Phenology of common beech (*Fagus sylvatica* L.) along the altitudinal gradient in Slovak Republic (Inner Western Carpathians)

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ABSTRACT: The onset and course of selected vegetative phenological phases of beech along the altitudinal gradient in Slovak Republic were studied. Observations were done in the Burda Mts. (200–300 m a.s.l.), Kremnické vrchy Mts. (500 m a.s.l.) and in the Poľana Mts. (900–1,000 m a.s.l., 1,200–1,400 m a.s.l.). Selected spring phenological phases (budburst and leaf unfolding) as well as autumn phenological phases (autumn colouring and leaf fall) were investigated over the period of 5 years (2007–2011). The earliest onset of spring phenological phases during the period of study was found at the lowest-lying sites in the Burda Mts. By contrast, the latest one was observed at the uppermost site in the Poľana Mts. The dynamics of autumn phenological phases had the opposite course compared to spring phenophases. The earliest onset, observed in the uppermost locality in the Poľana Mts., was gradually delayed with decreasing altitude. The phenological gradient, expressing a shift in the onset of spring phenophases along the gradient, reached the mean values of 2.83–3.00 days per 100 m of an increase in altitude. In the case of autumn phenological phases the gradient ranged from –1.00 to –1.78 days per 100 m. On average, the growing season of beech lasted from 128 to 181 days along the altitudinal gradient. Significant correlations ($P < 0.001$) were calculated between the date of the onset of phenophases and altitude.

Keywords: beech forests; phenological phases; altitude; Burda Mts.; Kremnické vrchy Mts.; Poľana Mts.

In the context of global changes in environmental conditions we observe greater extremes in weather conditions. Therefore, changes in competitive relationships among trees are expected (Bolliger et al. 2000). Phenological responses of trees can serve as a potential bioindicator (Saxe et al. 2001; Cleland et al. 2007; Škvareninová 2007; Škvareninová et al. 2008). The increase in temperature induces earlier spring budding, which may increase the risk of damage to the tree assimilation system by late spring frosts (Kramer 1995; Dittmar et al. 2006). Water deficit during the growing season can cause the weakening of their competition (Gessler et al. 2007). On the other hand, relatively positive effects can be expected, e.g. extension of the growing season due to rising average air temperature (Chmielewski, Rötzer 2001). Plants tolerate these changes and adapt to them, but only to a certain extent. Therefore, it is important to know their responses to the limits of their ecological existence. Common beech is a tree species of oceanic climate, dislikes frosts and drought or permanent waterlogging. It is included in the International Phenological Gardens program (Chmielewski 1996). Beech accounts for the highest proportion in forests of the Slovak Republic exceeding 31.6%. The vertical incidence ranges from about 150 m up to 1,450 m a.s.l. Ecological optimum is identical to production optimum, which is the elevation from 450 m to 900 m a.s.l. Due to particularly favourable temperature and humidity conditions, beech shows a good vitality there. Near the lower limit of its natural range

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the limiting factor of its existence is drought. On the contrary, there is generally enough moisture near the upper limit, but the lack of warmth is evident. Phenology of common beech was studied by several authors (Cicák, Štefančík 1993; Heide 1993; von Wuehlisch et al. 1995; Falussi, Calamassi 1997; Štefančík 1997; Priwitzer, Miňďáš 1998; Chmura, Rozkowski 2002; Schieber 2006; Bednářová, Merklová 2007; Merklová, Bednářová 2008; Barna et al. 2009; Schieber et al. 2009). Only a few works were devoted to the investigation of phenological responses of beech along the vertical gradient (Rötzer, Chmielewski 2001; Dittmar, Elling 2006; Vitasse et al. 2009; Čufar et al. 2012).

The aim of the work was to evaluate the onset and course of selected vegetative phenological phases of common beech over a period of five years (2007–2011) on the borders of its ecological occurrence in Slovak Republic in the Inner Western Carpathians.

MATERIAL AND METHODS

Study sites

Phenological research was conducted in beech stands located in three neovolcanic mountains in Slovak Republic – Burda Mts., Kremnické vrchy Mts. and Polana Mts., which are located south of the main line of the climate in Slovak Republic (Zlatník 1978). The orographic units belong to the Inner Western Carpathians (Fig. 1).

The Burda Mts. lie in the southeastern corner of the lower Danube Plain between the rivers Danube, Hron and Ipeľ and their height is relatively little differentiated (113–405 m a.s.l.). The area belongs to the warm climate, dry district with mild winter. Observations were done at two sites located north of the village of Chľaba. The first locality is situated at the beginning of the Veľká dolina valley (B1), the distance of the second one is about 1 km from the first site at the top near the cottage Ipeľ (B2). The Kremnické vrchy Mts. are situated in the central part of Slovak Republic. Phenological observations were carried out on an Experimental Ecological Stationary Kremnické vrchy Mts. (KV), which is located in the SE part of the above orographic unit. The locality belongs to the temperate climate zone, slightly damp to wet district. The Poľana Mts. are the highest volcanic mountain range in Slovak Republic. Southern foothills of the Poľana Mts. belong to the temperate climate, humid district. The other mountain territory is classified into a cold climate zone, slightly cool to cold mountain district (Lapin et al. 2002). Observations were done at five localities within this mountain chain. The lowest lying area is situated above the village of Priehalina (P1), the second location is Javorinka (P2). The other sites are located at Huklová (P3), Predná Poľana (P4) and Zadná Poľana (P5). Basic characteristics of the sites are listed in Table 1.

Phenological observations

Observations were done by a partially modified method for phenological monitoring used by the Slovak Hydrometeorological Institute (Braslavská, Kamenský 1996). The group of individuals consisted of 10 mature trees growing within a forest stand with good health conditions. Very soon or very late budding phenological forms were excluded. Visual observations were conducted in regular intervals – phenological phases were evaluated twice (in spring) or once a week (in autumn). The following phenological phases were observed and evaluated: budburst (BB), leaf unfolding 10% (LU 10), leaf unfolding 50% (LU 50), leaf unfolding 100% (LU 100), autumn colouring 10% (AC 10), autumn colouring 50% (AC 50), autumn colouring 100% (AC 100), leaf

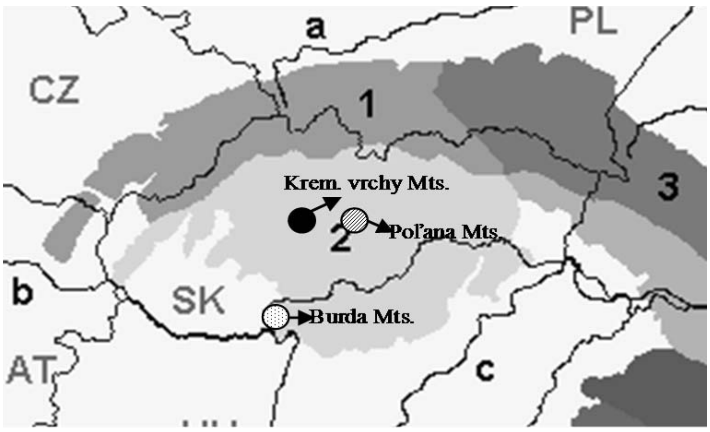

Fig. 1. Location of the research plots in Slovak Republic (1 – Outer Western Carpathians, 2 – Inner Western Carpathians, 3 – Outer Eastern Carpathians, a – Vistula River, b – Danube River, c – Tisza River)

Table 1. Characteristics of research sites along the altitudinal gradient

Orographic unit	Burda Mts.		Kremnické vrchy Mts.	Poľana Mts.				
Locality	B1	B2	KV	P1	P2	P3	P4	P5
Altitude (m a.s.l.)	200	300	500	900	1,000	1,200	1,300	1,400
Exposition	NE	NE	WSW	SE	SE	E	SE	SW
Average annual temperature (°C)	9.3	8.6	6.9	5.6	5.1	4.0	3.4	2.9
Average temperature IV–IX$_{1951–1980}$ (°C)	15.9	15.3	13.6	11.6	11.0	10.1	9.5	8.8
Average annual precipitation $_{1951–1980}$ (mm)	600	640	780	890	930	1,040	1,100	1,160
Average precipitation IV–IX$_{1951–1980}$ (mm)	355	385	420	500	530	575	610	640

fall 10% (LF 10), leaf fall 50% (LF 50) and leaf fall 100% (LF 100). The onset of phenophases was expressed as a sequence of days counted from 1 January – day of year (DOY). Climate data were taken from the databases of Slovak Hydrometeorological Institute and NMS (Hungary) as well as own data were used. The degree of correlation of two variables – the onset of phenological phase (expressed as DOY) as a dependent variable versus altitude as a regressor − was expressed by the coefficient of linear correlation (Pearson's product moment).

RESULTS

Spring phenophases

The onset of spring phenological phases of beech at localities at different altitudes in the period 2007–2011 is described in Table 2. On average, the earliest onset of spring phenophases was found in lowland areas in the Burda Mts. In opposite, the latest onset was observed in mountain areas of the Poľana Mts. The average onset of budburst (BB) in the lowermost site (locality B1) was recorded on 101st day of the year (i.e. 11 April). The onset of BB was delayed progressively with increasing altitude, the 36-day (i.e. BB on 17 May) delay was recorded at the highest altitudes. In relative terms, nearly about 36% more days are needed to reach the BB events.

The phenological gradient, which reflects a difference in the onset of events between the lowest and the highest site calculated per 100 m of altitude increase, reached +3.00 days per 100 m in this phenophase. A similar course was found out within the next three spring phenological phases – LU 10, LU 50, LU 100, when the difference ranged from

Table 2. The onset of spring phenophases of beech on study sites at different altitudes

Locality		B1	B2	KV	P1	P2	P3	P4	P5
Altitude (m a.s.l.)		200	300	500	900	1,000	1,200	1,300	1,400
Mean$_{2007–2011}$ (DOY)	BB	101	102	107	113	116	129	132	137
	LU 10	106	107	110	117	121	132	137	142
	LU 50	110	110	114	121	125	136	141	145
	LU 100	116	116	120	128	131	141	145	150
SD (± days)	BB	4.86	5.24	4.13	3.66	3.93	3.98	4.59	5.54
	LU 10	3.37	4.05	4.43	4.2	3.72	5.08	5.88	5.68
	LU 50	3.54	3.61	3.71	3.63	3.41	4.53	5.74	5.54
	LU 100	2.64	3.06	2.58	2.15	2.64	4.71	5.69	5.46
CV (%)	BB	4.81	5.12	3.87	3.24	3.38	3.09	3.46	4.03
	LU 10	3.17	3.78	4.02	3.59	3.08	3.84	4.3	4.01
	LU 50	3.23	3.27	3.26	3	2.72	3.34	4.08	3.81
	LU 100	2.28	2.64	2.14	1.69	2.02	3.34	3.93	3.65

DOY – day of year, BB – budburst, LU 10 – leaf unfolding 10%, LU 50 – leaf unfolding 50%, LU 100 – leaf unfolding 100%

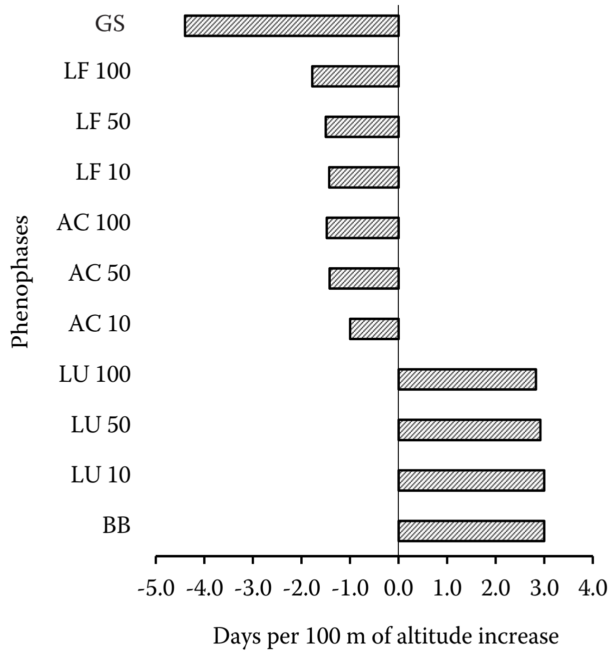

Fig. 2. Average shifts of the onset of phenophases and duration of growing season (GS) in the years 2007–2011

34 to 36 days along the altitudinal gradient. Phenological gradient ranged from +2.83 to +3.00 days per 100 m (Fig. 2).

The average length of the interval between the onsets of BB and LU 100 phases, which represents the major period of tree leafing, was relatively steady at all sites. It varied within the range of 12–15 days. A correlation analysis between the average onset of spring phenophases and altitude confirmed a statistically significant correlation ($P < 0.001$, Fig. 3).

Dating of the onset of spring vegetative phenophases varied depending not only on the altitude as mentioned above, but also between the compared years. The lowest year to year variability of the BB onset was found out within the middle mountain ranges (900–1,200 m a.s.l., localities P1–P3), while the highest variability was observed at the lowest sites (B1 and B2). As for leafing (LU 10, LU 50 and LU 100 phases), the lowest variability was observed at altitudes from 900 to 1,000 m a.s.l. On the other hand, the highest variability was found out in the areas situated above 1,300 m a.s.l. (Table 2).

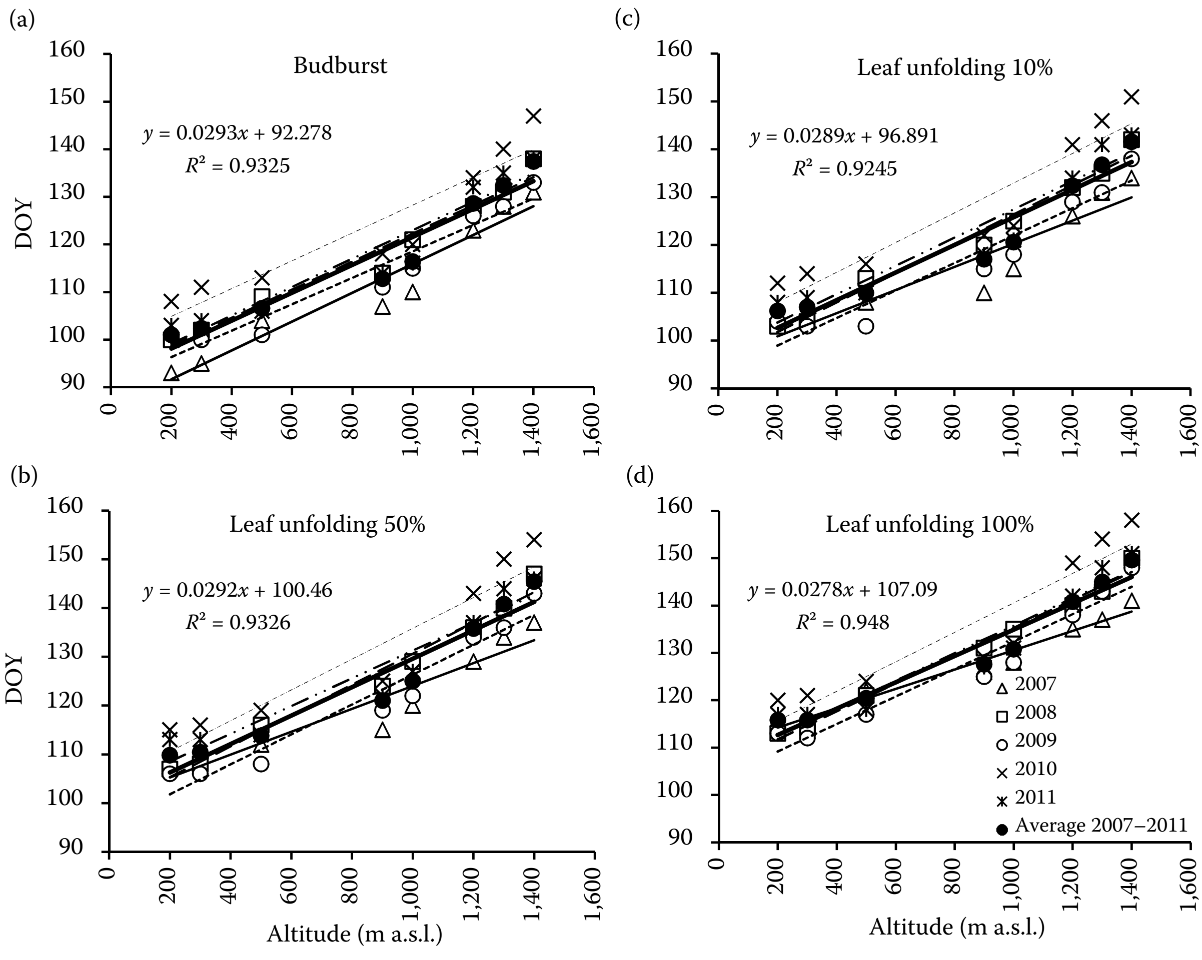

Fig. 3. Relationships between the average onset of spring phenological phases of beech and altitude during the growing seasons 2007–2011, in bold – averaged linear trend, DOY – day of year

Autumn phenophases

The average onset of autumn phenological events over the study period is presented in Table 3. It is obvious that the autumn events competed in the reverse order as it was in the case of spring phenophases. On average, the earliest onset of phenophases was observed at the uppermost locality P5 in the Poľana Mts. It is gradually delayed with decreasing altitude, therefore the latest onset of autumn phenophases was found out at low sites B1 and B2. The average onset of AC 10 phenophase was recorded on the 262nd DOY (i.e. 19 September) in the uppermost site P5, whereas it was recorded on the 274th DOY (i.e. 1 October) in the lowermost site B1. The onset of the next two phenophases AC 50 and AC 100 had a similar course. The interphase interval between AC 10 and AC 100 phenophases, representing a major period of leaf colouring, ranged from 25 days (site P5) to 31 days (sites B1 and B2) on average. Dynamics of leaf fall shows a similar trend as it was found in the case of autumn colouring. Phenophase LF 10 was first recorded in the mountain area P5 (i.e. on the 273rd DOY to 30 September) and the latest in low-located sites B1 and B2 (i.e. on the 290th DOY – 17 October). With increasing altitude, the onset of LF 50 and LF 100 phenophases shifted to the earlier dates. The difference in the onset of autumn phenophases between the highest and the lowest altitudinal sites ranged from 12 days (AC 10) to 22 days (LF 100). Delay of the onset of autumn phenophases in the lowest sites in relation to the highest ones was 4.6–7.3% in relative terms, which is considerably less than it was in the case of spring phenophases. This fact is confirmed by the value of the phenological gradient within the autumn phenological phases (Fig. 2).

Statistically significant correlations ($P < 0.001$) between the average onset of autumn phenophases and altitude were found like in the case of spring events (Fig. 4). The interphase interval between LF 10 and LF 100, which represents the main period of leaf fall, ranged from 28 days at P5 locality to 37 days at localities KV and P1. The average length of the interphase interval between AC 10 and LF 100 varied from 39 days (P5 locality) to 49 days (B1 locality).

Table 3. The onset of autumn phenophases of beech on study sites at different altitudes

Locality		B1	B2	KV	P1	P2	P3	P4	P5
Altitude (m a.s.l.)		200	300	500	900	1,000	1,200	1,300	1,400
$\text{Mean}_{2007–2011}$ (DOY)	AC 10	274	275	274	269	267	265	263	262
	AC 50	291	291	287	282	280	278	275	274
	AC 100	305	306	301	298	295	291	289	287
	LF 10	290	290	283	278	277	275	274	273
	LF 50	306	305	304	300	297	294	292	288
	LF 100	323	321	320	315	313	309	306	301
SD (± days)	AC 10	5.06	4.60	5.82	6.96	7.88	8.45	9.13	9.58
	AC 50	5.16	4.75	5.68	8.98	9.77	11.11	11.17	11.39
	AC 100	3.76	3.92	5.15	6.74	7.55	10.26	10.28	10.31
	LF 10	5.60	5.46	3.74	6.76	6.89	5.95	6.16	6.10
	LF 50	8.45	7.86	9.28	11.01	12.14	12.08	12.53	11.11
	LF 100	9.62	11.45	16.14	17.62	18.02	18.54	18.53	16.28
CV (%)	AC 10	1.85	1.67	2.13	2.59	2.96	3.19	3.47	3.65
	AC 50	1.78	1.63	1.98	3.18	3.49	4.00	4.06	4.16
	AC 100	1.23	1.28	1.71	2.27	2.56	3.52	3.56	3.59
	LF 10	1.93	1.88	1.32	2.44	2.49	2.16	2.25	2.23
	LF 50	2.77	2.58	3.05	3.67	4.08	4.11	4.29	3.86
	LF 100	2.98	3.57	5.05	5.59	5.76	6.00	6.05	5.40

DOY – day of year, AC 10 – autumn colouring 10%, AC 50 – autumn colouring 50%, AC 100 – autumn colouring 100%, LF 10 – leaf fall 10%, LF 50 – leaf fall 50 %, LF 100 – leaf fall 100%

The average duration of the growing season for beech, defined as a period between the average onset of LU 50 and AC 50 phenophases, lasted from 128 days (P5) to 181 days (B1 and B2) depending on the altitude. On average, an about 30% shorter growing season was observed at the highest altitudes compared to the lowest ones. The duration of the growing season shortened about 4.4 days per each altitudinal 100 m in the vertical gradient. Variability of the growing season length increased with increasing altitude (Fig. 5)

The analysis showed that the increasing altitude was related to higher variability in the onset of all LC phenophases. As for LF phenophases, it was

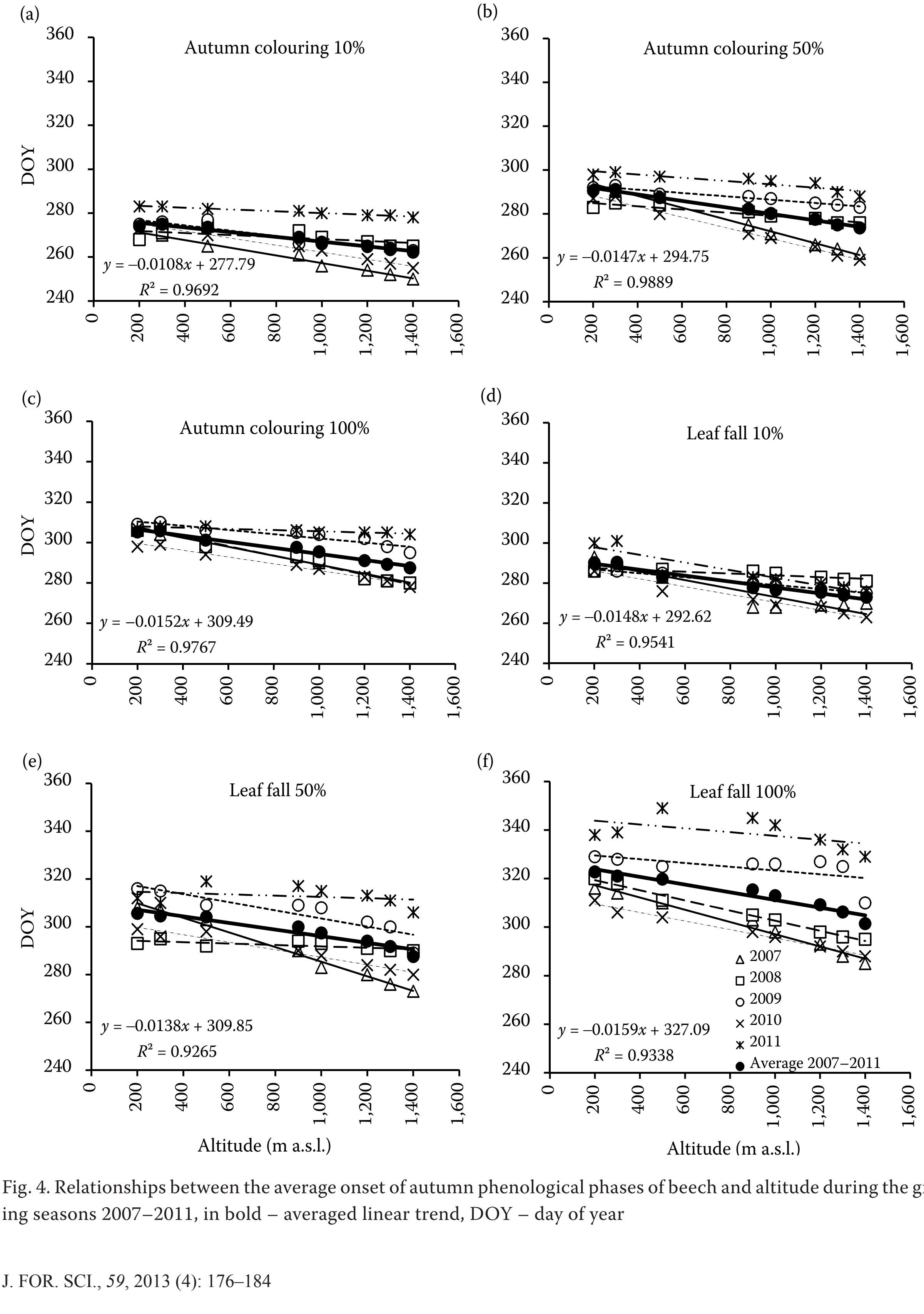

Fig. 4. Relationships between the average onset of autumn phenological phases of beech and altitude during the growing seasons 2007–2011, in bold – averaged linear trend, DOY – day of year

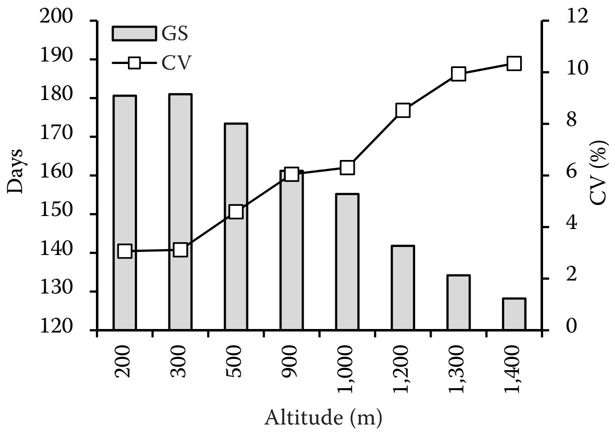

Fig. 5. Growing season (GS) duration and variability of the growing season length along the altitudinal gradient (CV – coefficient of variation)

slightly different. Variability in the onset of LF 10 phenophase was almost the same at all sites. Dating of the onset of LF 50 and LF 100 phenophases showed a higher year to year variability. The altitude increase caused an increase in variability, with the exception of the uppermost site P5 (Table 3).

DISCUSSION

It is known that the timing of the onset of spring phenophases is affected by various factors, e.g. by the sum of chilling temperatures in the dormant season, length of the photoperiod, onset of forcing temperatures or sum of effective temperatures (Heide 1993). The climate of our study area is characterized as transitional oceanic-continental (continentality index is around 31%), therefore it is expected that the condition of sufficient sums of chilling temperatures is generally satisfied. The length of the photoperiod at the time of average leaf unfolding is more than 13 h, which is sufficient. Forcing temperatures are therefore a major factor in our study area, which may vary quite significantly in particular years and affect the onset of spring phenophases (temporal variability of temperature). Also the spatial variability of temperatures is evident, e.g. along the altitudinal gradient. In general, with increasing altitude the temperature decreases, and thus the total sum of effective temperatures. We found out that the average onset of spring phenophases was significantly correlated with altitude. The earliest onset was observed at the lowest altitudes and vice versa. This fact was associated with a decrease in temperature due to the increasing altitude, the vertical temperature gradient in spring reached –0.6°C per 100 m of an increase in altitude (Fig. 6). The gradient in spring phenological events averaged +3.00 days per 100 m, so a temperature drop of 1°C was associated with delay in the onset of spring phenophases by about 5 days. Kramer (1996) found out that the leaf unfolding of beech was accelerated by 3.6 days per 1°C. Similarly, Rötzer and Chmielewski (2001) using regression coefficients calculated the faster leaf unfolding of beech by 3.2 days per 1°C. Dittmar and Elling (2006) reported that the spring leaf unfolding of beech was delayed by about 2 days per each 100 m a.s.l. in southern Germany. Vitasse et al. (2009) indicated the acceleration of leafing by about 1.1 days per 100 m of a decrease in altitude.

It is interesting that we found a relatively small difference between the average onsets of BB events and LU 100 events across the vertical gradient. It seems that the dynamics of leafing is relatively the same regardless of the altitude. The onset of autumn phenological phases depends, among other biological properties of trees, on the impact and interaction of several climatic factors. The length of the photoperiod plays an important role in addition to temperature and humidity. No model of successful prediction of the onset of AC phase has been designed yet. Dittmar and Elling (2006) found that the autumn leaf colouring (AC) does not depend on the altitude. Estrella and Menzel (2006) reported that warm September moderately correlated ($r = 0.56$) with a delay in the onset of AC phase of beech. Čufar et al. (2012) also found a correlation between the temperature in August and September and the onset of AC, but the amount of monthly precipitation was not significantly corre-

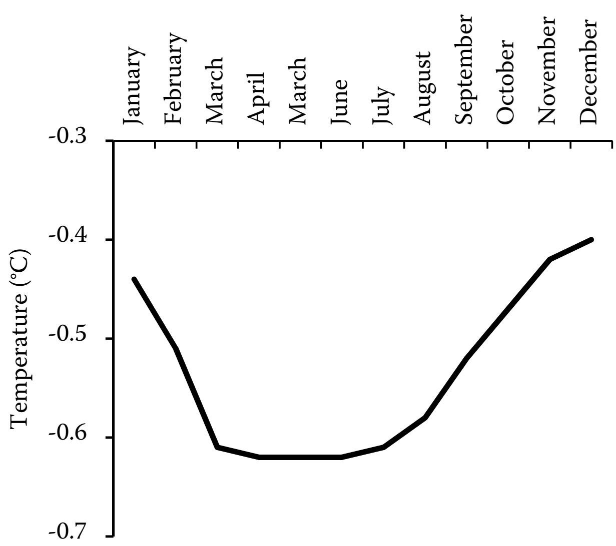

Fig. 6. Average temperature gradient (per each 100 m) in the period 2007–2011

lated with AC. Our comparison of the average onset of autumn phenophases showed the opposite order to that of spring phenophases, but differences between sites within the gradient were significantly smaller. It is also evident from the value of the phenological gradient, which was about +1.4 days per 100 m. During the period of research, the temperature gradient in September was on average about –0.5°C per 100 m (Fig. 6), the delay of the onset of AC phase would be represented by 2.8 days per 1°C in this case. A correlation between the average monthly temperature in September and the onset of AC 50 was also found by us, especially for high altitudes, but the insufficient data set of five years of research does not allow us to make more concrete conclusions. Variability in the length of the growing season (defined as the period between the onsets of LU 50 and AC 50 phenophases) increased with increasing altitude. If we assume that the extension of the growing season depends mainly on the earlier onset of spring phenophases, we note that the trend of increasing spring temperatures can cause the prolongation of the growing season in the near future, especially at higher elevations. Beech can be vulnerable at these locations due to a higher risk of damage to the assimilation apparatus by late spring frosts. The onset of LF 10 shows the lowest variability around the gradient, while LF 50 and LF 100 phenophases varied slightly more with increasing altitude. It should be noted that the actual leaf fall is influenced not only by physiological processes (formation of cork layers followed by vascular rupture) but also by mechanical factors such as wind, rain or snow, which are highly variable and hardly predictable from year to year.

CONCLUSIONS

Phenological responses to changes in environmental conditions seem to be a useful tool for ecological research at present. Increased attention is paid to the study of changes in environmental conditions caused by global changes, such as climate change. Due to the increasing variability of the main meteorological elements throughout the year, there are different phenological responses of trees. For a more objective understanding of these processes it is therefore important to know the responses of plants at the margin of their existence, e.g. along the vertical gradient. During the period 2007–2011, we studied the onset and course of spring and autumn phenological phases of beech along the altitudinal gradient from 200 to 1,400 m a.s.l. in the Slovak Republic. We found out the earliest onset of spring phenophases at low altitudes. Conversely, the latest onset of the phenophases was observed at the highest altitudes. The average onset of autumn phenophases had an opposite course to that of spring phenophases – with decreasing altitude it was gradually delayed. The phenological gradient for spring phenophases ranged from +2.83 to +3.00 days per 100 m and from –1.00 to –1.78 days per 100 m for autumn phenological phases. The length of the growing season was about 128 days at the highest altitudinal sites and increased to 181 days at the lowest sites. We found a significant correlation ($P < 0.001$) between the onset of phenophases and altitude.

The results of phenological observations can contribute to the dissemination of knowledge regarding the phenological responses of plants as bioindicators of changing environmental conditions. Plant selection practice may use these results to select appropriate phenological forms (late-budding phenological forms) and the subsequent forest stands could be restored mainly in specific environmental conditions.

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