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Effect of biometeorological variables on the onset of phenophases derived from MODIS data and visual observations

Vplyv biometeorologických premenných na nástup fenofáz odvodených z MODISu a z vizuálnych pozorovaní

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Abstract

In this study we analyzed the effect of selected biometeorological variables on the onset of phenophases in three beech stands in different climatic areas (warm, moderately warm and cold). We have focused on two phenophases – leaf unfolding and leaf colouring. Timing of both phenophases was identified visually and using series of MODIS satellite images. The data were collected during a 13-year period (2000–2012). For the spring period, we found a significant dependence between temperature and precipitation-based biometeorological variables and leaf unfolding in both datasets – those based on visual and remote sensing-based observations. The average air temperature in the period from February–April was the most significant factor which initiated the onset of beginning of leaf unfolding in all three investigated stands. The evapotranspiration-based biometeorological variables (climatic water balance, actual evapotranspiration, dryness index) had no effect on the onset of the beginning of leaf unfolding observed using both methods. The high precipitation totals in April caused the later onset of leaf unfolding in all stands. The relationship between the first autumn phenophase – leaf colouring and biometeorological variables was found significant in beech stand in the warm climatic area only.

Keywords: *Fagus sylvatica*; phenology; biometeorological variables; MODIS

Abstrakt

V práci sme analyzovali vplyv biometeorologických premenných na nástup fenologických fáz v troch bukových porastoch nachádzajúcich sa v rozdielnych klimatických oblastiach (teplej, mierne teplej a studenej). Sledovanými fenofázami boli začiatok zalistenia a začiatok žltnutia listov. Ich nástup bol sledovaný vizuálne a s použitím satelitných údajov MODIS. Pozorovania prebiehali počas 13-ročného obdobia (2000–2012). V jarnom období sme zistili významný vplyv biometeorologických premenných založených na teplote a zrážkach na začiatok zalistenia bukových porastov zisteného obomi – vizuálnym aj satelitným sledovaním. Najvýznamnejšou z týchto premenných bola priemerná teplota vzduchu od februára do apríla, ktorá vyvolávala skorší nástup začiatku zalistenia na všetkých troch bukových stanovištiach. Vyššie úhrny zrážok v mesiaci apríl spôsobovali na sledovaných stanovištiach neskorší nástup tejto fenofázy. Naopak, premenné založené na evapotranspirácií (klimatická vodná bilancia, aktuálna evapotranspirácia, index sucha) nemali žiaden vplyv na začiatok zalistenia zistený oboma metódami. Vzťah medzi prvou jesennou fenofázou – začiatkom žltnutia listov a biometeorologickými premennými bol významný iba na bukovom stanovišti nachádzajúcom sa v teplej klimatickej oblasti.

Kľúčové slová: *Fagus sylvatica*; fenológia; biometeorologické premenné; MODIS

Introduction

The reactions of vegetation to climate change conditions have been widely discussed in recent studies on phenology, climatology and remote sensing. The phenological phases responding to the fluctuation of meteorological elements are sensitive and easy-to-observe reactions of vegetation to climate change (Badeck et al. 2004). In the middle latitudes, the onset of the phenophases like bud bursting, leaf unfolding, flowering, etc. is effected by the air temperature (Ahas et al. 2000; Sparks et al. 2000; Defila & Clot 2000; Menzel 2003). It was proved that higher temperatures during the spring period evoke earlier onset of tree species spring phenophases (Chmielewski & Rötzer 2001; Menzel et al. 2006; Kramer 1996; Pálešová 2012). But there are other meteorological elements that could be limiting environmental factors for tree species in the climate change conditions: the lack of rainfall amount and uprising evapotranspiration during the growing season (Škvarenina et al. 2004). In Slovakia, there is the assumption that changed bioclimatic conditions especially from the 1st to the 3rd (partially the 4th) vegetation belt disturb existing plant (primarily beech) communities and their species compositions. However, favourable temperature conditions with sufficient water balance in the higher vegetation tiers (from the 5th) may represent climatic conditions appropriating the presence of deciduous tree species like beech (Škvarenina et al. 2004).

In the past, the onset of phenophases could be observed only visually. During the last decades, the methods of phenological observations using remote sensing data (Kang et

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Corresponding author. Veronika Lukasová, e-mail: veronika.brandysova@gmail.com al. 2003; Zhang et al. 2003; Fisher & Mustard 2007), and simple or hemispherical digital photography (Nagai et al. 2010; Možný et al. 2012; Felts et al. 2011) have been developed. The remote sensing data have significant potential in monitoring of vegetation dynamics on a regional to global scale. The first studies from the field of remote sensing phenology utilized data from the radiometer AVHRR. The dates of the beginning and end of the growing season were derived and the length of the growing season was calculated. Later, after the Terra and Aqua spacecrafts with the spectroradiometer MODIS were launched into orbit, the phenology was monitored more precisely (Zhang et al. 2003; Fisher et al. 2006; Soudani et al. 2012). Vegetation indices were proposed to be the biophysical indicators of the changing amount and quality of green vegetation, e.g. *NDVI* – Normalized Difference Vegetation Index (Beck et al. 2006; Narasihman & Stow 2010; Soudani et al. 2012), *EVI* – Enhanced Vegetation Index (Zhang et al. 2003; Ganguly et al. 2010), *PVI* – Perpendicular Vegetation Index (Guyon et al. 2011), *WDRVI* – Wide Dynamic Range Vegetation Index (Jönsson et al. 2010). The vegetation index commonly used in remote sensing phenology is the ratio index NDVI, which is calculated from the reflectance of vegetation in the red and near infrared band. Healthy (green) vegetation absorbs the incoming visible radiation and reflects the near infrared radiation (Weier & Herring 2011).

This study was focused on the forests stands with dominant occurrence of European beech – *Fagus sylvatica* L. (subspecies *F. sylvatica* ssp. *sylvatica*), which is continually distributed across Europe. Beech is a competing proficient tree species, which does not grow only in very shallow soils with low water capacity, on wet or flooded soils with permanently or periodically low air capacity, and in the harsh mountain climate. The lower border of the European beech extension belongs to the warm climate area, dry to moderately moist precinct. The general occurrence of beech forests is localized in moderately warm to cold climate area, moderately to very moist precinct within the 2nd to 6th altitudinal vegetation belt. The upper border of sporadic occurrence of beech is localized on the transition between the moderately cold and cold mountain precincts in the cold climate area (Gömöry et al. 2011).

In this study, we examined what are the limiting meteorological variables that had the most significant effect on the onset of vegetative phenophases of European beech.

2. Material and methods

2.1. Investigated forest stands

The beech stands analyzed in this study were established in three contrasting climatic areas – warm, moderately warm and cold (Table 1). The three beech stands were selected from the phenology network of the Slovak Hydrometeorological Institute. The homogeneity of beech stands in surrounding areas was verified on the basis of the Forest Management Plan database and Landsat-based tree species composition map of the Slovak forests as well (Bucha 1999). The species composition map derived from Landsat was aggregated from 30 m to 250 m pixels corresponding to MODIS images. The 250 m pixels with more than 60% of beech were classified as a “beech” class and used for further satellite based phenology analyses. The pixels on the boundary between beech forests and other land cover classes or forest types were excluded due to possible spectral contamination (Wolfe et al. 2002).

2.2. Visual phenological observations

In each stand, phenological observations were performed on a sample of ten representative overstory beeches. The method by Braslavská & Kamenský (1996) was used during the 13-year period (2000–2012). In spring, one phenological stage of leaf unfolding was observed: first leaf (*VIS_LU_10*), when 10% of leaves of monitored trees were unfolded. In autumn, one stage of the phenophase leaf colouring was observed: beginning leaf colouring (*VIS_LC_10*), when 10% of leaves of monitored trees changed their colour to yellow or brown.

2.3. Phenology metrics from MODIS data

The MOD09GQ (MYD09GQ) daily surface reflectance products from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua satellites were used to calculate the seasonal course of NDVI. The MOD09GQ (MYD09GQ) consists of the red spectral band (RED 620–670 nm) and near infrared spectral band (NIR 841–876 nm) with 250 m spatial resolution. We checked the recorded reflectance at pixel level in each individual image for possible clouds; fog, aerosols, etc. according to the flags in the quality control data (MOD09GA, MYD09GA) (Vermote et al. 2011). The image pixels that did not match the quality criteria in the quality analysis, were eliminated from further analyses. Based on the MOD09GQ and MYD09GQ products we calculated daily NDVI for each of the stands in the period 2000–2012.

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad [1]$$

Phenological metrics. The normalized difference vegetation index (NDVI) was considered as a suitable indicator of changing amount, quality and structure of European beech assi-

Table 1. Description of investigated beech stands.

Stand	Altitude [m a.s.l.]	Aspect	Tree species composition [%]			Climatic area	T [°C]	P [mm]
			beech	coniferous	deciduous			
Železná Studienka	304	NW	60	20	20	Warm	9.4	645
Zvolen	566	SW	65	—	35	Moderately warm	7.6	745
Poľana	1051	SE	80	15	5	Cold	4.9	924

T – average annual air temperature during period 1961–1990; P – average annual precipitation totals during period 1961–1990.

milatory organs (Brandýsová & Bucha 2012). NDVI temporal profiles were modelled with sigmoid logistic function proposed by Fisher et al. (2006) using the software program Phenological profile (Bucha & Koreň 2009):

$$v(t) = v_{min} + v_{amp} \quad \frac{1}{1+e^{m_1 - n_1 t}} - \frac{1}{1+e^{m_2 - n_2 t}} \qquad [2]$$

Where $v(t)$ represents the value of the vegetation index NDVI. We used a four-parameter method (4D). Parameters v_{min} and v_{amp} were predefined (Bucha et al. 2011). They represent the minimal value (v_{min} = 0.4295) and amplitude of NDVI (v_{amp} = 0.4971) of beech stands in Slovakia. Phenological metrics was taken from the study Brandýsová (2013). The satellite-derived phenological markers were identified by inflection point of that sigmoid logistic function (Fig. 1) as follows:

- Inflection point in the spring period – *SAT_LU_1*, as a time when the assimilatory organs of overstory beeches started unfolding;
- Inflection point in the autumn period – *SAT_LC_2*, as a time when the assimilatory organs of overstory beeches were almost recoloured.

We used only the first phenological marker in spring: *SAT_LU_1*. This marker corresponds with the visually observed phenophase beginning of leaf unfolding (Brandýsová 2013). As the dependence between satellite derived and visually observed onset of autumn phenophases was not revealed in our previous research (Brandýsová 2013), only the effect of selected biometeorological variables on visually observed leaf coloring phase was investigated.

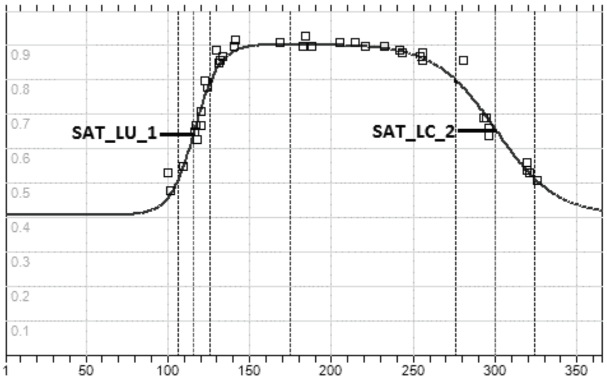

Fig. 1. Inter-annual course of normalized differentiated vegetation index (NDVI) in selected beech stand in Slovakia fitted by the sigmoid logistic function. The inflection points of this function were used for the evaluation of forest stands phenology. Two phenophases were marked – beginning of leaf unfolding (*SAT_LU_1*) and leaf coloring (*SAT_LC_2*). On the x axis: day of year, on the y axis: NDVI.

2.4. Biometeorological variables

The data from meteorological stations (Table 2) were obtained from the Slovak Hydrometeorological Institute. The data were used to analyze the effect of local meteorological conditions (especially temperature, precipitation and evapotranspiration-based) on the onset of phenological phases in beech stands. The meteorological stations from which the data were transferred to the positions of investigated forest stands were selected on the basis of minimal horizontal and vertical distance (Fig. 2).

Table 2. Meteorological stations assigned to the phenological stands and distance between them.

Phenological stand	Meteorological station	Horizontal distance [km]	Vertical distance [m]
Železná Studienka	Bratislava – Koliba	3	17
Zvolen	Banská Štiavnica	21	9
Poľana	Lom nad Rimavicou	12	33

The differences between monthly average air temperatures and precipitation totals from the 30-year normal were calculated. The earliest and latest days of the onset of phenophases of the period 2000–2012 were considered in terms of these differences.

We defined biometeorological variables based on the air temperature, precipitation and evapotranspiration to find out which of them affected most significantly the onset of visually observed and satellite derived phenological phases.

i) Average air temperature (AAT_p) of defined period:
where $T_{average}$ is average daily air temperature, *n* is number of days. We calculated:

$$AAT_p = \frac{\Sigma T_{average}}{n} \qquad [3]$$

- average air temperature of the period February–April: $AAT_{II–IV}$,
- average air temperature of the period March–April: $AAT_{III–IV}$,
- average air temperature of February: AAT_{II},
- average air temperature of April: AAT_{IV},
- average air temperature of the period August–September: $AAT_{VIII–IX}$,
- average air temperature of September: AAT_{IX}.

ii) Number of days below a prescribed temperature threshold:

- number of chilling days (n_{CD}; $T_{min} < 0$): number of days with minimum daily air temperature below 0 °C, counted from the end of the growing season in the previous year to the onset day of the beginning of leaf unfolding,
- number of frozen days (n_{FD}; $T_{max} < 0$): number of days with maximum daily air temperature below 0 °C, counted from the end of the growing season in the previous year to the onset day of the beginning of leaf unfolding.

iii) Climatic water balance (CWB):

- climatic water balance of the period January–April: $CWB_{I–IV}$,
- climatic water balance of the period April–September: $CWB_{IV–IX}$,
- climatic water balance of the period July–September: $CWB_{VII–IX}$,

$$CWB = P - PET \qquad [4]$$

where *P* is precipitation total (mm) and *PET* is potential evapotranspiration. *PET* was calculated according to a modified method of Tornthwait and Mather (1955) (Novák 1995):

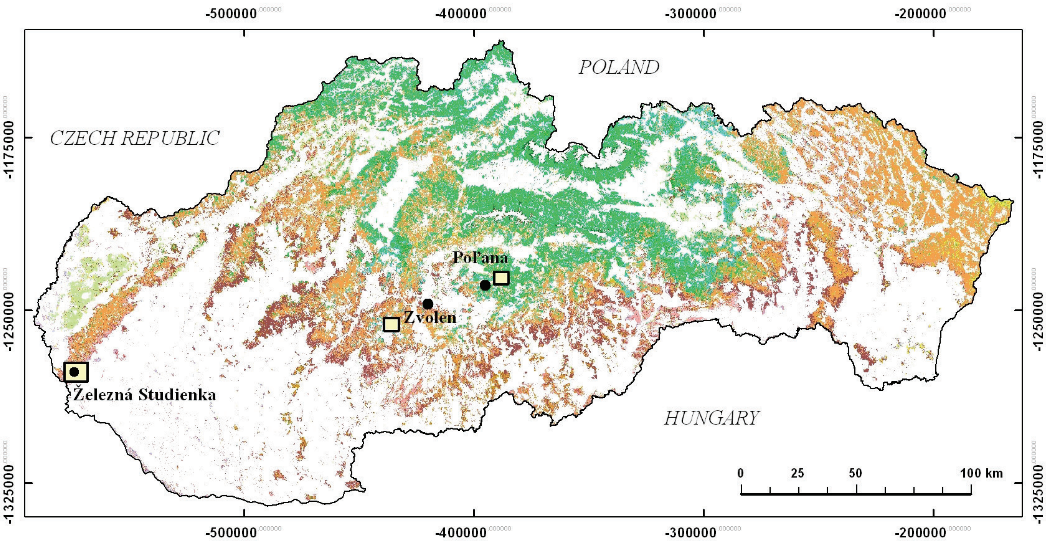

Fig. 2. Location of 3 beech test stands – marked with a black circle, and meteorological stations – marked with a square.

$$PET = 0.535 \, . \, f \left(\frac{10 \, . \, T_m}{I} \right)^a \qquad [5]$$

where PET (mm) is potential evapotranspiration of months, T_m (°C) average monthly air temperature, f is correction factor depending of the length of the month and latitude:

$$f = k \, . \, s_o \qquad [6]$$

where k is number of days coefficient, so is maximal duration of sunshine during the day (h).

I is temperature index calculated as a sum of twelve monthly indices:

$$I = \sum_{j=1}^{12} i_j \, ; \qquad i_j = \left(\frac{T_m}{5} \right)^{1.514} \qquad [7]$$

and a is exponent calculated using $a = (0.0675 \, . \, I^3 - 7.71 \, . \, I^2 + 1792 \, . \, I + 47239) \, . \, 10^{-5}$

iv) Actual evapotranspiration E_a of Turc (1961) (Novák 1995):

- actual evapotranspiration of the period January–April: $E_{a,I-IV}$,
- actual evapotranspiration of the period April–September: $E_{a,IV-IX}$,
- actual evapotranspiration of the period July–September: $E_{a,VII-IX}$,

$$E_a = P \, . \, [0.9 + (P^2 \, . \, L^{-2})]^{-1/2} \qquad [8]$$

where P is precipitation total (mm), and $L = 300 + 2.5T + 0.05T$, where T is average air temperature of the period.

v) Dryness index (DI) of Budyko (1958):

- dryness index of the period January–April: DI_{I-IV},
- dryness index of the period July–September: DI_{VII-IX},

$$DI = PET \, / \, P \qquad [9]$$

where PET [mm] is potential evapotranspiration of the period, P is precipitation total [mm]. Thresholds for different climate regimes were defined as:

- $0 < DI \leq 1.1$ – humid (surplus moisture regime; steppe to forest vegetation),
- $1.1 < DI \leq 2.3$ – semi-humid (moderately insufficient moisture; savannah),
- $2.3 < DI \leq 3.4$ – semi-arid (insufficient moisture; semi-desert),
- $3.4 < DI \leq 10$ – arid (very insufficient moisture; desert),
- $10 < DI$ – hyper-arid (extremely insufficient moisture; desert) (Gao & Giorgi 2008; Škvarenina et al. 2009).

vi) Precipitation total of April: P_{IV}

3. Results

3.2. Climatic variability and onset of phenophases in investigated stands

Average values of biometeorological variables derived from meteorological data recorded during the period 2000–2012 are noted in table 3. The between-stand differences in biometeorological variables and onset dates of the phenophases corresponded to climatic areas, where the test stands are located.

Stand 1 – Železná Studienka

The average onset day of the visually observed phenophase *VIS_LU_10* in the stand Železná Studienka was in the period 2000–2012 DOY 108. The earliest onset was recorded on DOY 102 in the years 2007 and 2009; the latest onset day was on DOY 114 in theyears 2004 and 2006.

The average onset day of satellite-derived beginning of leaf unfolding was the same as that from visual observations. The earliest onset was on DOY 101 in 2007 and the latest was on DOY 113 in 2004.

The year 2007, when both methods recorded the earliest onset of LU_10, had a distinctive positive temperature deviation from normal during the winter and spring months compared to other years. On the contrary, in the year 2004, when the latest onset day of *LU_10* was observed, the absolute temperature differences from normal were especially during the first three months the lowest in comparison with other years with some negative values (Fig. 3).

Table 3. Average onset days of observed phenophases and average values of investigated biometeorological variables during the period 2000–2012 in forest stands.

Onset day of the phenophase	Železná Studienka		Zvolen		Poľana	
	average	st. dev.	average	st. dev.	average	st. dev.
VIS_LU_10	108	4	115	4	119	4
SAT_LU_10	108	4	115	4	123	5
VIS_LC_10	270	3	261	9	252	4
Biometeorological variables						
$AAT_{II–IV}$ [°C]	6.2	1.2	3.9	1.2	1.3	1.1
$AAT_{III–IV}$ [°C]	8.8	1.1	6.4	1.0	3.7	1.0
AAT_{II} [°C]	1.0	2.6	–1.0	2.4	–3.6	2.1
AAT_{IV} [°C]	11.8	1.7	9.4	1.4	6.7	1.4
$AAT_{VIII–IX}$ [°C]	18.3	1.1	15.9	1.1	13.6	1.1
AAT_{IX} [°C]	15.7	1.7	13.4	1.7	11.2	1.8
n_{CD} (-)	73	22	99	16	127	20
n_{FD} (-)	24	9	31	12	51	14
$CWB_{I–IV}$ [mm]	106	52	160	67	172	65
$CWB_{IV–IX}$ [mm]	–226	135	–138	157	–99	207
$CWB_{VII–IX}$ [mm]	–118	79	–88	86	–46	103
$E_{a, I–IV}$ [mm]	166	33	184	35	254	66
$E_{a, IV–IX}$ [mm]	336	58	325	46	334	33
$E_{a, VII–IX}$ [mm]	220	61	210	62	254	66
$DI_{I–IV}$ (-)	0.48	0.16	0.32	0.14	0.23	0.09
$DI_{VII–IX}$ (-)	1.86	0.87	1.47	0.57	1.23	0.51
P_{IV} [mm]	191	51	228	64	219	63

The average onset day of the visually observed beginning of leaf colouring was on DOY 270. The earliest *VIS_LC_10* occurred in 2003 on DOY 263, the latest onset occurred in 2010 on DOY 276. The year 2003 differed from the others with the temperature considerably above normal in June (+4.7 °C) and August (+4.8 °C), while the precipitation totals were below the normal nearly all year. In the year 2010, the precipitation totals had the highest positive deviation from normal, especially during the growing season (Fig. 3).

In this stand, 70% of months of the period 2000–2012 had positive temperature deviations from normal, 28% of months had negative temperature deviations from normal and 2% of months were equal to normal. From the aspect of precipitation, 51% of months were below, 48% of months were above and 1% of months were equal to normal.

Stand 2 – Zvolen

The average visually observed onset day of beginning of leaf unfolding in the stand Zvolen was 115. The earliest onset was recorded on DOY 110 in 2007 and 2009, the latest on DOY 122 in 2005.

The average MODIS-derived onset of the beginning of leaf unfolding was DOY 116. The earliest onset of SAT_LU_1 occurred on DOY 110 in 2009 and on DOY 111 in 2007.

The average monthly air temperatures were considerably above the normal in the year 2007 in this stand too. The first

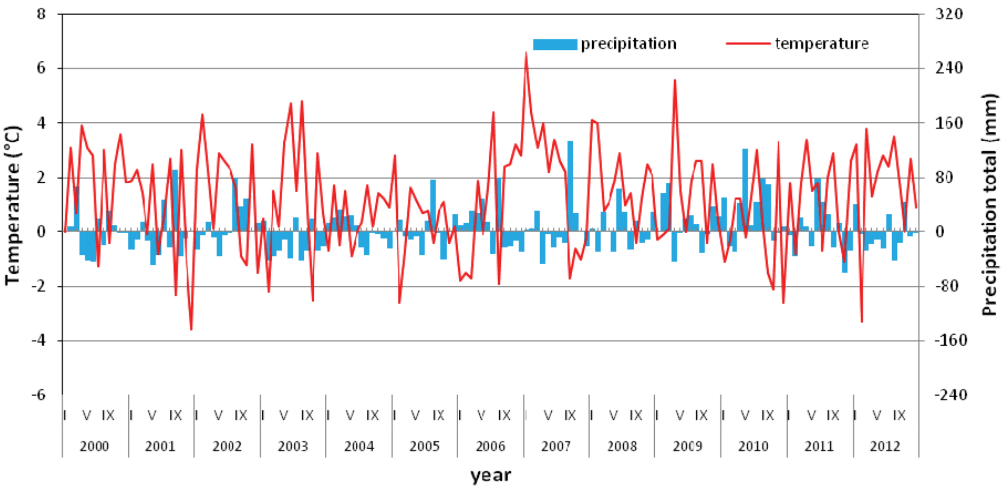

Fig. 3. Differences between average monthly air temperatures and precipitation totals in the period 2000–2012 and in the reference period 1961–1990 in the stand Železná Studienka.

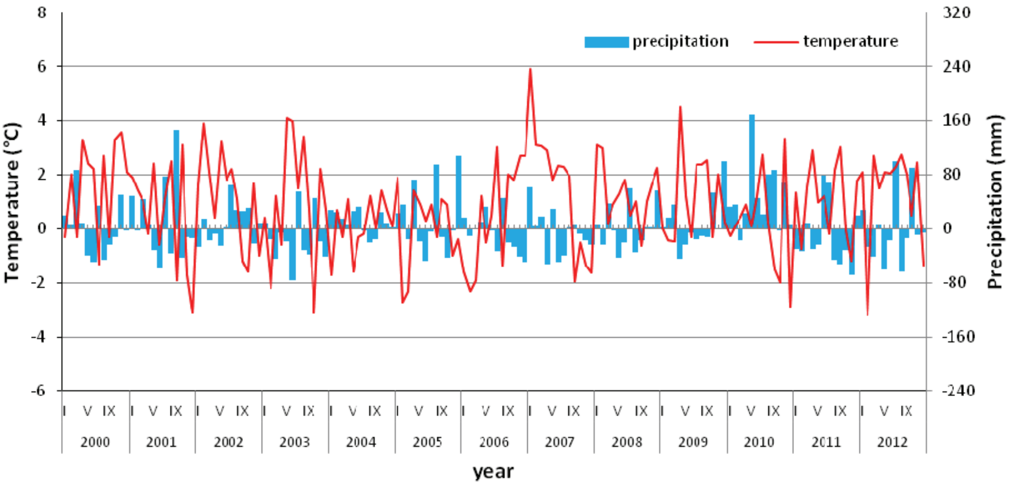

Fig. 4. Differences between average monthly air temperatures and precipitation totals in the period 2000–2012 and in the reference period 1961–1990 in the stand Zvolen.

half of this year was the warmest against the other years. In the year 2009, the highest average April air temperature was recorded. The years 2004 and 2005, when the latest onset of LU_10 were observed, were characterized by normal to below-normal average monthly air temperatures especially in the first half of the years (Fig. 4).

The average onset day of beginning of leaf colouring was DOY 261. The leaves began yellowing at first on DOY 244 in 2003, when the precipitation totals of the growing season but especially in the summer were significantly below normal, and August was considerably hot. The latest onset was observed on DOY 275 in 2007, when the average monthly air temperatures were above normal during the whole growing season, and the precipitation totals in the period of August and September were normal.

In this stand, 67% of months of the period 2000–2012 had positive temperature deviations from normal, 32% of months had negative temperature deviations from normal and 1% of months were equal to normal. From the aspect of precipitation, 53% of months were below and 47% of months were above normal.

Stand 3 – Poľana

The visually observed average day of the onset of *VIS_LU_10* was DOY 119. The earliest leaf unfolding started on DOY 111 in 2008, the latest on DOY 128 in 2003. The year 2008 (same as 2007 and 2002) was ranked among the years with considerably above-normal temperature, especially in the first half of the year. On the contrary, the year 2003 belonged to years with the coldest first quarter in the period 2000–2012.

The MODIS-derived average onset day of *SAT_LU_1* was DOY 123. The earliest beginning of leaf unfolding was recorded on DOY 111 in 2007. The latest onset of *SAT_LU_1* was on DOY 131 in 2005. The air temperature in the first quarter of this year was below normal to normal (Fig. 5).

In the stand Poľana, the leaves started yellowing on average on DOY 252. The earliest visually observed *VIS_LC_10* was recorded on DOY 245 in 2001 and 2002, the latest on DOY 257 in 2006 and 2010. The years 2001 and 2002 were characterized by sufficient to excess of precipitation amount during summer and hot temperatures. The average monthly air temperatures in the years 2006 and 2010 were above-normal during the growing seasons (Fig. 5).

In the stand Poľana, 73% of months of the period 2000–2012 had positive temperature deviations from the normal (1961–1990), 25% of months had negative temperature deviations from normal and 2% of months were equal to normal. From the aspect of precipitation, 60% of months were below normal, and 40% of months were above normal.

3.2. Dependence between onset of phenophases and biometeorological variables

Spring period

The significant dependence between temperature-based biometeorological variables and leaves unfolding, visually observed (*VIS_LU_10*) as well as satellite-derived (*SAT_LU_1*), were discovered in the spring period. The higher AAT of the previous periods shifted the time of leaf unfolding to earlier days (Fig. 6). The average air temperature of the period from February to April was the most significant factor which evoked the onset of beginning of leaf unfolding in all three stands (Table 4). When considering only the *VIS_LU_10*, the effect of the number of chilling days was significant in Železná Studienka and Zvolen and number of frozen days in the stand Poľana. When considering the *SAT_LU_1*, the number of chilling days was the most significant element evoking the beginning of leaf unfolding in Železná Studienka and the number of frozen days in Poľana (Table 4). The increasing number of these days, when minimum or maximum daily air temperature did not exceed the temperature of 0°, delayed the onset of leaf unfolding.

The evapotranspiration-based biometeorological variables had no effect on the onset of beginning of leaf unfolding observed with both methods. But we discovered that the high precipitation total of April (P_{IV}), when the beginning of leaf unfolding usually begins, was the biometeorological element which caused the later leaf unfolding onset in all stands (Table 4).

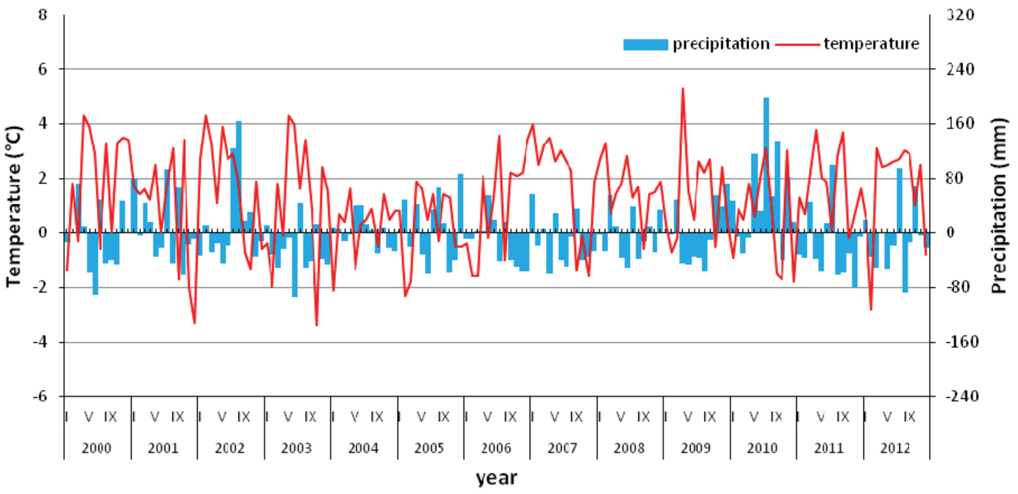

Fig. 5. Differences between average monthly air temperatures and precipitation totals in the period 2000–2012 and in the reference period 1961–1990 in the stand Poľana.

Table 4. Correlation between phenological phases (beginning of leaf unfolding and leaf coloring) and biometeorological variables in three investigated beech stands.

Response variables	Explanatory variables	n	Železná Studienka		Zvolen		Poľana	
			r_{yx}	b	r_{yx}	b	r_{yx}	b
Spring period								
VIS_LU_10	$AAT_{II–IV}$	13	**–0.72**	**–2.4**	**–0.65**	**–2.1**	**–0.79**	**–2.6**
	$AAT_{III–IV}$	13	**–0.81**	**–3.1**	–0.45	ns	**–0.75**	**–2.7**
	AAT_{II}	13	–0.34	ns	**–0.59**	**–1.0**	**–0.57**	**–1.1**
	AAT_{IV}	13	**–0.51**	**–1.2**	–0.38	ns	**–0.66**	**–1.7**
	n_{CD}	13	**0.61**	**0.11**	**0.56**	**0.13**	0.16	ns
	n_{FD}	13	0.39	ns	0.36	ns	**0.69**	**0.23**
	$CWB_{I–IV}$	13	0.28	ns	0.16	ns	0.01	ns
	E_a	13	0.07	ns	0.03	ns	0.00	ns
	$DI_{I–IV}$	13	–0.24	ns	–0.23	ns	–0.20	ns
	P_{IV}	**13**	**0.56**	**0.08**	**0.76**	**0.09**	**0.46**	**0.07**
SAT_LU_1	$AAT_{II–IV}$	13	**–0.82**	**–2.6**	**–0,81**	**–2.7**	**–0.66**	**–2.9**
	$AAT_{III–IV}$	13	**–0.77**	**–2.8**	**–0.63**	**–2.3**	**–0.56**	**–2.7**
	AAT_{II}	13	**–0.53**	**–0.8**	**–0.69**	**–1.3**	**–0.55**	**–1.3**
	AAT_{IV}	13	**–0.59**	**–1.4**	**–0.48**	**–1.3**	**–0.51**	**–1.8**
	n_{CD}	13	**0.67**	**0.12**	**0.63**	**0.15**	**0.54**	**–0.30**
	n_{FD}	13	**0.55**	**0.23**	**0.48**	**0.15**	**0.65**	**0.19**
	$CWB_{I–IV}$	13	0.31	ns	0.13	ns	0.12	ns
	$E_{a, I–IV}$	13	0.04	ns	–0.01	ns	0.01	ns
	$DI_{I–IV}$	13	–0.20	ns	–0.30	ns	–0.14	ns
	P_{IV}	13	**0.59**	**0.08**	**0.72**	**0.09**	**0.65**	**0.12**
Autumn period								
VIS_LC_10	$AAT_{VIII–IX}$	13	**–0.49**	**1.3**	0.18	ns	0.00	ns
	AAT_{IX}	13	0.05	ns	0.01	ns	0.39	ns
	$CWB_{IV–IX}$	13	**0.77**	**0.02**	–0.14	ns	–0.15	ns
	$CWB_{VII–IX}$	13	**0.50**	**0.02**	0.08	ns	0.04	ns
	$E_{a, IV–IX}$	13	**0.73**	**0.04**	–0.10	ns	–0.26	ns
	$E_{a, VII–IX}$	13	0.45	ns	0.09	ns	–0.05	ns
	$DI_{VII–IX}$	13	**–0.60**	**–2.0**	0.07	ns	0.11	ns

AAT – average air temperature, n_{CD} – number of chilling days, n_{FD} – number of frozen days, CWB – climatic water balance, E_a – actual evapotranspiration, DI – dryness index, P – precipitation total , n – number of analyzed years, r_{yx} – correlation coefficient, b – regression coefficient, significant values are highlighted by bolt, ns – non significance.

Autumn period

The relationship between investigated biometeorological variables and the first autumn phenophase was not as apparent as in the case of leaf unfolding. The Climatic Water Balance of the period from July to September and also of the period from April to September had significant effect on visually observed beginning of leaf colouring only in the stand Železná Studienka – the lower the negative values of *CWB*, the earlier onset of leaf colouring (Fig. 7a). Also the Actual Evapotranspiration of the growing season (April–September) was a significant factor on the *VIS_LC_10* only in stand Železná Studienka – the lower the negative values of E_a, the earlier onset of leaf colouring (Fig. 7a). The higher Average Air Temperatures of August–September evoked the earlier onset of leaf colouring in the stand Železná Studienka (Fig. 7b). In this stand also the higher values of Dryness Index of the summer (July–September) affected the onset of *VIS_LC_10* (Table 4). The low negative values of *CWB* and E_a together with high *AAT* of the months before onset of *VIS_LC_10* caused the earlier onset of this phenophase only in the stand Železná Studienka at 304 m a.s.l. in the warm climatic area. In the other stands (in moderately warm and cold climatic areas) no statistically significant relationship with biometeorological variables and *VIS_LC_10* was discovered.

4. Discussion

Temperature effect on phenology in the spring period

Some authors reported that the overcoming of the winter dormancy of European beech is effected by the previous freezing period, and that the effect of the increasing temperature and photoperiod is minimal (Falusi & Calamassi 1990; Kramer 1994; Caffarra & Donnelly 2011). However most authors consider just increasing temperature to be a driving force of the onset of spring phenophases (Braslavská 2000; Rötzer & Chmielewski 2001; Badeck et al. 2004; Menzel et al. 2006; Pálešová 2012 etc.). According to the previous studies, the onset day of spring phenophases depends most significantly on the temperature of the previous 2–3 months (Piao et al. 2006). The analyses of phenological and meteorological data from the International Phenological Gardens revealed that the beginning of the growing season was affected mainly by the average air temperature of March,

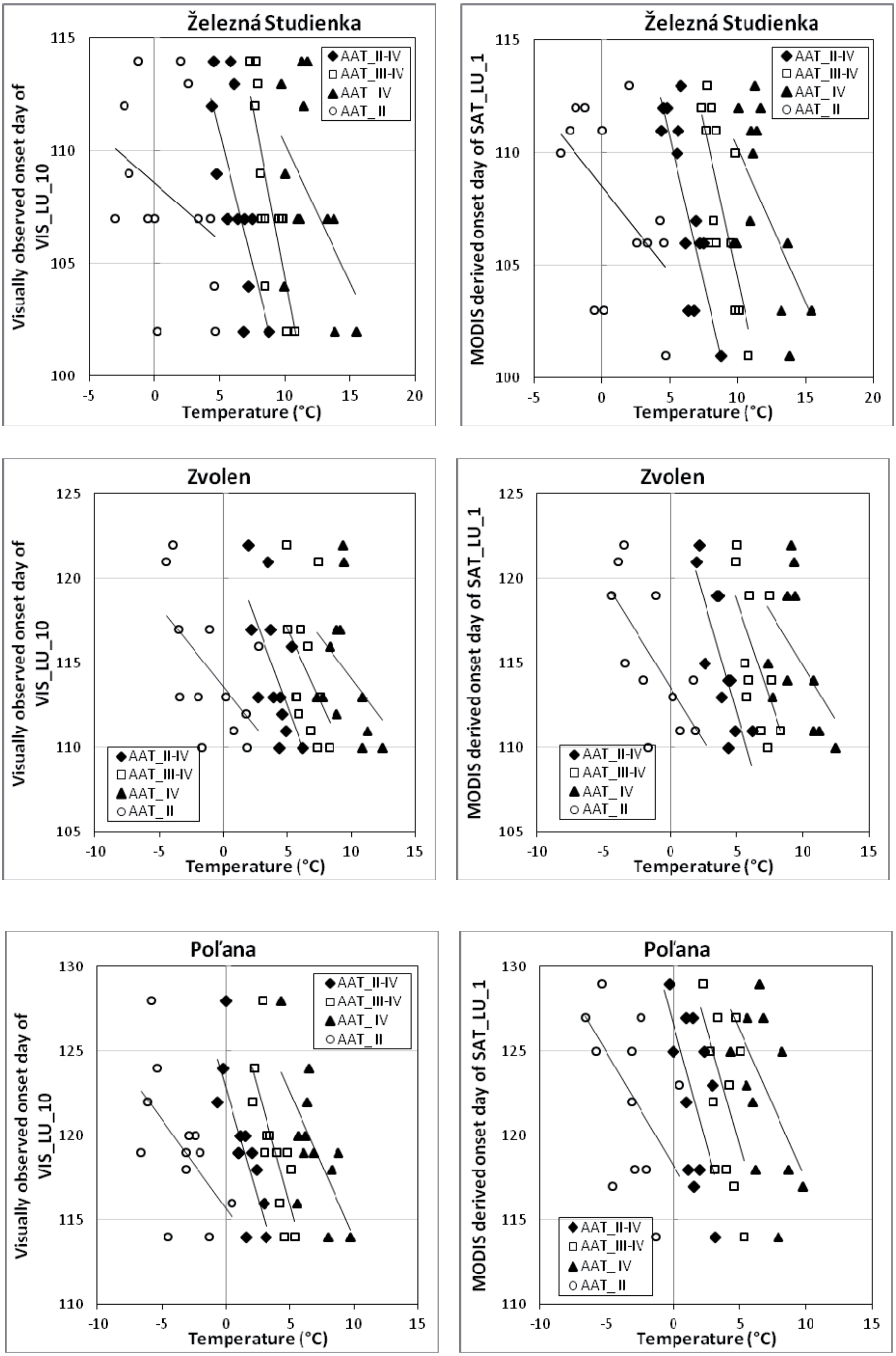

Fig. 6. Relationships between visually observed and MODIS-derived onset days of the beginning of leaf unfolding (*LU_10*) and average air temperatures calculated for the periods February–April (*AAT_II–IV*), March–April (*AAT_III–IV*), February (*AAT_II*), and April (*AAT_IV*).

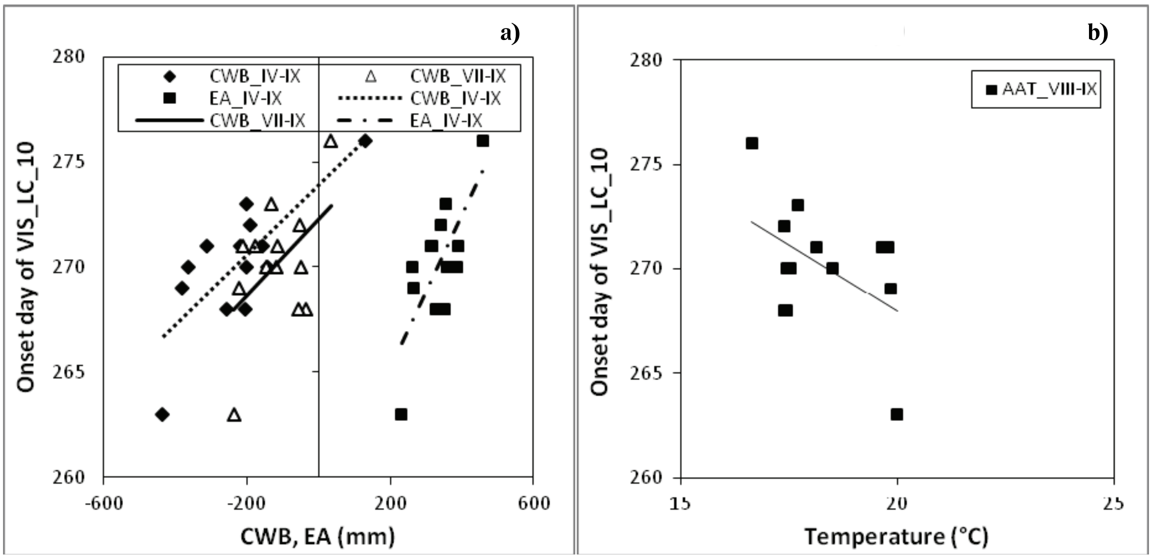

Fig. 7. Relationship between investigated biometeorological variables and beginning of leaf colouring (*VIS_LC_10*) in the stand Železná Studienka: a) *CWB_IV–IX* – Climatic Water Balance during the period April–September; *CWB_VII–IX* – Climatic Water Balance during the period July–September; *EA_IV–IX* – Actual Evapotranspiration during the period April–September; b) *AAT_VIII–IX* – Average Air Temperature during the period August–September.

but also of February and partially of April – the higher the temperature in late winter, the earlier onset of leaf unfolding (Chmielewski & Rötzer 2001). Menzel et al. (2006) found a clear reaction of the plant phenological phases to the increasing temperature. Most of the phenophases correlated with the average temperature of the month when the phenophase began and of the previous month. The trend in leaf unfolding of European beech agreed with the increasing temperature in March ($r = -0.86$). Our results confirmed that the beginning of leaf unfolding of European beech depended on the air temperature of the previous 2–3 months. We revealed the most significant relationship between average air temperature of the period February–April and the beginning of leaf unfolding in all three stands. But the other temperature based biometeorological variables had a significant effect. Previous studies from Slovakia revealed a significant relationship between Average Air Temperature of the period March–April ($PTV_{III–IV}$) and *LU_10*:
i) Barna et al. (2009) - $r = -0.61$,
ii) Schieber et al. (2009) - $r = -0.86$,
iii) Braslavská (2000) on the localities below 500 m a.s.l. - $r = -0.83$, and on the localities above 500 m a.s.l. - r = –0.76.

In this study similar results were discovered with data from both the satellite and visual phenological methods. In the stand Železná Studienka (below 500 m a.s.l.) we revealed - $r = -0.81$ and –0.77, for visual and satellite method respectively. In the stands Zvolen and Poľana (above 500 m a.s.l.) we revealed - $r = -0.45$ and –0.63 for Zvolen and - $r = -0.75$ and –0.56 for Poľana, for visual and satellite method respectively (Table 4).

Higher temperatures of the months before the onset of spring phenological phases caused the shift to the earlier onset. The bud bursting of European beech advanced by 3.2 days·°C^{-1} (Rötzer & Chmielewski 2001) to 3.6 days·°C^{-1} (Kramer 1996). On the contrary Menzel et al. (2001) pointed out a weaker sensitivity of beech to increasing winter and spring temperatures. Also Vitasse et al. (2009a) reported, that beech showed weaker sensitivity to higher spring temperatures with the advance of bud bursting by 2.1 days·°C^{-1} and advance of leaf unfolding by 1.9 days·°C^{-1}. Our analyses revealed the advance of the beginning of leaf unfolding by 2.1–2.9 days·°C^{-1} of average temperature of the period February–April, 2.3–3.1 days·°C^{-1} of average temperature of the period March–April, 0.8–1.3 days·°C^{-1} of average air temperature of February and 1.2–1.8 days·°C^{-1} of average air temperature of April for particular stands and methods (Table 4). A much bigger advance of the beginning of leaf unfolding by 2.5 days·°C^{-1} of average temperature of April found by Pálešová (2012).

Besides average temperature, beginning of leaf unfolding significantly depended on the number of chilling and frozen days as well. The increasing number of chilling days delayed the onset of *VIS_LU_10* and *SAT_LU_1* by 1.5–2.3 days·10 days^{-1} and increasing number of frozen days led to delay of *VIS_LU_10* and *SAT_LU_1* by 1.1–3 days 10 days^{-1} (Table 4) for a particular stand. Pálešová (2012) also found the delay of bud swelling with increasing number of chilling and frozen days.

The significant impact of the temperature also revealed the evaluation of timing of the earliest and the latest onset days of the beginning of leaf unfolding from deviations in temperature and precipitation from normal on beech stands. The earliest onset of the beginning of leaf unfolding occurred in the years when the temperature of months of the first quarter of the year were considerably above normal and higher than in the other years. On the contrary in the period 2000–2012, the latest onset days of beginning of leaf unfolding occurred in the years with the coldest first quarter.

Temperature effect on phenology in autumn period

Most of the studies focused on the onset of autumn phenophases (Chmielewski & Rötzer 2001; Menzel 2002; Sparks & Menzel 2002) showed a weak relationship between temperature and the onset. Our study revealed dual results. The average air temperature of the period August–September had a significant effect on the onset of leaf colouring, but only in the stand Železná Studienka where the *VIS_LC_10* advanced by 1.3 days·°C^{-1}. However in the other stands the effect of temperature was not significant (Table 4). Estrella & Menzel (2006) and Čufar et al. (2012) found the opposite relationship between the air temperature and leaf colouring ($r = 0.56$), when the increasing temperature delayed the onset of this phenophase. The reason may be the location of our stand Železná Studienka in a warm climatic area, where the high temperatures in summer could have a negative effect on the condition of trees and leaves. Vitasse et al. (2009b) considered just average temperature of the period August–November to be the main factor affecting the general leaf colouring of beech forests in France.

Climatic water balance effect on phenology

The importance of temperature and day length in determining the end of the growing season varies among plant species with certain groups solely dependent on photoperiod (Howe et al. 1996). This dependence on the length of the photoperiod has a substantially positive impact on forests in the current global warming conditions: while temperatures may increase over time, day length remains unchanged, limiting the potential of woody plants controlled mainly by the length of the photoperiod to extend their growing season (Way 2011). In this study, we did not test the effect of the length of photoperiod on the onset of phenophases, but we used this parameter as an input for the calculation of potential evapotranspiration according to Tornthwait and Mater (1955). Škvarenina et al. (2004) considered the climatic water balance to be the appropriate variable for characterizing the climatic conditions of the area. The input values for calculation were just potential evapotranspiration and precipitation (Baumgartner & Liebscher 1990). Following this assumption, we tested the effect of climatic water balance, actual evapotranspiration, dryness index and precipitation on the onset of spring and autumn phenophases.

– The study stands Železná Studienka and Zvolen were located in the 3rd **vegetation belt (oak-beech)**. According to Walter's climadiagram, the precipitation prevails over the evapotranspiration. However, the climatic water balance climadiagram pointed out that in the period March–August potential evapotranspiration prevails over the precipitation and the lack of water is less than 100 mm. In the stand Železná Studienka, the *CWB* of the period April–September was on average –226 mm, and *CWB* of the period July–September was –118 mm (Table 3). The effect of these *CWBs* on the onset of leaf colouring was significant (Table 4). *CWB* of the period January–April was not significant; the *CWB* values were positive (on average 106 mm). This was caused by the low level of potential evapotranspiration before the growing season. The Actual Evapotranspiration in this period was also lower – on average 166 mm – than in the summer season (July–September), when it was on average 220 mm (Table 3). The Dryness Index for the summer season was also significant in this stand (Table 4). In the years 2004 and 2012 it exceeded the value 2.3, which indicated a semi-arid climate regime and in 2003 *DI* (3.8) indicated even an arid regime. However, the average *DI* (1.9, Table 3) of the period 2000–2012 characterized the a semi-humid regime. In the Zvolen stand, the effect of *CWB*, E_a, *DI* was not significant (Table 4), although this stand is located in the same belt as Železná Studienka. The *CWB* of the period April–September was on average –138 mm, and *CWB* of the period July–September was –88 mm (Table 3). These values are similar to that published in Škvarenina *et al.* (2002). The dryness index of the summer season was in comparison with Železná Studienka smaller, with maximal value 2.2 in the year 2007. The average *DI* in the period 2000–2012 was 1.5 (Table 3). All these values classified the climate regime in the Zvolen stand as a semi-humid.

– The Poľana stand is located in the **5th vegetation belt (fir-beech).** The water balance in the general growing season is positive. The precipitation totals in the summer exceed the sum of 100 mm. The effect of *CWB*, E_a, *DI* on the beginning of leaf unfolding and leaf colouring was not significant. The maximal dryness index was 2 in the year 2009. The average summer *DI* in the period 2000–2012 was 1.2 (semi-humid) with 6 humid summers in this period. The precipitation totals of summer really exceeded 100 mm published for this vegetation belt by Škvarenina et al. (2002). However, the climatic water balance still had negative values in both analyzed periods (April–September and July–September) (Table 3).

The timing of the onset of spring and autumn phenophases reflect the sensitivity of European beech to the amount of available water in the soil profile (Střelcová et al. 2008; Nielsen & Jorgensen 2003). Bagar et al. (2001) found out that increasing sums of effective air temperatures together with lower precipitation totals caused earlier termination of assimilation and thus earlier onset of the leaf colouring. We discovered a similar pattern in the stand Železná Studienka, where the high average air temperatures of the period August–September advanced the phenophase *VIS_LC_10*. Schieber et al. (2009) detected the dependence between cumulative precipitation total of the period May–August and the leaf colouring in beech forests ($r = 0.58$). In this study, we tested this biometeorological variable only in relation to beginning of leaf unfolding and found a significant dependence between the precipitation total of April and *VIS_LU_10* and *SAT_LU_1*. Spring rainfalls are usually accompanied by the drop of temperature. This could be the reason why the higher precipitation totals delayed the onset of the beginning of leaf unfolding. According to findings of *CWB* published in Minďáš et al. (2011), deterioration of conditions could be expected for beech up to the 4th vegetation belt and improvement of conditions for beech from the 5th to the 7th vegetation belts. We found a statistically significant effect of *CWB* only in the stand Železná Studienka (3rd veg. belt), where the low negative values of *CWB* caused earlier onset of leaf colouring.

The significant impact of the high temperature and low amount of available water was also visible from the evaluation of the earliest and latest onset days of the beginning of leaf colouring from deviations in temperature and precipitation from normal. This corresponded with results of Kramer (1995). He presented that higher average temperatures in the period of summer-autumn together with the previous dryness period forced the onset of autumn phenophases.

5. Conclusion

It was found that air temperature is one of the most significant elements affecting the onset of spring phenophases in the tested area of beech stands. In this study, we calculated biometeorological elements of the beginning of leaf unfolding based on the minimum, maximum and average daily air temperatures: Average Air Temperature of the period February–April (AAT_{II-IV}), Average Air Temperature of the period March–April (AAT_{III-IV}), Average Air Temperature of February (AAT_{II}), Average Air Temperature of April (AAT_{IV}), Number of chill and frozen days (n_{CD}, n_{FD}). We also tested the effect of evapotranspiration-based biometeorological variables: Climatic Water Balance of the period January–April (CWB_{IV-IX}), Actual Evapotranspiration (E_a), Dryness Index (DI) and precipitation total of April (P_{IV}). The average air temperature of the period from February to April was the most significant factor which evoked the onset of beginning of leaf unfolding in all three stands. Compared with visual phenological observations, for satellite observation more significant correlations with biometeorological variables were found. This could result from the subjective error of an observer when he evaluates the phenological phases visually. This error is eliminated by the use of the digital image analyses of the satellite data.

The dependence of the onset of autumn phenophases on the external biometeorological variables has been poorly studied and characterized. From the variables which may affect the onset of autumn phenophases we had chosen: Climatic Water Balance of the growing period (April–September) (CWB_{IV-IX}) and of the period July–September (CWB_{VII-IX}), Actual Evapotranspiration (E_a), Dryness Index (DI), Average Air Temperature of the period August–September ($AAT_{VIII-IX}$) and Average Air Temperature of September (AAT_{IX}). The effect of these biometeorological variables on the beginning of leaf colouring was significant only in the stand Železná Studienka.

The analysis of the relationship between biometeorological variables and onset of the phenophases of the period 2000–2012 pointed to the inappropriate climate conditions for beech in the 3rd vegetation belt in warm climate area. As suspected Škvarenina et al. (2004), here the unfavorable climatic conditions - high temperatures in August and September and low negative values of climatic water balance in the summer season - caused an earlier onset of leaf colouring and shortening of the growing season. On the contrary, the high temperatures in the early spring caused the advance of beginning of leaf unfolding and thereby increased the risk of damage by the late frosts. Therefore, the cultivation of beech in the 3rd vegetation belt requires increasing attention paid to the climate conditions.

This kind of research is necessary to achieve further noticeable progress in phenological modelling by using the expanding area of remote sensing observation.

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