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ORIGINAL PAPER

Phenological changes and reduced seasonal synchrony in western Poland

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Abstract Botanical gardens offer continuity for phenological recording in observers, protocols and plant specimens that may not be achievable from other sources. Here, we examine phenological change and synchrony from one such garden in western Poland. We analysed 66 botanical phenophases and 18 interphase intervals recorded between 1977 and 2007 from the Poznań Botanical Garden. These were examined for trends through time and responsiveness to temperature. Furthermore, we derived measures of synchrony for start of spring and end of autumn events to assess if these had changed over time. All 39 events with a mean date before mid-July demonstrated a significant negative relationship with temperature. Where autumn events were significantly related to temperature, they indicated a positive relationship. Typically, spring events showed an advance over time and autumn events a delay. Interphase intervals tended to lengthen over the study period. The measures of synchrony changed significantly over time suggesting less synchrony among spring events and also among autumn events. In combination, these results suggest increases in growing season length. However, responses to a changing climate were species-specific. Thus, the transitions from winter into spring and from autumn into winter are becoming less clearly defined.

Keywords Botanical garden · Fall (autumn) · Flowering · Leafing · Temperature response · Trends

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Introduction

Phenology is one of the most sensitive responses of the natural world to a changing climate. Of all the evidence considered by the IPCC in its most recent report, the bulk of evidence of changes to the natural world concerned phenological change (Rosenzweig et al. 2008). Indeed, phenological change may be seen as a vanguard for wider change in the environment (Cleland et al. 2007).

Plant phenology has been shown to be very responsive to temperatures, and a number of multi-species studies have reported shifting phenology, particularly to earlier leafing and flowering in spring (Bradley et al. 1999; Menzel and Fabian 1999; Abu-Asab et al. 2001; Fitter and Fitter 2002; Peñuelas et al. 2002; Menzel et al. 2006). However, many of these papers covered data only up to the end of the twentieth century and had a focus on spring events. Reports on autumn phenology are much less common (but see Menzel and Fabian 1999), and there have been few multi-species papers covering the first few years of the twenty-first century which, because of their exceptional warmth, would be expected to be associated with exceptionally early spring phenology (e.g. White et al. 2009).

Studies that report many species have distinct advantages. They allow a comparison between species without the confounding environmental differences associated with different studies. Studies of records from a limited geographical area have further benefits in that the genetic diversity of the recorded material is likely to be smaller and the studied environment likely more homogenous (e.g. Hepper 2003). In this respect, botanical gardens may be particularly valuable in recording phenology. They are often long-established with their own meteorological station and continuity of personnel. Careful observation of various phases of the same species may well be possible without the need to search the environment to locate a particular species.

There have been few studies that have looked at several phases of the same species and the relationships between successive phases. Furthermore, there have been few multi-species studies from Eastern Europe (see maps in: Rosenzweig et al. 2008).

In this paper, we examine a 31-year record (1977–2007) of 66 phenophases from the Poznań Botanical Garden (Poland). The studied species include a number of iconic and more obscure ones. Of the former, Horse Chestnut *Aesculus hippocastanum* has been widely planted in Europe, has very obvious phenological phases, and has been widely reported in the phenological literature, for example the two-century record of first leafing from Geneva, Switzerland (Defila and Clot 2001). The purpose of our paper is to (1) identify trends in plant phenology from early spring to late autumn, (2) estimate the responsiveness of species to mean monthly air temperatures, (3) investigate the interphase intervals of the same species, and (4) look at the consistency of changes at the beginning and end of the growing season.

Materials and methods

A large number of plant phenophases have been monitored at the Adam Mickiewicz University Botanical Garden in Poznań, Poland (www.ogrod.edu.pl/info_eng.php) (52º25′N 16º53′E). The Botanical Garden was founded in 1925, occupies an area of 22 ha at an altitude of 89 m asl and contains nearly 7,000 Special Collections. For this paper, we abstracted data on the dates of 66 phenophases for the period 1977–2007 incorporating 42 species (see Table 1 for list). All observations were made within the Garden and on a daily basis. The definitions of the phenophases used are as follows:First shoot – first shoots appearing above the ground; First leaf – first fully open leaf; First flower – first open flower; Pollen – first pollen shed; End of flowering – last flower; Earing – inflorescence of cereals emerges; Seeding – first ripe seeds produced; First senescence – first evidence of above ground portion of plants dying; Leaf colouring – first colour change; Die back – above ground portions of plant fully dead; Bare – all leaves fallen.

All dates were converted prior to analysis into days after 31 December, hereafter day of the year (DOY) where 1= 1 January,etc. Eighteen intervals between successive phenophases of the same species were calculated where considered biologically meaningful (see Table 2 for list).

Mean monthly air temperatures, collected to standard WMO guidelines, were obtained from the meteorological station situated within the Botanical Garden.

Trends through time were estimated using linear regression of phenophases on year. Temperature responses were estimated by regression of phenophases on the mean temperature for the three calendar months ending in the month in which the mean of the phenophase occurred; thus, for example, an event whose mean date was in May would be compared to the mean temperature from March to May. This is a rather broadbrush approach but has been shown to be usually sufficient, particularly for spring events (Estrella et al. 2007).

The 18 phenophase intervals were subjected to regression on year to check for trends over time. A correlation was calculated between the two phases from which the interval was derived. Finally the end phases were regressed on the first phases *after* fitting the 3-month mean temperature mentioned above. This was in order to see if the first phases influenced the later ones after temperature effects were removed.

To assess variability changes within early spring events we calculated the standard deviation annually among all six phenophases occurring, on average, before the end of March. These are the first six events in Table 1. A similar exercise to look at autumn variability was based on the standard deviation of the eight “bare” phenophases listed towards the end of Table 1. Trends in these variability measures were assessed by correlation with year.

Results

Trends through time

Table 1 summarises the examined phenophases, their trends through time and their response to the mean temperature of the three calendar months leading up to and including the mean date of that phase. Significant changes in timing were detected in 22 of the 66 phenophases; 14 significant advances and 8 significant delays. There was a strong association between timing of the phase and the trend through time (r_{64}=0.624, P <0.001; Fig. 1) with spring events tending to get earlier and autumn events later.

Response to temperature

In comparison with 3-monthly mean temperatures, 44 of the 66 phenophases showed a significant response to temperature (Table 1). Of these, 39 indicated earlier events with warmer temperatures. All events with mean dates before DOY 193 (July 12) had a significant negative relationship (warmer = earlier) with temperature. The five significantly positive relationships all occurred in events with mean dates post DOY 274 (October 1). Overall, a strong correlation between temperature response and mean date was also apparent (r_{64}=0.825, P <0.001; Fig. 2).

Table 1 A summary of the examined phenophases and the regressions of phenophases on year and on mean temperature

Scientific name	English name	Phase	Mean (DOY)	SD	*n*	Regression on year				Regression on 3 months temperature			
						slope days/year	SE	*P*	R^2	slope days/°C	SE	*P*	R^2
Corylus avellana	Hazel	Pollen	56.5	24.9	31	–0.83	0.48	0.097	9.2	**–8.94**	**1.31**	**<0.001**	**61.4**
Pulmonaria obscura	Suffolk Lungwort	First shoot	58.3	23.7	29	–0.28	0.49	0.572	1.2	**–8.60**	**1.40**	**<0.001**	**58.3**
Alnus incana	Grey Alder	Pollen	60.0	22.6	31	–0.81	0.44	0.074	10.6	**–7.95**	**1.23**	**<0.001**	**59.2**
Galanthus nivalis	Snowdrop	First flower	61.5	16.0	31	–0.62	0.31	0.051	12.5	**–5.62**	**0.88**	**<0.001**	**58.7**
Leucojum vernum	Spring Snowflake	First shoot	62.9	16.3	30	–0.62	0.32	0.061	12.0	**–5.42**	**0.94**	**<0.001**	**54.5**
Lysimachia punctata	Dotted Loosestrife	First shoot	63.1	21.1	31	–0.76	0.41	0.072	10.8	**–7.27**	**1.18**	**<0.001**	**56.7**
Corylus avellana	Hazel	First leaf	102.7	11.3	31	**–0.54**	**0.21**	**0.014**	**19.3**	**–5.18**	**0.97**	**<0.001**	**49.5**
Convallaria majalis	Lily of the Valley	First shoot	104.7	9.0	31	**–0.36**	**0.17**	**0.046**	**13.0**	**–3.45**	**0.88**	**<0.001**	**34.5**
Aesculus hippocastanum	Horse Chestnut	First leaf	104.8	7.8	31	**–0.31**	**0.15**	**0.044**	**13.3**	**–2.94**	**0.78**	**<0.001**	**33.0**
Primula veris	Cowslip	First flower	105.6	12.7	30	–0.35	0.27	0.197	5.9	**–4.59**	**1.28**	**<0.001**	**31.5**
Larix decidua	European Larch	First leaf	105.7	9.4	31	–0.31	0.18	0.105	8.8	**–3.81**	**0.89**	**<0.001**	**38.7**
Cimicifuga europaea	Bugbane	First leaf	108.5	8.5	24	0.47	0.23	0.056	15.6	**–2.39**	**0.98**	**0.023**	**21.3**
Betula pendula	Silver Birch	First leaf	108.9	9.2	31	–0.08	0.19	0.659	0.7	**–2.72**	**0.99**	**0.010**	**20.8**
Caltha palustris	Marsh Marigold	First flower	110.1	9.5	31	**–0.40**	**0.18**	**0.033**	**14.7**	**–3.57**	**0.94**	**<0.001**	**33.2**
Aristolochia clematitis	Birthwort	First shoot	110.3	9.4	31	–0.18	0.19	0.343	3.1	**–3.17**	**0.97**	**0.003**	**26.9**
Polygonatum multiflorum	Solomon's Seal	First leaf	111.1	8.8	30	–0.32	0.17	0.069	11.3	**–3.86**	**0.83**	**<0.001**	**43.5**
Fritillaria imperialis	Crown Imperial	First flower	111.2	7.9	30	–0.22	0.16	0.163	6.8	**–3.23**	**0.78**	**<0.001**	**37.9**
Syringa vulgaris	Lilac	First flower	126.1	7.6	31	**–0.44**	**0.13**	**0.002**	**27.7**	**–4.56**	**0.89**	**<0.001**	**47.5**
Aesculus hippocastanum	Horse Chestnut	First flower	126.4	7.1	31	**–0.50**	**0.11**	**<0.001**	**40.1**	**–5.06**	**0.67**	**<0.001**	**66.4**
Taraxacum officinale	Dandelion	Seeding	129.3	7.6	31	**–0.52**	**0.12**	**<0.001**	**38.9**	**–5.26**	**0.73**	**<0.001**	**63.9**
Polygonatum multiflorum	Solomon's Seal	First flower	130.6	9.4	31	**–0.68**	**0.14**	**<0.001**	**43.2**	**–5.70**	**1.08**	**<0.001**	**49.1**
Primula veris	Cowslip	End of flowering	135.1	8.2	31	–0.22	0.16	0.185	6.0	**–5.03**	**0.93**	**<0.001**	**50.5**
Secale cereale	Rye	Earing	137.6	7.4	31	**–0.35**	**0.14**	**0.017**	**18.1**	**–4.64**	**0.83**	**<0.001**	**52.0**
Caltha palustris	Marsh Marigold	End of flowering	141.4	6.9	30	–0.05	0.14	0.742	0.4	**–3.71**	**0.87**	**<0.001**	**39.2**
Robinia pseudoacacia	False Acacia	First flower	146.6	9.4	31	–0.35	0.18	0.067	11.1	**–6.33**	**0.96**	**<0.001**	**60.0**
Sambucus nigra	Elder	First flower	148.1	10.0	31	–0.36	0.19	0.073	10.7	**–7.91**	**0.65**	**<0.001**	**83.7**
Leucojum vernum	Spring Snowflake	First senescence	151.5	10.7	30	–0.41	0.22	0.068	11.4	**–7.17**	**1.08**	**<0.001**	**61.1**
Physocarpus opulifolius	Ninebark	First flower	151.6	9.3	31	0.04	0.19	0.834	0.2	**–5.61**	**1.09**	**<0.001**	**47.8**
Fritillaria imperialis	Crown Imperial	First senescence	154.8	12.0	31	–0.28	0.24	0.259	4.4	**–5.55**	**1.80**	**0.004**	**24.7**
Aruncus sylvestris	Bridewort	First flower	154.9	7.1	31	–0.18	0.14	0.212	5.3	**–4.25**	**0.95**	**<0.001**	**40.6**
Clematis recta	Erect Clematis	First flower	155.5	7.8	31	–0.23	0.15	0.138	7.4	**–4.87**	**1.00**	**<0.001**	**44.9**
Caltha palustris	Marsh Marigold	Seeding	158.0	11.3	31	0.08	0.23	0.718	0.5	**–3.83**	**1.82**	**0.044**	**13.3**
Cichorium intybus	Chicory	First flower	176.1	11.0	31	**–0.48**	**0.21**	**0.026**	**15.9**	**–6.39**	**1.49**	**<0.001**	**38.9**
Lilium martagon	Martagon Lily	End of flowering	182.5	9.0	31	**–0.48**	**0.16**	**0.005**	**23.7**	**–5.55**	**0.88**	**<0.001**	**58.0**
Lupinus polyphyllus	Garden Lupin	Seeding	184.2	16.0	31	–0.61	0.31	0.055	12.1	**–6.11**	**2.14**	**0.008**	**21.9**
Hieracium umbellatum	Umbellate Hawkweed	First flower	190.2	10.0	30	0.11	0.21	0.627	0.9	**–3.10**	**1.40**	**0.035**	**15.0**
Astragalus glycyphyllos	Wild Liquorice	End of flowering	190.8	12.4	29	**–0.61**	**0.24**	**0.019**	**18.8**	**–6.75**	**1.47**	**<0.001**	**44.0**
Tilia cordata	Small–leaved Lime	End of flowering	192.2	9.9	31	–0.25	0.20	0.217	5.2	**–5.69**	**1.05**	**<0.001**	**50.3**

Table 1 (continued)

Scientific name	English name	Phase	Mean (DOY)	SD	n	Regression on year				Regression on 3 months temperature			
						slope days/year	SE	P	R^2	slope days/°C	SE	P	R^2
Lysimachia punctata	Dotted Loosestrife	End of flowering	193.0	10.7	31	**–0.42**	**0.20**	**0.050**	**12.6**	**–6.03**	**1.16**	**<0.001**	**48.4**
Solidago canadensis	Canadian Goldenrod	First flower	205.6	14.8	31	**1.15**	**0.21**	**<0.001**	**50.3**	–0.25	2.23	0.913	0.0
Campanula trachelium	Nettle-leaved Bellflower	Seeding	229.3	9.3	31	–0.02	0.19	0.913	0.0	–2.21	1.41	0.127	7.9
Sedum spectabile	Butterfly Stonecrop	First flower	239.6	9.3	31	**0.50**	**0.17**	**0.006**	**23.5**	1.49	1.44	0.310	3.5
Lysimachia punctata	Dotted Loosestrife	Seeding	242.5	11.7	31	0.42	0.22	0.070	10.9	–1.75	1.81	0.340	3.1
Cimicifuga europaea	Bugbane	Seeding	246.1	15.1	17	–0.36	0.54	0.522	2.8	–2.89	2.99	0.349	5.9
Solidago canadensis	Canadian Goldenrod	Seeding	247.3	13.9	31	**0.66**	**0.26**	**0.015**	**18.7**	1.24	1.91	0.523	1.4
Sambucus nigra	Elder	Seeding	251.0	12.4	30	0.14	0.26	0.613	0.9	–1.82	1.75	0.307	3.7
Aesculus hippocastanum	Horse Chestnut	Seeding	256.2	7.4	31	–0.05	0.15	0.724	0.4	–0.16	1.03	0.877	0.1
Aesculus hippocastanum	Horse Chestnut	Leaf colouring	269.9	10.0	28	**–0.48**	**0.20**	**0.027**	**17.5**	–0.35	1.48	0.817	0.2
Betula pendula	Silver Birch	Leaf colouring	274.5	10.9	31	0.21	0.22	0.358	2.9	**4.82**	**2.01**	**0.023**	**16.5**
Corylus avellana	Hazel	Leaf colouring	276.6	12.5	30	0.20	0.26	0.444	2.1	**4.96**	**2.35**	**0.043**	**13.8**
Cimicifuga europaea	Bugbane	Die back	286.6	11.4	19	–0.04	0.35	0.912	0.1	–1.42	2.94	0.636	1.4
Colchicum autumnale	Meadow Saffron	End of flowering	287.1	10.6	31	**0.44**	**0.20**	**0.037**	**14.2**	0.03	2.13	0.987	0.0
Vincetoxicum hirundinaria	Swallow-wort	Die back	291.5	13.5	31	0.13	0.27	0.637	0.8	–3.19	2.64	0.238	4.8
Paeonia officinalis	Peony	Die back	296.2	13.2	31	**0.54**	**0.25**	**0.040**	**13.8**	1.37	2.65	0.610	0.9
Aesculus hippocastanum	Horse Chestnut	Bare	308.0	7.0	28	0.02	0.16	0.894	0.1	0.55	1.20	0.649	0.8
Acer platanoides	Norway Maple	Bare	312.3	8.0	30	0.25	0.16	0.122	8.3	1.74	1.31	0.193	6.0
Phlox paniculata	Perennial Phlox	Die back	312.8	9.4	31	–0.23	0.19	0.229	4.9	–0.23	1.58	0.884	0.1
Viburnum opulus	Guelder Rose	Bare	313.3	8.4	31	–0.12	0.17	0.499	1.6	0.56	1.41	0.696	0.5
Syringa vulgaris	Lilac	Bare	314.1	8.2	31	–0.03	0.17	0.870	0.1	2.18	1.33	0.112	8.5
Paeonia sinensis	Chinese Peony	Die back	314.7	8.9	31	0.01	0.18	0.972	0.0	1.38	1.47	0.357	2.9
Iris sibirica	Siberian Iris	Die back	314.9	10.7	31	–0.13	0.22	0.552	1.2	**3.76**	**1.66**	**0.031**	**15.1**
Betula pendula	Silver Birch	Bare	316.9	10.2	31	**0.56**	**0.18**	**0.005**	**24.6**	**3.89**	**1.56**	**0.019**	**17.5**
Tilia cordata	Small-leaved Lime	Bare	317.8	9.8	31	**0.55**	**0.17**	**0.003**	**25.9**	**3.80**	**1.49**	**0.017**	**18.2**
Lysimachia punctata	Dotted Loosestrife	Die back	319.2	10.6	31	0.08	0.22	0.709	0.5	1.70	1.76	0.342	3.1
Larix decidua	European Larch	Bare	326.5	11.9	31	0.27	0.24	0.258	4.4	3.81	1.88	0.052	12.4
Salix fragilis	Crack Willow	Bare	326.7	15.1	31	**1.21**	**0.21**	**<0.001**	**53.3**	4.39	2.41	0.079	10.3

Regressions in bold are statistically significant $P<0.05$, phenophases are arranged in order of mean date

DOY Day of year (days after 31 December)

A highly significant correlation existed between the regression estimates of phenophase on year and the regression estimates of phenophase on temperature, i.e. columns 7 and 11 in Table 1 ($r_{64}=0.741$, $P<0.001$).

Trends and temperature responses in interphase intervals

Table 2 lists the 18 considered intervals. Seven of these had changed significantly during the study period; all of them getting longer. Fifteen of the 18 intervals had positive trends through time suggesting extended phase intervals for the majority of species, some of which can be interpreted loosely as the length of the growing season. For 7 of these intervals significant positive correlations existed between the two phases used to derive the interval (Table 2). However, the correlations were not typically large suggesting that the intervals are rarely predetermined, but rather influenced by annual climatic conditions. In fact only 3 of the earlier phases were significant in modelling the later phase once temperature effects had been accounted for (Table 2).

Table 2 Trends in 18 phase intervals, the correlation between the two phases and the significance of the earlier phases in a regression model after fitting 3-month temperature

Scientific name	Phase	Earlier phase	Mean (DOY)	SD	*n*	Regression on year				Correlation between phases	Influence and significance of earlier phase after fitting temperature	
						slope days/year	SE	*P*	R^2	*r*	Slope days/day	*P*
Aesculus hippocastanum	Seeding	First flower	129.7	8.4	31	**0.444**	**0.151**	**0.006**	**23.1**	0.34	0.367	0.066
Aesculus hippocastanum	Leaf colouring	First leaf	164.9	9.4	28	–0.134	0.208	0.526	1.6	**0.48**	**0.637**	**0.010**
Aesculus hippocastanum	Bare	First leaf	203.0	10.8	28	0.366	0.230	0.124	8.8	–0.01	–0.011	0.950
Aesculus hippocastanum	Bare	Leaf colouring	38.1	11.9	28	0.500	0.248	0.055	13.5	0.06	0.035	0.805
Betula pendula	Leaf colouring	First leaf	165.5	14.8	31	0.288	0.298	0.341	3.1	–0.08	–0.035	0.869
Betula pendula	Bare	First leaf	208.0	11.6	31	**0.640**	**0.204**	**0.004**	**25.4**	0.29	0.329	0.086
Betula pendula	Bare	Leaf colouring	42.5	12.6	31	0.352	0.250	0.169	6.4	0.29	0.153	0.370
Caltha palustris	Last flower	First flower	31.7	7.6	30	**0.321**	**0.146**	**0.037**	**14.7**	**0.59**	0.233	0.107
Caltha palustris	Seeding	First flower	48.0	13.2	31	0.485	0.253	0.066	11.2	0.20	0.103	0.645
Cimicifuga europaea	Die back	First leaf	180.9	12.8	17	–0.776	0.432	0.093	17.7	0.18	0.319	0.396
Corylus avellana	Leaf colouring	First leaf	174.0	16.5	30	**0.764**	**0.314**	**0.022**	**17.5**	0.06	0.160	0.426
Larix decidua	Bare	First leaf	220.7	14.4	31	**0.581**	**0.273**	**0.042**	**13.5**	0.11	0.141	0.532
Leucojum vernum	Senescence	First shoot	88.4	15.3	29	0.294	0.333	0.385	2.8	**0.44**	–0.019	0.845
Lysimachia punctata	Seeding	Last flower	49.5	14.1	31	**0.840**	**0.242**	**0.002**	**29.3**	0.20	0.166	0.496
Lysimachia punctata	Die back	First shoot	256.1	19.9	31	**0.842**	**0.376**	**0.033**	**14.7**	**0.36**	0.176	0.055
Primula veris	Last flower	First flower	29.5	11.9	30	0.107	0.255	0.676	0.6	**0.42**	0.014	0.899
Sambucus nigra	Seeding	First flower	103.0	12.4	30	0.501	0.247	0.053	12.8	**0.41**	**0.475**	**0.039**
Solidago canadensis	Seeding	First flower	41.7	14.2	31	–0.493	0.275	0.083	10.0	**0.51**	**0.480**	**0.005**

Results in bold are statistically significant $P<0.05$

DOY Day of year (days after 31 December)

Inter-species variability in spring and autumn

The standard deviation between the six early phenophases plotted against year is shown in Fig. 3. This has significantly increased over time (r_{29}=0.520, P=0.003) and is greater in early springs (correlation with the mean date of the six phenophases r_{29}=–0.502, P=0.004). The standard deviation between the eight “bare” phenophases plotted against year is shown in Fig. 4. This has also significantly increased over time (r_{29}=0.553, P=0.001) and is greater in *late* autumns (correlation with the mean date of the eight phenophases r_{29}=0.720, P<0.001).

Discussion

Botanical gardens can offer many advantages in studies of phenology and climate impacts (Donaldson 2009; Primack and Miller-Rushing 2009). They are typically long established, with professional staff and good archives. There is typically a stability in both staffing and methods that results in continuity of recording protocols, and a longevity that can rarely be achieved when records are made by individuals (but see Fitter and Fitter 2002). Phenological recording may often involve the same specimen in a relatively small area and thus eliminate some of the noise associated with phenological records made in the wild over large areas. Their compact area also makes interspecies comparisons more valid since environmental conditions will be much more similar. Many botanical gardens, such as that in Poznań, also have their own meteorological station enhancing the value of the plant records that have been made. Botanical garden archives offer additional possibilities (Miller-Rushing and Primack 2008; Donaldson 2009; Primack and Miller-Rushing 2009). Sadly, we are not aware of any other contemporary species-rich data sources within Poland with which to compare our data.

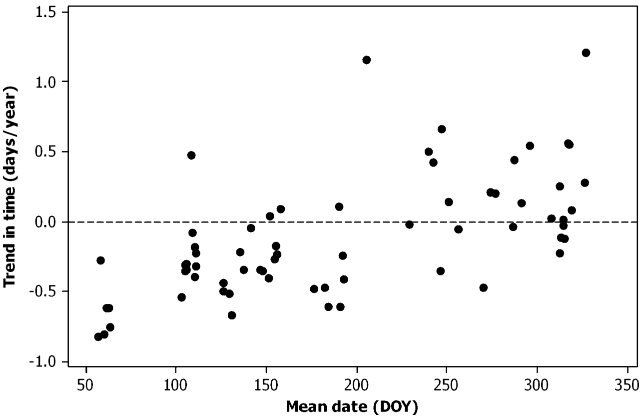

Fig. 1 Trends through time (days/year) for 66 phenophases recorded at the Poznań Botanical Garden in the period 1977-2007 plotted against the mean date (day of the year) of the phenophase. A *dotted reference line* has been added; phases below the line got earlier, above the line later

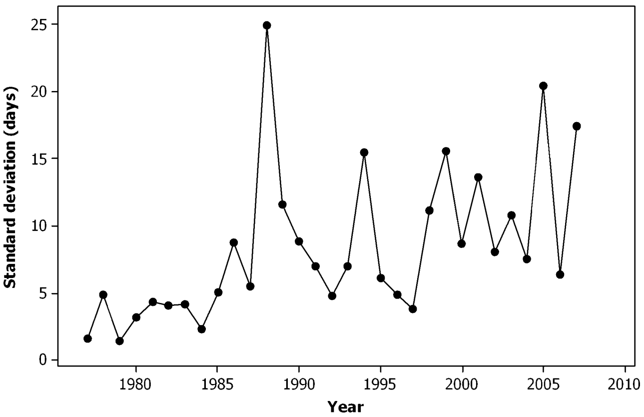

Fig. 3 The standard deviation between the dates of six early phenophases recorded at the Poznań Botanical Garden for the period 1977–2007

The results reported here confirm the responsiveness of plant phenology, particularly of spring events, to temperature. These help to confirm the value of plant phenology as a climate change indicator. Autumn events have typically been equivocal in their response to temperature but our results suggest a delay in autumn events associated with rising temperatures. Further work is needed to tease apart the relative importance of mean temperature and other autumn drivers such as wind, sunshine and frost on leaf fall. We investigated 18 interphase intervals. Seven of these had become significantly longer which broadly suggests a lengthening of the growing season. In all but three cases the earlier phase timing was not significant after temperature had been accounted for. Thus it appears that the later phases are far more influenced by prevailing temperature than the timing of preceding phases. However, for *Aesculus hippocastanum*, leaf colouring appeared positively correlated with earlier phases suggesting that early leafing resulted in an earlier end of season. However, this pattern was not apparent in *Betula pendula* or *Corylus avellana*. Further investigation of whether leaves have a limited lifetime ("shelf life"), thus associating early springs with early autumns, may be justified (see also Cleland et al. 2007).

We calculated a measure of spring synchrony based on the standard deviation between the dates of the six early spring events, and a similar one for autumn based on the standard deviation between the bare dates for eight tree species. Both of these measures increased significantly over time indicating reduced synchrony in both seasons. Whilst we are limited in the choice of phenophases to assess synchrony, examination of their coefficients for trend and temperature response in Table 1 do not suggest that synchrony measures are overly influenced by a single phenophase. We believe that most people associate the seasons, particularly spring and autumn, with biological events. These results suggest that the sharply

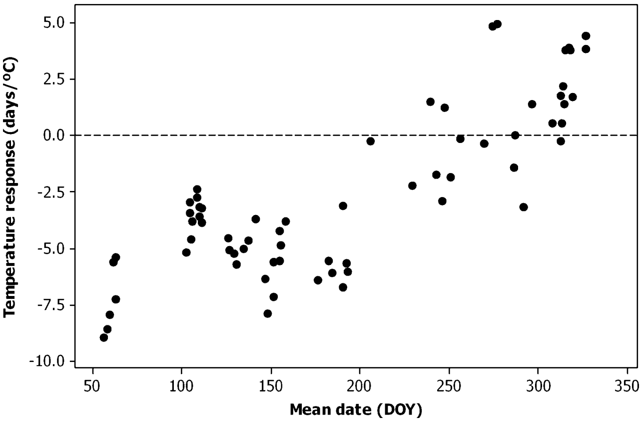

Fig. 2 Temperature responses (days/°C) for 66 phenophases recorded at the Poznań Botanical Garden in the period 1977-2007 plotted against the mean date (day of the year) of the phenophase. A *dotted reference line* has been added; phases below the line getting earlier with warmer temperatures, above the line later

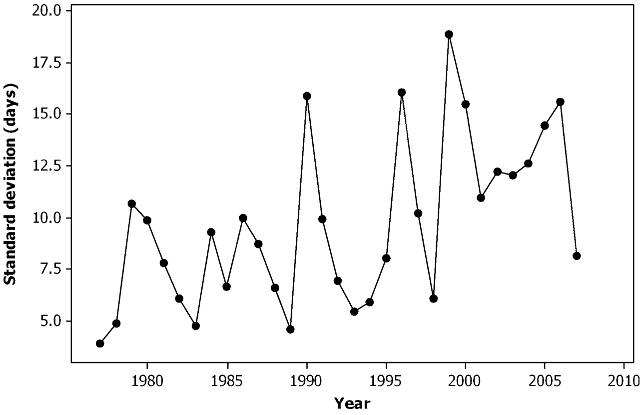

Fig. 4 The standard deviation between the dates of eight "bare" phenophases recorded at the Poznań Botanical Garden for the period 1977–2007

defined spring at this mid-continent location at the beginning of our study period (low standard deviation in Fig. 3) has become less consistent over time. A similar change has occurred in autumn. Thus the perceived boundaries between winter and spring, and between autumn and winter, have become increasingly blurred. The consequences of this phenomenon to wildlife, particularly those with specific dependent links in food webs, remains to be seen.

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