ARSO 2003). However the number of stations included in this study was higher for Germany (*ca.* 1,550 in 2003) than for Slovenia (12). The data have been collected and quality checked by the

respective national weather services. For both countries, national mean annual onset dates were calculated. In Germany the data were restricted to altitudes below 700 m in order to exclude very late events; in Slovenia, only one station was situated above 700 m. Although station densities differ in both countries, the calculated national means may be representative for each country due to an enormous sample size in Germany and due to careful and spatially representative site selection in the Slovenian network. In order to study the spread of *C. ohridella* across the country, Germany was divided into three latitudinal bands (south <50°N, middle 50–52.5°N, north >52.5°N).

Temperature data

The temperature data set TYN CY 1.1, created by Mitchell et al. (2002) for Germany and Slovenia, was downloaded from the Tyndall Centre for Climate Change Research (http://www.cru.uae.ac.uk/~timm/climate/index.html). The data set comprises monthly mean temperatures from 1951 to 2000. For the Slovenian analysis, the temperature records were restricted to the 1961–2000 time period, comparable to the phenological data.

Methods

The Bayesian approach to analyse the functional behaviour of the phenological time series and their trends followed exactly the methodology introduced by Dose and Menzel (2004). Three different models were employed to describe the time series. The constant model represents the hypothesis of no change with a functional behaviour constant in time and an associated zero rate of change. The linear model assumes a linear change of the observed phenomenon with an associated constant rate of change. The change-point model allows for a time-varying trend. Its development starts from triangular functions, hence two linear segments, which match at particular change-point choices. The result of the Bayesian marginalization rule is a superposition of all possible triangular functions for the present data weighted by their respective change-point probability. An analogous procedure is applied to the trend estimation. The probabilities of the three models given time series data are also calculated with Bayesian model theory. If none of the three models exhibits a dominant probability, then we eliminate the variable 'model' from the calculation by a further marginalization step, superposing the three answers for functional behaviour and trend weighted with the respective model probabilities. The latter averaging process does not modify the shape of the trend derived from the change-point model, but adds 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. This latter model averaged information for functional behaviour and trend is further used in our paper. Instead of significance levels, which are not provided by Bayesian statistics, we talk about a trend different from zero, when the range of the annual trend ± variance does not include zero.

Results

Model probabilities and trends of leaf unfolding, leaf colouring and growing season

Table 1 summarises the model probabilities for each of the three models (one change-point, linear, and constant models) and the trends with confidence ranges (variance) at the end of the time series. The respective model-averaged functional behaviours and the trends against year are displayed in Fig. 1. These results confirm that leaf unfolding in spring has generally advanced in the last 4 (Slovenia) to 5 (Germany) decades (Fig. 1, upper line). However, the Bayesian approach reveals differences across species and countries.

In Germany, we find a strong preference for the change-point model to describe phenological spring (between 61% for birch and 98% for oak) with maximum change-point probabilities in 1970 and 1979 (horse chestnut) and 1978/79 (birch, beech, oak). This means a linear interpretation of the time series is by far not the best choice. The respective rates of change (trends) of the model-averaged functional behaviours underline that from the mid 1960s (horse chestnut, birch) and end of 1970s (beech, oak) onwards, the trends are negative and range between −0.30 (birch) and −0.46 (oak) days year^{-1} in 2003. The confidence ranges are given by the variance and indicate that the trends are clearly different from zero.

In Slovenia, three of four leaf unfolding estimates also seem to advance; however the negative trends reached in 2004 are not different from zero (Table 1). Similarly to Germany, oak displays the strongest trends and the highest preference for the change-point model among all species. For horse chestnut and birch, the linear model is almost as good as, or even better than, the one change-point model. Beech leaf unfolding in Slovenia is delayed for 5 decades (1961–1990), although the rate of change declined; the negative advancing trend in the 2000s is not different from zero. A previous separate analysis of Slovenian data with linear regression methods revealed that half of the stations had negative and half had positive trends; development towards earlier onset dates was mainly observed in urban areas.

Leaf colouring trends in autumn (Fig. 1, middle row) are slightly positive for birch, beech and oak over the last 3

Table 1 Results of Bayesian non-parametric function estimation for four deciduous broad-leaved tree species (horse chestnut *Aesculus hippocastanum L.*, birch *Betula pendula L.*, oak *Quercus robur L.*, beech *Fagus sylvatica L.*) and three indicators of the growing season (national means of leaf unfolding, leaf colouring, length) in Germany (1951–2003) and Slovenia (1961–2004)

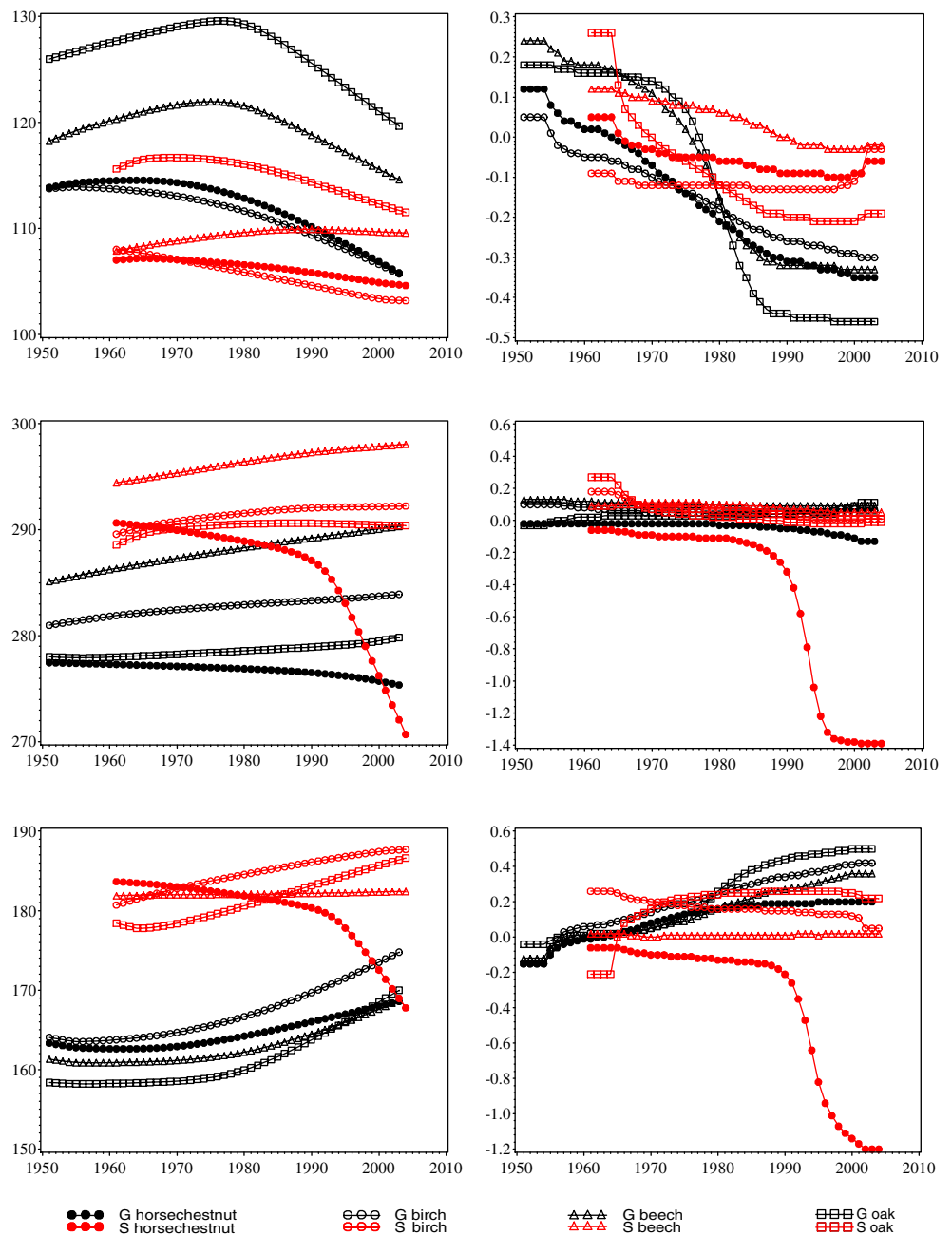|			Model probabilities			Trend
			Change-point	Linear	Constant	[Days year^{-1} in 2003/04]
Germany (1951–2003)	Leaf unfolding	H. chestnut	0.74	0.25	0.01	−0.35±0.11
		Birch	0.61	0.36	0.03	−0.30±0.12
		Beech	0.96	0.03	0.01	−0.33±0.03
		Oak	0.98	0.02	0.00	−0.46±0.03
	Leaf colouring	H. chestnut	0.43	0.36	0.21	−0.13±0.07
		Birch	0.43	0.39	0.18	0.11±0.06
		Beech	0.42	0.43	0.15	0.06±0.04
		Oak	0.44	0.55	0.01	0.09±0.03
	Growing season	H. chestnut	0.58	0.34	0.08	0.20±0.09
		Birch	0.73	0.27	0.00	0.42±0.15
		Beech	0.78	0.21	0.01	0.36±0.12
		Oak	0.91	0.09	0.00	0.50±0.07
Slovenia (1961–2004)	Leaf unfolding	H. chestnut	0.40	0.37	0.23	−0.06±0.12
		Birch	0.38	0.46	0.16	−0.03±0.37
		Beech*	0.47	0.28	0.25	−0.02±0.06
		Oak	0.68	0.28	0.04	−0.19±0.09
	Leaf colouring	H. chestnut	0.99	0.01	0.00	−1.39±0.24
		Birch	0.52	0.23	0.25	−0.01±0.03
		Beech*	0.46	0.34	0.20	0.01±0.06
		Oak°	0.43	0.45	0.12	0.05±0.07
	Growing season	H. chestnut	0.88	0.12	0.00	−1.20±0.58
		Birch	0.44	0.48	0.08	0.05±0.32
		Beech*	0.27	0.31	0.42	0.02±0.09
		Oak°	0.55	0.44	0.01	0.22±0.15
	Leaf colouring oak-horse chestnut	Slovenia°	0.96	0.04	0.00	2.67±1.72
		Germany-south	0.93	0.07	0.00	0.55±0.06
		Germany-middle	0.93	0.07	0.00	0.52±0.06
		Germany-north	0.84	0.16	0.00	0.43±0.07

°4 years missing, *9 years missing. The trend is given with the respective variance

decades, indicating delayed leaf colouring over time. The trends reached in 2003/04 in Germany are different from zero (between 0.06 and 0.11 days year^{-1}), whereas the confidence ranges of the respective leaf colouring trends in Slovenia include zero (Table 1). For these three species, there is no clear preference for the change-point or linear model. The observations on the fourth species seem to be affected by the horse chestnut leaf-miner, as in both countries horse chestnut leaf colouring is advancing, in Slovenia very sharply from 1993 onwards (maximum change-point probability 0.17 in 1993, 99% probability of the change-point model) and in Germany more gradually (43% probability of the change-point model). Both advancing trends are clearly different from zero.

In Germany and Slovenia, the growing seasons for all but one species (horse chestnut in Slovenia) have length-

ened over the last 4 to 5 decades (Fig. 1, bottom row). We observe for all four species stronger trends in Germany than in Slovenia, clearly positive in 2003 (between 0.20 and 0.50 days year^{-1}). It is quite obvious that the main effect for this lengthening is due to an earlier start, less to a later end of the growing season (Table 1). In Slovenia, the growing season for birch, beech and oak is lengthening; however only for oak is the trend achieved in 2004 clearly different from zero (0.22 days year^{-1}). In both countries, the advancing observed leaf colouring dates of horse chestnut in autumn lead to species-specific differences in both countries. Whereas in Germany the growing season of horse chestnut is now the shortest of the four species with the smallest positive trends in 2003, we find in Slovenia an extreme shortening from the 1990s onwards, resulting in high trends (−1.20 days year^{-1} in 2004).

Fig. 1 Bayesian non-parametric function estimates for four deciduous tree species in Germany (1951–2003) (black) and Slovenia (1961–2004) (red). Left column: onset dates [day of the year], right column: trends [days year^{-1}], upper line: spring leaf unfolding [day of the year], middle: autumnal leaf colouring [day of the year], bottom: length of the vegetation period [days]

Legend:
- ● ● ● G horsechestnut
- ● ● ● S horsechestnut
- ○ ○ ○ G birch
- ○ ○ ○ S birch
- △ △ △ G beech
- △ △ △ S beech
- ⊞ ⊞ ⊞ G oak
- ⊞ ⊞ ⊞ S oak

The horse chestnut leaf-miner and observed leaf colouring dates

The leaf-miner *Cameraria ohridella* causes premature defoliation of horse chestnut trees and heavily infested trees can be completely defoliated in September (Salleo et al. 2003). Thus, since the 1990s, depending on the spread of the insect, observed leaf colouring dates of horse chestnut in the phenological networks may be disturbed by visible damage caused by this pest species, although this should not be the case. In Germany, leaf colouring is clearly defined as autumnal leaf colouring. Infested plant speci-

mens, regardless of whether by pathogens or diseases, should be disregarded (DWD 1991). With this in mind, since 2000 the manager of the phenological network of the German Meteorological Service has continuously given the observers warnings against the horse chestnut leaf-miner (Ekko Bruns, DWD, personal communication). Similarly, in Slovenia observers have been informed about the infection since 1996.

As the observed mean leaf colouring dates of horse chestnut in Slovenia seem to be decisive for the length of the growing season, we display the respective time series in Fig. 2. In the upper panel, time series of observed leaf

colouring dates and estimated functional behaviour both display a sharp alteration from 1990 onwards; the widening confidence margins derive from higher variability of the observed dates at the end of the time series. The advancing trends (Fig. 2, lower panel) have been almost stable for the last 8 years with relative small uncertainty.

We tested whether the observed diverging results for horse chestnut, advancing leaf colouring dates in both countries, and in Slovenia even a shortening of the growing season, can be related to leaf damage by the horse chestnut leaf-miner. Therefore, we determined, by station and year, the differences between leaf colouring dates of oak and horse chestnut. These time spans were equally treated by Bayesian non-parametric function estimation (Fig. 3). We
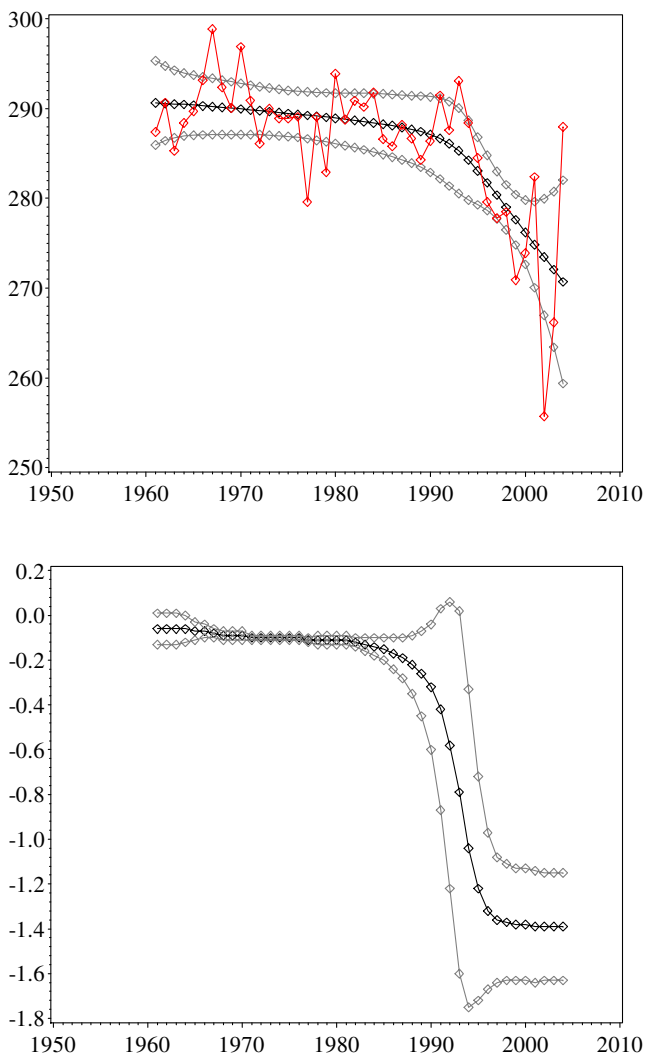

Fig. 2 Bayesian non-parametric function estimates for horse chestnut leaf colouring dates in Slovenia (1961–2004). Upper line: onset dates [day of the year], red: observations, black: average functional behaviour, grey: confidence range (± variance), bottom line: trends [days year^{-1}], grey: confidence range (± variance)
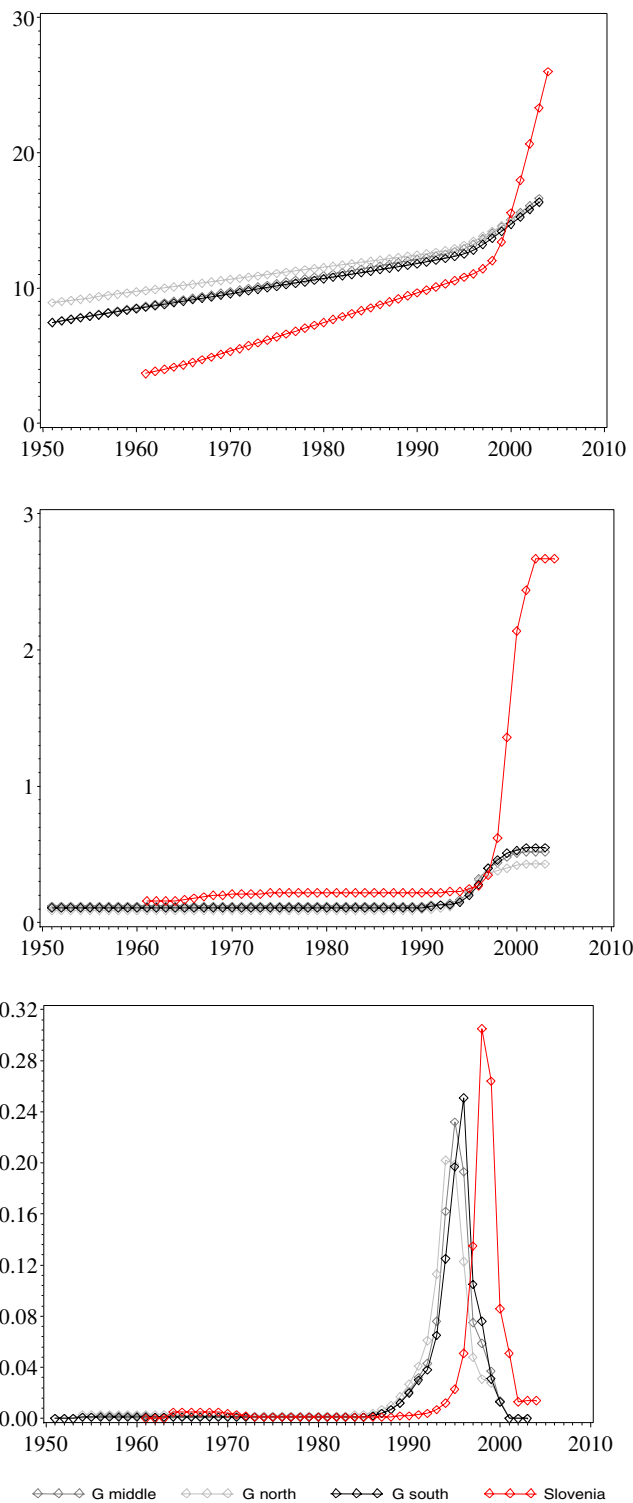

Fig. 3 Bayesian non-parametric function estimates for the time span between horse chestnut and oak leaf colouring dates in Germany (1951–2003) (black: south <50°N, grey: middle 50°–52.5°N, light grey: north >52.5°N) and Slovenia (1961–2004) (red). Upper line: time span [days], middle: trends [days year^{-1}], bottom: probability of the change-point

Table 2 Pearson correlation coefficients (r) of four deciduous broad-leaved tree species (horse chestnut *Aesculus hippocastanum L.*, birch *Betula pendula L.*, oak *Quercus robur L.*, beech *Fagus sylvatica L.*) and monthly mean temperatures in Germany (G, 1951–2000) and Slovenia (S, 1961–2000) (only values of the most significant month are given)

	C	n	Horse chestnut		Birch		Beech[*]		Oak[°]	
			Month	r	Month	r	Month	r	Month	r
Spring	G	50	March	**−0.71**	March	**−0.70**	April	**−0.79**	April	**−0.83**
	S	40	March	**−0.79**	March	**−0.78**	March	*−0.33*	March	−0.50
Autumn	G	50	May	**−0.61**	Sept.	**0.54**	Sept.	**0.63**	Sept.	**0.59**
	S	40	June	−0.42	No month sign		Sept.	0.53	Sept.	*0.39*
Growing season	G	50	March	**0.62**	March	**0.62**	April	**0.59**	April	**0.68**
	S	40	March	0.44	March	**0.70**	March	0.59	March	0.50

Bold significant <0.0001, normal <0.001, italics <0.08. °4 years missing autumnal observations, *9 years missing

know that the horse chestnut leaf-miner entered Bavaria (Germany) in 1992 from Austria; spreading west and north it colonised major parts of Germany in only 7 years. In 1998, *C. ohridella* could be detected across two thirds of

Germany (Heitland and Freise 2001). In Slovenia, *C. ohridella* was first mentioned in 1995 (Milevoj and Maček 1997); however the moths were probably introduced into Slovenia around 1 year earlier. In 1996, it was observed in
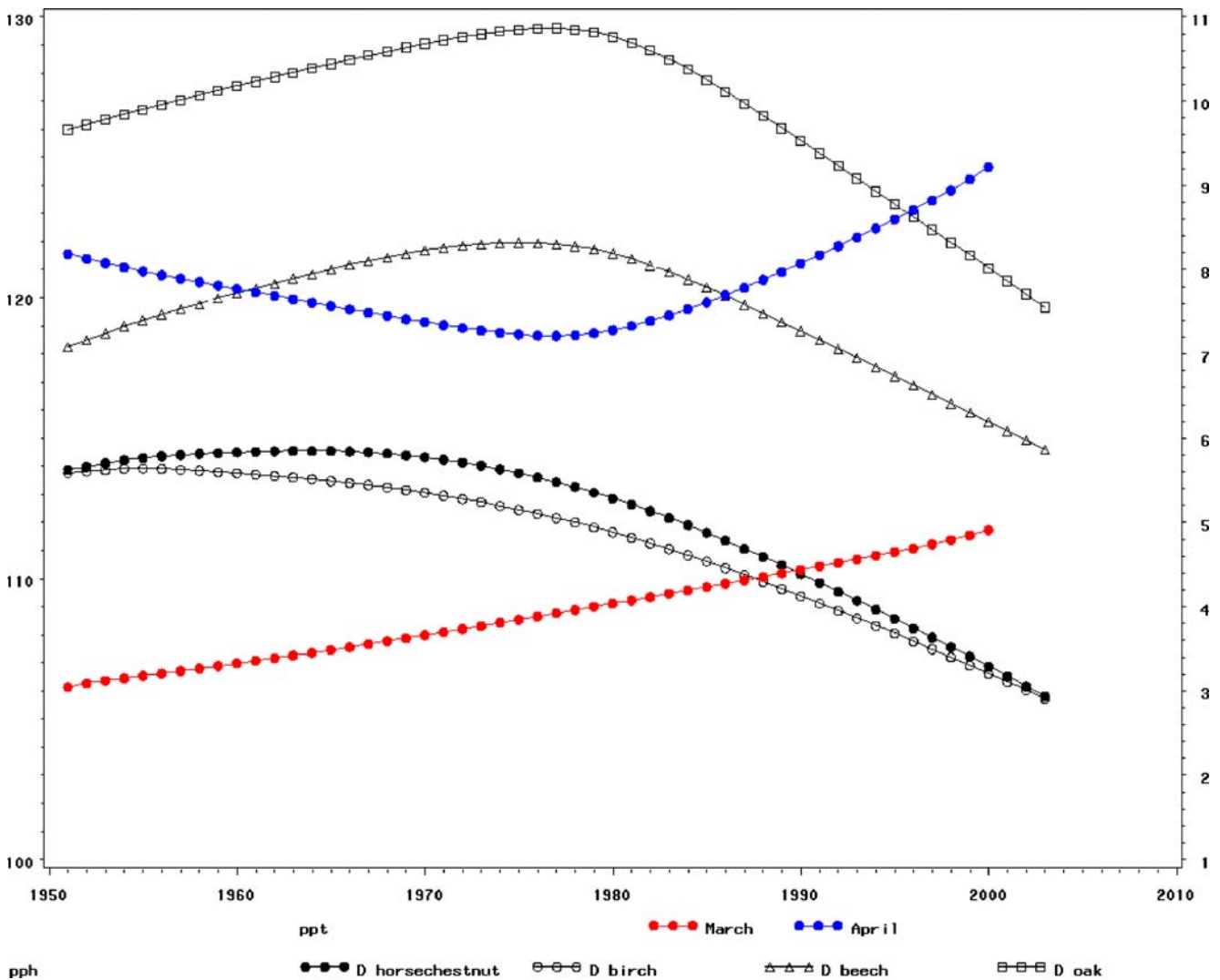

Fig. 4 Bayesian non-parametric function estimates for spring leaf unfolding of four deciduous tree species in Germany (1951–2003) [day of the year] (black, left y-axis) and relevant mean national monthly temperatures (1951–2000) [°C] (right y-axis)

Table 3 Results of Bayesian non-parametric function estimation for selected mean monthly temperatures (see Table 2) in Germany (1951–2000) and Slovenia (1961–2000)

		Model probabilities			Trend
		Change-point	Linear	Constant	[°C year^{-1} in 2000]
Germany (1951–2000)	March	0.41	0.49	0.10	0.063±0.094
	April	0.94	0.03	0.03	0.144±0.062
	May	0.55	0.40	0.05	0.156±0.180
	September	0.34	0.26	0.40	0.077±0.066
Slovenia (1961–2000)	March	0.39	0.50	0.11	0.074±0.130
	April	0.81	0.11	0.08	0.487±0.601
	June	0.97	0.02	0.01	0.207±0.039
	September	0.41	0.33	0.26	0.033±0.033

The trend is given with the respective variance

Maribor, Ormo, and Ljubljana; in 1997 it was already widely present in Slovenia, and by the following year it had spread throughout the country (Milevoj 2004). At the phenological stations, the pest was identified later, from 1997 to 2002.

Figure 3 (middle row) mirrors this spread with rapidly increasing time spans between oak and horse chestnut leaf colouring from the end of the 1990s onwards. The maximum change-point probability for Slovenia is reached in 1998, equivalent to the reported observations of the moths. In Germany, the spread from south to north is not reflected in the change-point probabilities as their maxima occur earlier in the north and middle parts.

Temperature triggers of leaf unfolding, leaf colouring, and growing season

Spring phenological changes and alteration of the length of the growing season are clear indicators of recent temperature changes (see Sparks and Menzel 2002; Menzel 2002). Table 2 provides the necessary information on how spring/ autumn phases and the length of the growing season are related to mean national monthly temperatures. March is the most decisive month for leaf unfolding in both countries with correlation coefficients up to −0.83. This means that for spring leaf unfolding between 49% and 69% of the common variance are explained by March temperatures (Fig. 4). Only beech and oak in Germany, with much later bud burst than birch and horse chestnut, exhibit higher correlations with April temperatures. The same pattern is true for the length of the growing season. Here, for the growing season of birch and horse chestnut, 38% of the common variance is explained by March temperatures, for beech and oak, between 35% and 46% are explained by April temperatures.

Leaf colouring in autumn of birch, beech and oak is mostly influenced by September temperatures with warmer late summers leading to later leaf colouring. In this case, only the results for Germany are highly significant ranging between r=0.54 and 0.63 (R^2=29% to 40%). For horse chestnut in both countries, however, we reveal a different triggering factor: Warm May (Germany) and June (Slovenia) leads to earlier leaf colouring. This finding might be related to stages in the annual development of the horse chestnut leaf-miner, finding better conditions in those warmer years.

We examined whether the mean temperature records of the months identified above (Table 2) exhibited similar model probabilities (constant temperature, linear change or change-point model) in the Bayesian analysis (Table 3). Except for September temperature in both countries, the constant model is by far the least likely one. Linear and change-point models reveal similar probabilities for March (Germany, Slovenia) and May (Germany) temperature. In contrast, April temperature in Germany and April and June temperature in Slovenia can be better described by the change-point model indicating discontinuous changes over recent decades. All trends in 2000 indicate warming, the values for April and September (Germany) and June and September (Slovenia) temperatures are clearly different from zero.

Discussion

Different mean dates of leaf unfolding, leaf colouring and length of the growing season across countries mirror the main climatic differences between Slovenia and Germany. Slovenia's climate can be characterised as Mediterranean on the coast and continental with warm dry to hot summers and cold winters in the plateaus and valleys to the east. In Germany, we find moderately cool or cold, also wet winters and fairly mild wet summers, only occasionally dry. Leaf unfolding of the four species is on average ca. 8 days earlier, leaf colouring ca. 10 days later and the growing

season ca. 18 days longer in Slovenia than in Germany (see Fig. 1). We know that leaf unfolding is clearly related to spring temperatures, e.g. for Germany a temperature response of ca. -4.5 days $°C^{-1}$ for horse chestnut leaf unfolding is reported (Menzel et al. 2005, 2006).

However, these differences in phenological means across countries are not stable in time. For birch, beech, and oak, we find a stronger advance of leaf unfolding in Germany than in Slovenia in recent decades: The average trend at 2003 of the 4 deciduous tree species in Germany amounts to -0.36 days $year^{-1}$ in contrast to -0.08 days $year^{-1}$ in Slovenia. As leaf colouring is only slightly delayed in both countries, this change in spring tends to determine the length of the growing season in both countries. These findings confirm previous results by the traditional linear regression method. Menzel et al. (2006) have found a stronger general spring advance and a stronger advance of leaf unfolding of beech in Germany than in Slovenia, related to a higher spring warming.

A similar ranking across species of the trends achieved in 2003/04 is found in both countries: In spring, oak changes most, followed by horse chestnut, beech, and birch. Changes in leaf colouring are most similar for all countries and species, except horse chestnut. Consequently, the lengthening of the growing season is most marked for oak, followed by birch, beech and finally horse chestnut, and this ranking is again the same in both countries. We conclude that there is some preliminary evidence that the rank order of responses and trends of different species might be similar across countries. However, more studies have to verify this.

Our study clearly detects an influence of the damage caused by the horse chestnut leaf-miner on leaf colouring dates in Slovenia and Germany. Our results demonstrate that first reported occurrence dates of the pest are generally associated with years of maximum change-point probability of the Bayesian analysis. However, we cannot relate these change-points in the Bayesian analysis of recorded leaf colouring dates to the known spatial spread of the pest. Probably this analysis in latitudinal bands is disturbed by a none-exclusively directional spread, as Gilbert et al. (2004) reported that C. ohridella is generally observed first in highly populated locations, due to anthropogenic transfer by cars, trucks, or trains, before colonising the countryside. Other known effects of horse chestnut leaf-miner include reduced seed size and weight in heavily damaged trees (Thalmann et al. 2003) and sometimes a second flowering in early autumn. Second flowering was reported e.g. in September 2000 in Munich and Frankfurt, probably as a reaction to a warm and dry summer (Heitland and Freise 2001). The phenomenon of second flowering of horse chestnut has also been observed in recent years in Slovenia. Second flowering can equally be induced by climatic

drought stress in hot and dry years or damage caused by the pathogen *Guignardia aesculi*. However, phenological observations in these national networks are not able to resolve the amount of second flowering in autumn, because only regular spring flowering is observed and kept in the data bases. Our study demonstrates that in special cases, phenological onset dates may be affected by biological factors, such as pest and diseases, and a careful interpretation of the reported results is necessary.

Our Bayesian analysis also allows us to interpret major differences between leaf unfolding of birch/horse chestnut and beech/oak in Germany. The change-point model is highly preferred in the case of beech and oak (96% and 98% model probability, Table 1). The highest change-point probabilities are always identified in 1978/79; however the values are higher for beech and oak (maximum of 8.1% and 10.1%, respectively) than for birch and horse chestnut (3.8% and 3.5%). The feature can be explained by Tables 2, 3 and Fig. 3: birch and horse chestnut leaf unfolding are mainly triggered by March temperatures, which have been gradually increasing in recent decades, leading to a smoother advancing of leaf unfolding of those species. Beech and oak leaf unfolding, occurring on average not in April but at the beginning of May, are predominantly triggered by April temperatures. April monthly mean temperature exhibits cooling from 1951 till the end of the 1970s and a sharp warming from then onwards (see Fig. 3). This trait is mirrored in the respective phenological data series, underlining that phenology is an integrating bio-indicator of climate change. However, species-specific differences have to be taken into account. Depending on the mean onset dates, time series of these observations reflect temperature changes of different periods in spring.

References

ARSO (2003) Navodila za fenološka opazovanja. p51

Defila C, Clot B (2005) Phytophenological trends in the Swiss Alps, 1951–2002. Meteorol Z 14(2):191–196

Deschka G, Dimic N (1986) *Cameraria ohridella* n. sp. aus Mazedonien, Jugoslawien (Lepidoptera, Lithocelletidae). Acta Ent Jugosl 22/1:11–23

Dose V, Menzel A (2004) Bayesian analysis of climate change impacts in phenology. Global Change Biology 10:259–272

DWD (1991) Anleitung für die phänologischen Beobachter des Deutschen Wetterdienstes. Vorschriften und Betriebsunterlagen Nr. 17. Deutscher Wetterdienst, Offenbach am Main

Fitzjarrald DR, Acevedo OC, Moore KE (2001) Climatic consequences of leaf presence in the eastern United States. J Climate 14:598–613

Gilbert M, Grégoire JC, Freise JF, Heitland W (2004) Long-distance dispersal and human population density allow the prediction of invasive patterns in the horse chestnut leafminer *Cameraria ohridella*. J Anim Ecol 73:459–468

Heitland W, Freise J (2001) Verbreitung der Roßkastanien-Miniermotte, *Cameraria ohridella* (Lep., Gracillariidae) in Deutschland. [Distribution of the horse-chestnut leaf miner, *Cameraria ohridella* (Lep., Gracillariidae) in Germany]. Mitt Dtsch Ges Allg Angew Ent 13:131–134

Heitland W, Freise JF, Sturm A, Lenz N (2005) Die Rosskastanien-Miniermotte *Cameraria ohridella* DESCHKA & DIMIC, 1986 (Lepidoptera, Gracillariidae): Gründe ihres Erfolgs als Blattschädling an der weiß blühenden Gewöhnlichen Rosskastanie *Aesculus hippocastanum* (Hippocastanaceae) und Möglichkeiten zur Bekämpfung. Entomologie heute 17:157–172

IPCC (2001) McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (Eds) Climate Change 2001: Impacts, Adaptation & Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, Cambridge University Press, p 1000

Keeling CD, Chin JFS, Whorf TP (1996) Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. Nature 382:146–149

Kramer K (1995) Phenotypic plasticity of the phenology of seven European tree species in relation to climatic warming. Plant Cell Environ 18:93–104

Matsumoto K, Ohta T, Irasawa M, Nakamura T (2003) Climate change and extension of the Ginkgo biloba L. growing season in Japan. Glob Chang Biol 9:1634–1642

Menzel A (2002) Phenology, its importance to the Global Change Community. Climatic Change 54:379–385

Menzel A (2003) Plant phenological anomalies in Germany and their relation to air temperature and NAO. Clim Change 57(3):243–263

Menzel A, Fabian P (1999) Growing season extended in Europe. Nature 397:659

Menzel A, Estrella N, Fabian P (2001) Spatial and temporal variability of the phenological seasons in Germany from 1951–1996. Glob Chang Biol 7:657–666

Menzel A, Estrella N, Testka A (2005) Temperature response rates from long-term phenological records. Clime Res 30:21–28

Menzel A, Sparks TH, Estrella N, Koch E et al (2006) European phenological response to climate change matches the warming pattern. Glob Chang Biol 12:1969–1976

Milevoj L (2004) The occurrence of some pests and diseases on horse chestnut, plane tree and Indian bean tree in urban areas of Slovenia. Acta Agriculturae Slovenica 83(2):297–300

Milevoj L, Maček J (1997) Rosskastanien-Miniermotte (*Cameraria ohridella*) in Slowenien. Nachrichtenblatt Deutscher Pflanzenschutzdienst 49(1):14–15

Mitchell TD, Hulme M, New M (2002) Climate data for political areas. Area 34:109–112

Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR (1997) Increased plant growth in the northern high latitudes from 1981–1991. Nature 386:698–702

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421:57–60

Salleo S, Nardini A, Raimondo F, Assunta Lo Gullo M, Pace F, Giacomich P (2003) Effects of defoliation caused by the leaf miner *Cameraria ohridella* on wood production and efficiency in *Aesculus hippocastanum* growing in north-eastern Italy. Trees 17:367–375

Simova-Tošić D, Filev S (1985) Contribution to the horse chestnut miner. Zastita bilja 36:235–239 (in Serbocroat)

Sparks TH, Menzel A (2002) Observed changes in seasons: an overview. Int J Climatol 22:1715–1725

Thalmann S, Freise J, Heitland W, Bacher S (2003) Effects of defoliation by horse chestnut leafminer (*Cameraria ohridella*) on reproduction in *Aesculus hippocastanum*. Trees 17:383–388

Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TCJ, Fromentin JM, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395

Zhou LM, Tucker CJ, Kaufmann RK, Slayback D, Shabanov NV, Myneni RB (2001) Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. J Geophy Res 106(D17):20069–20083