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# **Long-term changes in spring and autumn tree phenology in the Czech Republic**

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Diploma thesis

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# **Dlouhodobé změny v jarní a podzimní fenologii dřevin v České Republice**

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Diplomová práce  
v oboru Ochrana přírody

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Wilhelmshaven, Německo 2012



## **Declaration**

I declare that I have written this dissertation only by myself under supervision of Peter Adamík and with using cited sources only.

Wilhelmshaven, 2012

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Eva Kolářová

## **Acknowledgment**

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## Abstract

One of the ways how to assess the impacts of global climate change on plants is analyzing their long-term phenological records. In the presented thesis the phenological series of 19 common tree species and their 8 phenophases, spanning 64 years (1946–2010) and covering the whole area of the Czech Republic were investigated. For each species the changes in annual mean values ( $\mu$ ) were analyzed to find out the shifts in the timing of the event and analogously the standard deviation was investigated to detect the changes in duration of the phenophase. The results agreed with the findings of other authors – the advancement of onset of spring phenophases and subsequent acceleration of fruit ripening and delay of autumn phenophases. The most considerable shifts in timing of spring phenophases were displayed by early-successional shorter-lived species (*Cornus sanguinea*, *Crataegus laevigata*, *Prunus spinosa*, *Robinia pseudoacacia* a *Tilia cordata*) which is attributed to the better adaptation to changing environment conditions and to the fact that many of them need for breaking the dormancy only the crossing of temperature threshold and not the completion of photoperiod and chilling as others do. The most marked shift in timing of onset of phenophases was found for beginning of fruit ripening of conifers which, in contrary to deciduous trees, delayed the fruit ripening up to 2.89 days per year as was found for *Pinus sylvestris* during period 1976–2010. With regards of the change in duration of the phenophases no consistent patterns were revealed. Although the great shifts in duration of some phenophases of *Alnus glutinosa* and *Salix caprea* suggested the theory about of the more rapid reaction of early successful species to climate change. The growing season was defined as the time period between leaf unfolding and leaf colouring. In the Czech Republic the growing season has extended by on average 24.5 days during the last 34 years. The most considerable prolongation was showed by *Robinia pseudoacacia* by 35.2 days during 1976–2010.

**Key words:** autumn phenophase, climate change, fruit ripening, growing season, long-term dataset, photoperiod, spring phenophase, temperature threshold

## Abstrakt

Jedním ze způsobů jak zhodnotit vliv globální změny klimatu na rostliny je analýza dlouhodobých fenologických záznamů. V prezentované studii jsem zkoumala fenologické řady 19 běžných druhů Evropy a jejich 8 fenofází zahrnující časové období 64 let (1946–2010) a pokrývající prakticky celé území České Republiky. U každého druhu jsem testovala trend v posunu nástupu fenofáze pomocí analýzy jeho průměrných hodnot ( $\mu$ ) a obdobně jsem detekovala změny v délce trvání dané fenofáze vyhodnocením standardní odchylky ( $\sigma$ ). Zjištěné výsledky v posunech časování fenofází odpovídaly zjištěním jiných autorů tj. dřívější nástup jarních fenofází a následné urychlení plození a naopak opoždění podzimních fenofází. Nejvýraznější posuny v nástupu jarních fenofází byly zjištěny u raně sukcesních krátkověkých dřevin (*Cornus sanguinea*, *Crataegus laevigata*, *Prunus spinosa*, *Robinia pseudoacacia* a *Tilia cordata*) což je připisováno jejich lepšímu přizpůsobení se měnícím se podmínkám prostředí a také faktu, že u řady z nich je ukončení dormance limitováno pouze překročením určitého teplotního prahu a ne délkou fotoperiody či jarního mrazu. Největší posuny v nástupu fenofáze vůbec jsem zaznamenala u počátku zrání plodů u jehličnanů, které v rozporu s listnatými stromy, opožděly zrání až o 2.89 dnů za rok, jak bylo zjištěno u *Pinus sylvestris* v období 1976–2010. V délce trvání fenofází jsem nezjistila žádný výrazný vzorec, přestože značné posuny v délce některých fenofází u *Alnus glutinosa* a *Salix caprea* opět podpořily teorii o výraznější reakci raně sukcesních dřevin na změnu klimatu. Vegetační sezóna, kterou jsem určila jako rozmezí od počátku olisťování po žloutnutí listů, se v České Republice prodloužila průměrně o 24.5 dne za 34 let. Největší prodloužení jsem zjistila pro *Robinia pseudoacacia* a to o 35.2 dne v období 1976–2010.

**Klíčová slova:** jarní fenofáze, fotoperioda, podzimní fenofáze, teplotní práh, vegetační sezóna, změna klimatu, zrání plodů



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# 1. Introduction

Phenology is a branch of bioclimatology; it is a discipline which follows up the progress and changes in the life of healthy living organisms and thus assesses the influence of weather and climate on plants, animals and human beings (Sobíšek *et al.*, 1993).

Nature has been subject to human's attention since the time immemorial. Thus many countries have a long-standing tradition in observing phenological events. At first, recording of these long-term phenological series started out of the curiosity for understanding the dynamics of natural processes, such as beginning of flowering, harvesting time, bird arrivals or spawning in amphibians. Later on, phenology based upon long-term records, spanning several centuries, has emerged as an essential tool for studying global climate change – phenomenon influencing our planet in the present time.

Many studies dealing with the influence of global climate change have been recently published and the shifts in phenological events across the range of species, communities and trophic levels have been proved (Walter *et al.*, 2002; Root *et al.*, 2003; Visser & Both, 2005). In general, results suggest an advancement in spring and a delay in autumn phenology (Chmielewski & Rötzer, 2002; Rötzer & Chmielewski, 2001; Schwartz *et al.*, 2006; Sparks & Menzel, 2002). But at the same time, there are evidences that some species respond differently to natural and anthropogenic factors – displaying no or little change in phenological events. Moreover, the shifts are not constant, even though the species are closely connected as for example Visser & Holleman (2001) have revealed in their study of synchrony of oak bud burst (*Quercus robur*) and winter moth (*Operophtera brumata*) egg hatching.

Similar changes in timing of natural processes for a number of species including trees have been long recorded across Europe. However the shifts in phenophases are substantially different across Europe – an advancement of spring phenophases up to 4 weeks in Western and Central Europe and delay up to 2 weeks in Eastern Europe during the time period 1951–1998 (Ahas *et al.*, 2002). These spring phenological changes have shown close correlations with increasing mean temperature across 19 European countries (Menzel *et al.*, 2006). Accordingly, the growing season assessment coupled with data from International Phenological Garden for tree species across Europe showed that

1°C warming up in early spring (February–April) causes a seven days advance in the beginning of growing season (Chmielewski & Rötzer, 2001). And according to Menzel & Fabian (1999) the growing period has been lengthened by 10.8 days on average in Europe during the period 1959–1993.

In addition, studies at country levels have also brought interesting findings and have helped predicting how the vegetation in particular European regions will respond to climate change. Particularly, growing season widened up to 18 days in the Spanish Western Mediterranean region for 29 perennial species during the last 60 years (Gordo & Sanz, 2009). Garzía-Mozo *et al.* (2010) used phenological and pollen data in order to found that the flowering of olive (*Olea europaea*) has likewise significantly advanced (40 days) in this country during the period 1986–2008. Other studies come from Germany where the shifts in spring phenophases were in range of 6–11 days during the last 120 years (Schaber & Badeck, 2005) and the growing season has extended by a five days average between 1974–1996 in comparison to period 1951–1973 (Menzel *et al.*, 2001). Switzerland holds one of the oldest phytophenological series in Europe, which included the leaf bud burst of horsechestnut (*Aesculus hippocastanum*) in Geneva (recorded since 1808) and flowering of cherry trees (*Prunus avium*) in Liestal since 1894. For both plants was found advancement in onset of the phenophases by 0.23 d y<sup>-1</sup> for bud burst of horsechestnut and by 0.06 d y<sup>-1</sup> for flowering of cherry trees (Defila & Clot, 2001). Likewise the advance in onset flowering and peak of flowering of woodland herbaceous plants was documented by Sparks *et al.* (2009a) in Białowieża National Park in Poland. And finally, bud burst and flowering of native deciduous trees in Finland have advanced at rate of 3 to 11 days per century during the last 160 years (Linkosalo *et al.*, 2009).

Phenological observations have been performed since the second half of the 18<sup>th</sup> century in the Czech Republic, enabling long-term data series analysis in the face of global climate change. The comprehensive insight into the history and current status of European national phenological networks was presented by Nekovář (2008). Krška & Šamaj (2001) described in detail the history of meteorology in Czechia and Slovakia and Brázdil *et al.* (2011) pointed out at the early work in the phenology of I. R. Bohemian Patriotic–Economic Society in the first half of 19<sup>th</sup> century.

Most recent studies on Czech plant phenology deal with the influence of drought on agricultural systems (Hlavinka *et al.*, 2009) and climate conditions changes on crops (Možný *et al.*, 2009; Trnka *et al.*, 2011a), in middle (Trnka *et al.*, 2011b) and whole Europe

(Trnka *et al.* 2011c) as well. Although, there have been published some partial studies dealing with tree species and their phenology such as common hazel and common alder (Hájková & Nekovář 2008), the complex analysis of phenological shifts of tree species is still missing. Therefore, this study aims to identify and quantify trends in phenological events of 19 tree species across the Czech Republic through the interpretation of the last 64 years of phenological records.

## 2. Phenology observations in Czechia

### 2.1. History of Czech plant phenology

The origins of phenology in Czechia can be traced back to the first meteorologists, e.g., J. Stepling (1716–1778), A. Strnad (1746–1799) and M. A. David (1757–1836) in the second half of the 18th century (Nekovář 2010). J. Stepling, as the director of the Klementinum Observatory in Prague, launched the regularly meteorological observations in 1752 and later on also intended to attach phenological observations including recording of human diseases (Krška & Šamaj 2001). However as a founder of the Czech modern phenology is regarded A. Strnad who observed phenological phases of many wild plants, agriculture crops, fruit trees and also animals (Krška & Šamaj 2001). The results of his phenological observations he evenly added to his meteorological reports (Nekovář 2010).

The first phenological network was organized in 1780 when Societas meteorological Palatina joined to Academy of Science (Nekovář 2008). Apart from meteorological measurements, also phenological and nosological (about diseases) observations proceeded such as flowering and maturation of the important field crops, haymaking, harvests, fruit crops, plant diseases and the damages caused by insects. These observations were provided by doctors, foresters or general public, in other words by people who were able to record the observations, and then periodically sent data to Societas meteorological Palatina (Nekovář 2010). Later on, Med. Dr. Tadeáš Haenke (1761–1817) published *Blumenkalendar für Noumen in Jahre 1786*, the first phenological calendar printed in paper where the chosen bulb flowers were mentioned chronologically in tables according the beginning of flowering (Nekovář 2010).

First network of regular phenological observations in Czechia was founded by M. Seidl in 1830 under the aegis of *Economic Patriotic Society*. But gathered data was compiled more than 20 years later by lawyer Karl Fritsch (1812–1879) (Nekovář 2010). Fritsch himself observed hundreds of plant species and published more than 100 phenological papers but his most important merit was that as first compiled the instructions for phenology observers and thus founded the base for uniform methodology in Czechia and Austria (Krška & Šamaj 2001).

For the development of phenology in Moravia year 1861 was very important because *Naturforschender Verein in Brünn* was founded in Brno (Krška 2002). Thanks the exertion of members (e.g. Gustav von Niessl from Meyerdorf, Johann Gregor Mendel, Anton

Tomaschek), the society managed to extend the meteorological and phenological network and since 1867 published the reports from 13 phenological stations from Moravia and Silesia. The last yearbook was published for the year 1911 when the Meteorological committee (branch of *Naturforschender Verein in Brünn*) run 229 phenological stations (Krška & Vlasák 2008).

In 1923 Prof. Ing. Dr. Václav Novák (1888–1967) from Bioclimatological Institute of Agriculture established one of the first national phenology services in the world. More than 650 people such as teachers, gardeners, farmers, game wardens and forest adjuncts took part in the observations. In order to get the records from as many regions as possible, appeals were published in newspapers and journals. The phenological observations comprised 6 groups: 1. general activity in the field, 2. wild herbs, shrubs, ornamental and fruit trees, 3. field crop, 4. meadow crop, 5. forest plantation and 6. appendix. The data were successively processed and then the phenological yearbooks for 1923 and 1924 were published (Nekovář 2010). Soon after, in 1930s, there were 1200 phenology observers in Bohemia, 650 in Moravia and Silesia and 350 in Slovakia (Krška & Šamaj 2001) however the administration of such an extensive network brought many difficulties and the number of phenological stations started slightly decreasing (Nekovář 2008).

In 1954 was the phenological map of Bohemia and Moravia published and two years later also the handbook for phenology observers was released. Phenological yearbooks were systematically produced until 1960. Finally, the Meteorological service joined the Czech Meteorological Institute in 1954, which has run the phenological network until present.

## **2.2. Current state**

Since 1983 the phenological stations have been divided into 3 groups according to the observed subject. There are currently 83 stations for field crops monitoring, which follow up the phenological phases of 15 plant species, 32 stations for fruit trees (15 tree species) and 48 stations for wild plants (45 plant species) (Nekovář 2010) .

Observations are provided by volunteers who send their records to the Czech Hydrometeorological Institute every year. These records are imported into an Oracle electronic database. Also the long-term historic data traced back to 1923 are being gradually digitalized, saved into the database or further used in scientific research (Nekovář 2010).

### **2.3. International cooperation**

From 2004 the Czech Republic took part in the five-year project COST 725. Scientists from all 27 European Union countries along with Norway and Switzerland created the scientific platform for climate research. As a result, the analysis of more than 125 000 phenological series became part of IPCC (Intergovernmental Panel on Climate Change) report about climate change (Sparks *et al.* 2009b).

The Czech Republic nowadays participates in several international projects. One of them is named International Phenological Gardens of Europe and it was founded in Germany in 1957. The idea is to grow plants sharing their genetic origin across Europe and therefore all plants come from one parent garden in Ahrensburg. In 2010 there were 89 active phenological gardens spread in Europe and three of them are located in the Czech Republic - Doksany, Kostelec nad Černými Lesy and Křtiny u Brna (IPG 2010).

In the regard of international cooperation, it was necessary to unify phenological terminology. For this purposes, BBCH scale (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry), is nowadays applied. BBCH is supplemented with graphical sketches of plant vegetative and generative ontogenesis (Nekovář 2010).



## 3. Materials and Methods

### 3.1. Phenological data

The dataset for this study of the phenological trends in the Czech Republic was obtained from the Czech Hydrometeorological Institute archive and it involved 149 phenological stations across the Czech Republic (see Appendix, Map 1). The observation series covered around 90 years and more than 333 000 records were analyzed. The oldest series dated back to mid-1920s and last data came from 2010. There were 3 datasets 1923–1990, 1990–2004 and 1991–2010 gained, however observed species and phenological phases were not fully identical throughout the time. Thus 19 common European tree species were chosen into analysis (Table 1), but only if the records were available from all 3 datasets in order to get the longest series as was possible. In order to estimate the phenological trends the following eight phenological phases were used:

- *Beginning of flowering* (PK10)\* - less than 10% of flowers are in blossom
- *Flowering* (PK100)\* - over 50% of flowers are in blossom
- *Beginning of leaf unfolding* (PL10) \* - less than 10% of leaves have already appeared
- *Leaf unfolding* (PL100)\* - over 50% of leaves have already appeared
- *Leaf colouring* (ZL100)\* - over 50% of leaves have already coloured
- *Beginning of leaf falling* (OL10)\* - less than 10% of leaves have already fallen
- *Leaf falling* (OL100)\* - over 50% of leaves have already fallen
- *Beginning of fruit ripening* (ZP10)\* - less than 10% of fruits have become ripened

\* Czech equivalent according to the Czech Hydrometeorological Institute Guideline for observers

Because of lack of data, the phenophases leaf colouring, beginning of leaf falling and leaf falling could not be included for *Cornus mas*, *Picea abies* and *Pinus sylvestris* and the phenophase leaf unfolding for *Cornus mas*. Hence finally only 142 phenophases could be encompassed into this study. Likewise as in proceeding case, only the phenological phases which were observed for the whole time period from mid-1920s to 2010 were considered in this thesis.

**Table 1.** Plant species included in this study.

	<b>Czech name</b>	<b>Scientific name</b>	<b>English name</b>
1.	bez černý	<i>Sambucus nigra</i> L.	Black Elder
2.	borovice lesní	<i>Pinus sylvestris</i> L.	Scotch Pine
3.	bříza bělokorá	<i>Betula pendula</i> Roth	Silver Birch
4.	buk lesní	<i>Fagus sylvatica</i> L.	European Beech
5.	dřín jarní	<i>Cornus mas</i> L.	European Cornel
6.	dub letní	<i>Quercus robur</i> L.	Pedunculate Oak
7.	hloh obecný	<i>Crataegus laevigata</i> (Poir.) DC.	Midland Hawthorn
8.	javor klen	<i>Acer pseudoplatanus</i> L.	Sycamore
9.	javor mléč	<i>Acer platanoides</i> L.	Norway Maple
10.	jeřáb obecný	<i>Sorbus aucuparia</i> L.	Rowan
11.	lípa malolistá	<i>Tilia cordata</i> Miller	Small-leaved Lime
12.	líška obecná	<i>Corylus avellana</i> L.	Common Hazel
13.	modřín opadavý	<i>Larix decidua</i> Miller	European Larch
14.	olše lepkavá	<i>Alnus glutinosa</i> (L.) Gaertn	Common Alder
15.	slivoň trnka	<i>Prunus spinosa</i> L.	Blackthorn
16.	smrk ztepilý	<i>Picea abies</i> (L.) Karsten	Norway Spruce
17.	svída krvavá	<i>Cornus sanguinea</i> L.	Common Dogwood
18.	trnovník akát	<i>Robinia pseudoacacia</i> L.	Black Locust
19.	vrba jíva	<i>Salix caprea</i> L.	Goat Willow

### 3.2. Data processing and analysis

First, it was necessary to unify the data from the three datasets, merge them and create one homogenized phenological series per species and phenophase. There was a problem with different terminology of some phenological phases used in the datasets and that is why the methodology had to be checked to avoid joining the datasets incorrectly. For sequences of the phenological phases see Table 2. Afterwards all outliers were identified by the visual inspection of box plots of records for each species and phenophase. Some of the mistakes could arise during the digitalization of the original paper records or during data processing. In all cases when the records seemed to be clearly incorrect or suspicious they were removed from the final dataset. In spite of precise control of data for outliers, some incorrect values could escape my notice. But the large amount of data likely diluted the potential influence of the particular incorrect value and consequently it had a negligible effect on results. Although the phenological observations are standardized according the published methodology the personal approach of volunteers, who make the observations, must be taken into an account and also the fact of change in the observers through time and potential breaks in the phenological series sequence.

The limit for inclusion of values into the analysis was set as minimum of 10 observations for each phenophase in the each year for given tree species. All year-specific phenophases

which did not meet this criterion were excluded from further analysis. After this selection I got the final phenological series from 1946 to 2010 which were used in analyses.

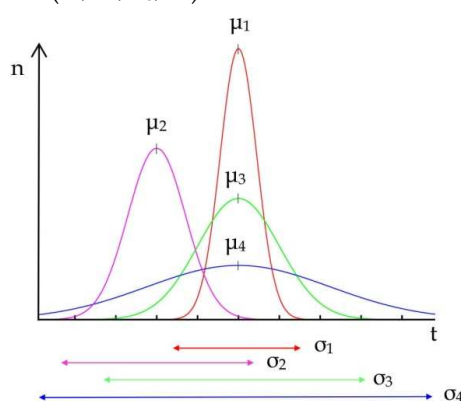
**Table 2.** Sequence of phenological phases between 1923–2010.

1923-1990	1991-2010
First flowers (První květy)	→ Beginning of flowering (Počátek kvetení 10% -PK10*)
Fully flowering (Všeobecné kvetení)	→ Flowering (Počátek kvetení 100% -PK100*)
First leaves (První listy)	→ Beginning of leaf unfolding (První listy 10% - PL10*)
Fully leaved (Všeobecné olistění)	→ Leaf unfolding (První listy 100%- PL100*)
Fully coloured leaves (Všeobecné žloutnutí)	→ Leaf colouring (Žloutnutí listí100%-ZL100*)
Beginning of leaf falling(Počátek opadávání listí)	→ Beginning of leaf falling (Opad listí 10%- OL10*)
End of leaf falling (Konec opadávání listí)	→ Leaf falling (Opad listí 100% -OL100*)
First ripped fruits (První zralé plody)	→ Beginning of fruit ripening (Zralost plodů - ZP10*)

\* Czech equivalent according to the Czech Hydrometeorological Institut Guidelines for observers

In order to evaluate the temporal trends, mean ( $\mu$ ) and standard deviation ( $\sigma$ ) were calculated for each phenophase of a given tree species in a given year. Mean gave us the information about the position of the phenophase in the calendar whereas standard deviation illustrated the variability in duration of the phenophase (Figure 1). In other words, as a consequence of the change in mean values the plants delay or advance the onset of phenophase, however the shift in standard deviation values means that the duration of the phenophase is either compressed or extended.

**Figure 1.** Temporal shifts in distribution of records are characterized by mean ( $\mu$ ) representing onset of phenophase during the year ( $\mu_1, \mu_2, \mu_3, \mu_4$ ) and standard deviation ( $\sigma$ ) which characterizes different duration of phenophase ( $\sigma_1, \sigma_2, \sigma_3, \sigma_4$ ).



To evaluate long-term trends in phenology, multiple regression models with year and quadratic effect of year as explanatory variables were used. First, quadratic regressions for the mean and the standard deviation for each phenophases and each species for the

period 1946–2010 were examined to find out the existence of potential non-linear trends. And unless the quadratic term was significant, then linear regression was calculated (Appendix, Table 5). Provided the quadratic regression fit was appropriate I determined the turn-point of the curve – the year when the recent linear trends starts. This was found as a local maximum or minimum of each quadratic function, in other words the point when derivatives of the quadratic functions were equal to 0. Afterwards by simply averaging all turn-points for mean and standard deviation I got the global turn-point (in this case year 1976). Then the linear regressions for all phenophases of each species were evaluated again for the period 1976–2010 to get the slope of the straight line which represents the change of phenophase in the time (Appendix, Table 6). A negative value of a trend for mean was considered as an advancement of the phenophase, whereas positive value represented a delay. Similarly, the negative values of standard deviation meant the compression and positive value indicated the expansion of the phenophase.

Mean values and values of standard deviation of all species were used to compare the variability of data for each phenophase in box plots (Figure 3 and 4). Next for each species was found the change in length of growing season for period 1976–2010 which was directly defined as the time span between the leaf unfolding and leaf colouring. The values of the slope of the linear regression straight line (which represents the change in phenophase onset per year) for each species were multiplied by the number of years. Then the difference was counted (Table 4).

**Table 3.** Percentage of the records during the week for the period 1946–2010.

<b>Day of the week</b>	<b>Percentage of records (%)</b>
Monday	14,48%
Tuesday	14,05%
Wednesday	13,97%
Thursday	14,00%
Friday	14,08%
Saturday	14,52%
Sunday	14,89%

The phenomenon which very often accompanies phenological data is that volunteers' effort is not constant during the week and the data are biased as a result of the preference of observers to make their phenological observations during the weekend. In order to find out this proclivity, the day of the week was assigned to each date of phenophase for each year and species and then the sum of days was counted (Table 3). Likewise in this study

there was slight bias on Sunday (14.89%) and Saturday (14.52%). The day with the lowest percentage of records was Wednesday (13.97%). Regardless I consider the observers' effort very stable during the week and thus the influence of biased data is only negligible and might not have a significant impact on the findings. All data were processed with MS Excel, MP (SAS Institute) and R.

## 4. Results

### 4.1. Temporal trends of plant phenology for the period 1946-2010

#### 4.1.1. Shifts in timing of phenophases

Viewed over all phenophases in mean values the majority showed significant trends spanning the period of 64 years; out of 142 phenophases 101 were significant and 41 were not significant (Appendix, Table 5). The figure emerged to be rather variable and not a single species showed entirely either linear or quadratic trend. The range of turn-points varied between 1947 for the beginning of fruit ripening of *Betula pendula* and 2010 for the beginning of leaf falling of *Acer platanoides*.

With a closer look at the phenophases it can be seen that 14 out of 19 species has significantly advanced the **beginning of flowering** (3 showed a significant linear trend) in contrary to the **flowering** where only 9 phenophases were significant, but majority of them (7 out of 9) fitted the polynomial regression model. Whereas the mean values of **beginning of leaf unfolding** phenophase showed one of the highest proportion of significant findings (16 out of 19), there were unexpectedly only 9 significant shifts of **leaf unfolding** phenophase. Because of the lack of data the phenophases leaf colouring, beginning of leaf falling and leaf falling could not be evaluated for the species *Cornus mas*, *Picea abies* and *Pinus sylvestris*. In spite of this, 13 species have significantly shifted the **leaf colouring**; moreover 11 species fitted a quadratic regression, which was the highest proportion of non-linear trends at all. Only *Corylus avellana* and *Crataegus laevigata* showed significant linear trends. In both cases of **beginning of leaf falling** and **leaf falling** 12 species showed significant shifts during the time period, but only 5, respectively 6 turn-points were found. And finally in a case of **beginning fruit ripening** with exception of the species *Acer platanoides*, *Acer pseudoplatanus* and *Salix caprea* (Appendix, Table 5) all other species displayed significant shifts (12 out of 16 were non-linear).

#### 4.1.2. Changes in the duration of phenophases

Investigated species did not display such as high number of significant shifts in standard deviation as in the mean. Out of 142 studied phenophases 76 were significant and 66 insignificant (Appendix, Table 5). The shifts in mean values accompanied often shifts in standard deviations (58 cases). In other words those phenophases which proved a shift in the position in the Julian day often changed the shape of distribution too. Expectedly the

species fitted both the linear and quadratic regression models. The earliest turn-point was found for flowering of *Prunus spinosa* (1967) and the latest (1997) for beginning of fruit ripening for *Alnus glutinosa*. By averaging of all turn-points of mean values and standard deviation I got the total turn-point which was determined as a year 1976.

In case of **beginning of flowering** 10 species out of 19 have significantly increased the variability in the length of this phenophase and analogously 11 species have significantly showed more variability in **flowering**. Nonlinear trends outweighed linear trends in both phenophases. Similarly as in mean values, the phenophase **beginning of leaf unfolding** showed the highest proportion of significant values (14 out of 19) and also the highest number of significant linear trends (11 species). Moreover, in 12 cases the shifts in mean were accompanied by change in standard deviation, which was the highest number of synchronization. In contrast, only 6 species showed significant increase of variability in the phenophase **leaf unfolding**. In case of **leaf colouring** there were again 6 species which showed significant change in the shape of the curve, but only one of them (*Prunus spinosa*) fitted quadratic regression model with turn-point in the year 1979. Out of 19 species, only 9 were significant in the case of **beginning of leaf falling** and subsequently 7 species showed significant change in **leaf falling** distribution data. In both cases only one species fitted the quadratic model – *Alnus glutinosa* in first case with the break-point in 1973 and *Fagus sylvatica* in the second case with turn-point in 1970. Because the flowering is closely related to ripening thus the phenophase **beginning of fruit ripening** also showed high proportion of significant values (13 out of 19). The majority of them (9 out of 13) were non-linear. And second highest proportion (10 species) of accompaniment of the change in the calendar by the change in data distribution.

## 4. 2. Temporal trends in plant phenology 1976–2010

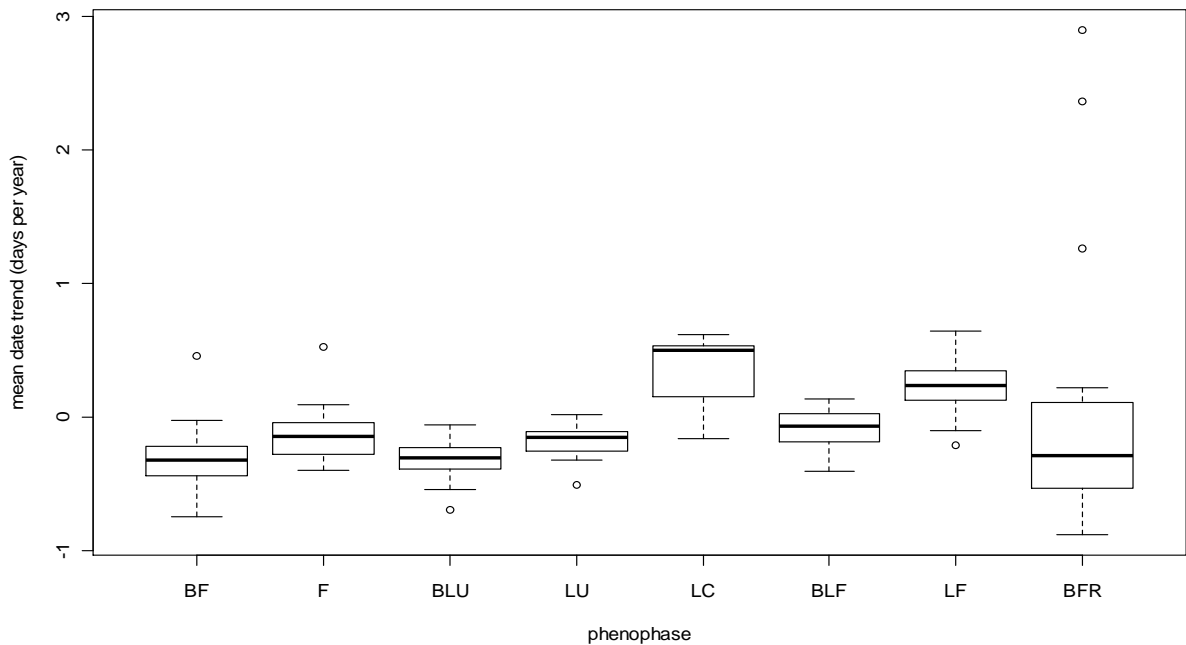
### 4. 2. 1. Shifts in timing of phenophases

Overall, the spring phenophases (BF, F, BLU, LU) were less variable and they rather advanced the onset whereas variability in data distribution of autumn phenophases (LC, BLF, LF) was higher and these phenophases had a tendency to delay their onset (Figure 2). The event beginning of fruit ripening advanced its onset but displayed the highest variance and 3 remote outliers were detected. These outliers presented the results of the beginning of fruit ripening of conifers which will be discussed later.

Out of 142 phenophases, only 88 showed significant shifts in timing and 54 were insignificant (Appendix, Table 6). Whereas the unequivocal trends in advancement of spring phenophases and fruit ripening were found, the shifts in timing of autumn phenophases were more variable. With a closer look at the **beginning of flowering** 13 species significantly advanced the onset of flowering. The greatest shift was documented in *Cornus sanguinea* ( $b = -0.599 \text{ d y}^{-1}$ ,  $P < 0.0001$ ), followed by *Tilia cordata* ( $b = -0.481 \text{ d y}^{-1}$ ,  $P = 0.0001$ ). Eight species significantly advanced their timing of **flowering** and again the most considerable shift was found in *Cornus sanguinea* ( $b = -0.405 \text{ d y}^{-1}$ ,  $P = 0.0002$ ) and then in *Prunus spinosa* ( $b = -0.334 \text{ d y}^{-1}$ ,  $P = 0.006$ ). The highest proportion of significant changes was found for **beginning of leaf unfolding** (16 out of 19) and all of them showed significant advancement. As in previous cases, *Cornus sanguinea* has the most markedly advanced the position in the calendar ( $b = -0.697 \text{ d y}^{-1}$ ,  $P = <.0001$ ) but also *Robinia pseudoacacia* displayed noticeable shift ( $b = -0.548 \text{ d y}^{-1}$ ,  $P = <.0001$ ). In the case of **leaf unfolding** the result was analogous to above mentioned phenophases – 8 species (out of 19) showed significant change in timing with the most substantial advancement in *Cornus sanguinea* and *Robinia pseudoacacia*. **Leaf colouring** was the first evaluated autumn phenophase and 12 out of 19 species showed significant delay. The most considerable shift was revealed in *Quercus robur* which has delayed by  $0.614 \text{ d y}^{-1}$  ( $P <.0001$ ) and *Acer pseudoplatanus* ( $b = 0.557 \text{ d y}^{-1}$ ,  $P = <.0001$ ). The **beginning of leaf falling** displayed somewhat unexpected findings. Out of 19 species only 6 of them showed significant shifts in timing, but 5 species have advanced the onset of event and only 1 species (*Quercus robur*) has delayed by  $0.129 \text{ d yr}^{-1}$  ( $P = 0.048$ ). In the case of **leaf falling** 11 species out of 19 have significantly delayed and again *Quercus robur* ( $b = 0.645 \text{ d y}^{-1}$ ,  $P = <.0001$ ) and *Corylus avellana* ( $b = 0.469 \text{ d y}^{-1}$ ,  $P = 0.01$ ) showed the most substantial change. Lastly 14 species showed significant shifts in onset of **beginning of fruit ripening**. Out of 14 species 4 have showed significant delay and 10 displayed significant advancement. Interestingly, three species which were the most delayed in beginning of ripening were represented by conifers *Pinus sylvestris* ( $b = 2.894 \text{ d y}^{-1}$ ,  $P = <.0001$ ), *Picea abies* ( $b = 2.362 \text{ d y}^{-1}$ ,  $P = <.0001$ ) and *Larix decidua* ( $b = 1.261 \text{ d y}^{-1}$ ,  $P = 0.031$ ). These shifts were the greatest revealed values at all from the whole study and these findings are noticeable since the rest of deciduous tree species (with exception the of *Acer pseudoplatanus*) displayed advancement in onset of fruit ripening. In contrary to conifers' delays *Betula pendula* ( $b = -0.773 \text{ d y}^{-1}$ ,  $P = <.0001$ ) and *Cornus sanguinea* ( $b = -0.637 \text{ d y}^{-1}$ ,  $P = <.0001$ ) revealed the greatest advancement.



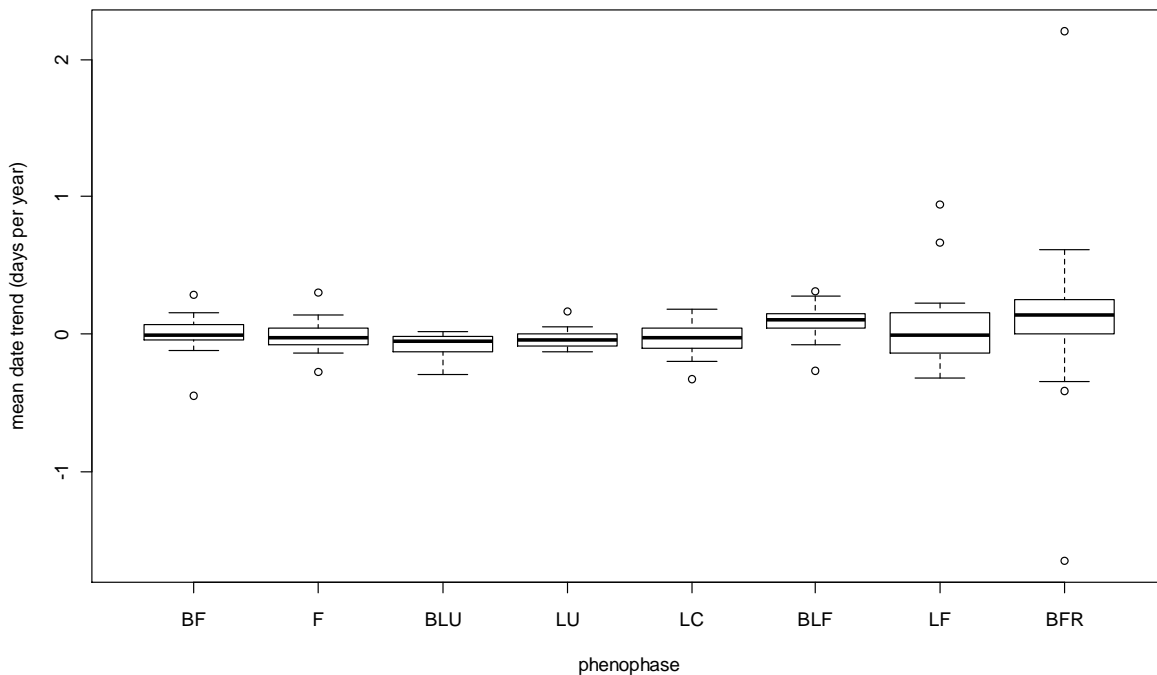
**Figure 2.** Box plot of temporal trends in mean for each phenophase during the period 1976–2010. Beginning of flowering (BF), flowering (F), beginning of leaf unfolding (BLU), leaf unfolding (LU), leaf colouring (LC), beginning of leaf falling (BLF), leaf falling (LF) and beginning of fruit ripening (BFR) are shown.



#### 4. 2. 2. Changes in the duration of phenophases

In general, the data for trends in standard deviation did not show such as a wide distribution as for the trends in mean values (Figure 3). The shifts were only small and no particular trend for spring or autumn phenophases was obvious. The **leaf falling** and **beginning of fruit ripening** displayed the highest variance in data distribution. Noticeable were the outliers in the case of beginning of fruit ripening which had a completely different pattern in trends. First one represented the prolongation of the event by *Alnus glutinosa* ( $b= 2.203 \text{ d y}^{-1}$ ,  $P= 0.0214$ ) and the second one exemplified the shortening of beginning of ripening by *Larix decidua* ( $b= -1.642 \text{ d y}^{-1}$ ,  $P= 0.0242$ ). Likewise the smaller number of significant temporal trends for the standard deviation was found in comparison with the mean values. Out of 142 phenophases 52 were significant and also the shifts in data distribution were not unequivocal. Less frequently (30 times) was the significant temporal shift in the calendar accompanied by the change in the shape of data distribution (Appendix, Table 6).

**Figure 3.** Bow plot of temporal trends in standard deviation for each phenophase during the period 1976–2010. Beginning of flowering (BF), flowering (F), beginning of leaf unfolding (BLU), leaf unfolding (LU), leaf colouring (LC), beginning of leaf falling (BLF), leaf falling (LF) and beginning of fruit ripening (BFR) are shown.



The first evaluated phenophase – **beginning of flowering** showed 4 significant compressions and 3 expansions in data distribution (Appendix, Table 6). Whereas the onset of flowering in the case of *Cornus mas* has been shortened by  $0.449 \text{ d y}^{-1}$  ( $P= 0.0008$ ) *Alnus glutinosa* has extended the time period of beginning of flowering by  $0.287 \text{ d y}^{-1}$  ( $P= 0.001$ ). Only 5 species showed significant change in **flowering** data distribution and the greatest positive slope was found for *Alnus glutinosa* ( $b= 0.302 \text{ d y}^{-1}$ ,  $P<.0001$ ). In the case of **beginning of leaf unfolding** all 9 species (out of 19) which displayed change in the variability shortened the duration of this phenophase. The most marked shift was found in *Cornus mas* ( $b= -0.293 \text{ d y}^{-1}$ ,  $P<.0001$ ) and *Cornus sanguinea* ( $b= -0.248 \text{ d y}^{-1}$ ,  $P<.0001$ ). Only 5 species showed significant shifts in **leaf unfolding**; four of them compressed and one (*Pinus sylvestris*) prolonged the duration of this phenophase by  $0.17 \text{ d y}^{-1}$  ( $P= 0.023$ ). All species displayed the compressions of data distribution for **leaf colouring**. *Corylus avellana* ( $b= -0.328 \text{ d y}^{-1}$ ,  $P= 0.0014$ ) and *Crateaegus laevigata* ( $b= -0.191 \text{ d y}^{-1}$ ,  $P= 0.0111$ ) have changed their variability the most. In the case of **beginning of leaf falling** 7 species showed significant shifts in data variability, but the majority (6 species) have significantly prolonged the duration of onset leaf falling and

only 1 species (*Quercus robur*) has shortened it by 0.268 d y<sup>-1</sup> (P= 0.0007). A closer look at the penultimate phenophase **leaf falling** shows that only 4 species shifted the variability. The greatest positive slope was found in *Fagus sylvatica* (b= 0.948 d y<sup>-1</sup>, P= 0.0013) in contrary to the negative slope in *Corylus avellana* which has shortened the onset of leaf falling by 0.315 d y<sup>-1</sup> (P= 0.0017). For **beginning of fruit ripening** the highest proportion of significant shifts (11 species out 19) was found. The greatest positive shift was showed by *Alnus glutinosa* which extended this phenophase by 2.203 d y<sup>-1</sup> (P= 0.0214), while in contrast *Larix decidua* compressed the phenophase by 1.64 d y<sup>-1</sup> (P= 0.0242).

#### 4. 2. 3. Temporal changes in the growing season

The growing season has extended by on average 24.5 d<sup>-1</sup> during the period 1976–2010 in the Czech Republic. The prolongation substantially varied among species from 2.11 d<sup>-1</sup> for *Alnus glutinosa* to 35.19 d<sup>-1</sup> for *Robinia pseudoacacia* per 34 years (Table 4). Some species shifted only one of the phenophase but so greatly that the value for total prolongation of the growing season was quite substantial such as in case of *Betula pendula*, *Cornus sanguinea* and *Salix caprea*. Noticeable shifts were found for *Quercus robur*, *Fagus sylvatica* and *Larix decidua* which are important tree species for the forest industry.

**Table 4.** Temporal trends of the growing season for the period 1976–2010. The change in timing of leaf unfolding (slope LU) and leaf colouring (slope LC) per 1 year and per 34 years and the total prolongation of the growing season (GS) per 34 years are shown.

Species	slope LU (d <sup>-1</sup> )	slope LU per 34 years (d <sup>-1</sup> )	slope LC (d <sup>-1</sup> )	slope LU per 34 years (d <sup>-1</sup> )	prolongation of GS (d <sup>-1</sup> )
<i>Acer platanoides</i>	-0.215	-7.31	0.490	16.66	23.97
<i>Acer pseudoplatanus</i>	-0.294	-10.00	0.557	18.94	28.93
<i>Alnus glutinosa</i>	-0.223	-7.58	-0.161	-5.47	2.11
<i>Betula pendula</i>	-0.196	-6.66	0.535	18.19	24.85
<i>Cornus mas</i>	-0.387	-13.16	-	-	-
<i>Cornus sanguinea</i>	-0.697	-23.70	0.061	2.07	25.77
<i>Corylus avellana</i>	-0.303	-10.30	0.359	12.21	22.51
<i>Crataegus laevigata</i>	-0.397	-13.50	0.122	4.15	17.65
<i>Fagus sylvatica</i>	-0.316	-10.74	0.513	17.44	27.81
<i>Larix decidua</i>	-0.305	-10.37	0.503	17.10	27.47
<i>Picea abies</i>	-0.237	-8.06	-	-	-
<i>Pinus sylvestris</i>	-0.061	-2.07	-	-	-
<i>Prunus spinosa</i>	-0.445	-15.13	0.513	17.44	32.57
<i>Quercus robur</i>	-0.395	-13.43	0.614	20.88	34.31
<i>Robinia pseudoacacia</i>	-0.548	-18.63	0.487	16.56	35.19
<i>Salix caprea</i>	-0.216	-7.34	0.541	18.39	25.74
<i>Sambucus nigra</i>	-0.522	-17.75	-0.019	-0.65	17.10
<i>Sorbus aucuparia</i>	-0.291	-9.89	0.183	6.22	16.12
<i>Tilia cordata</i>	-0.330	-11.22	0.529	17.99	29.21

## Discussion

### 5.1. Shifts in timing of phenophases

Overall my results indicate a general trend in an advancement of spring phenophases and fruit ripening and a delay of autumn phenophases. Similar results have been widely described by other authors (Gordo & Sanz, 2009; Rötzer & Chmielewski, 2001; Schwartz et al. 2006; Menzel *et al.* 2006). The spring phenophases' shifts were stronger and showed the higher proportion of significant values than the autumn phenophases, whose changes were highly variable. The mean break-point year was found to be in 1976 which was close to the global turn-point for Spain (1973) found by Gordo & Sanz (2009). Additionally, there is accordance with the claim that two main time warm periods taking place in the 20<sup>th</sup> century –between 1910 and 1945 and from 1976 onwards (Walther *et al.* 2002). This is sketched in for instance by studies from the USA about lengthening of frost-free season by 5–11 days and subsequent growing season prolongation since mid-1970s (Easterling 2002; Kunkel *et al.* 2004).

The primary force driving the onset of the spring phenophases is air temperature (Fitter & Fitter, 2002; Chmielewski & Rötzer, 2002). But the fact which is sometimes overlooked is that plants employ (in temperate zone) another two factors controlling the end of dormancy – chilling and photoperiod (Estrella *et al.*, 2009; Körner & Basler, 2010; Tooke & Battey, 2010). It is generally assumed that long-lived, late successional species (*e.g.* *Fagus* spp.) that become a dominant in mature forests are sensitive to photoperiod whereas shorter-lived, early successional and pioneer species, such as *Corylus* spp., *Populus* spp., *Betula* spp., are photoperiod-insensitive (Körner & Basler, 2010). Theoretically, the plants whose spring phenophases are triggered only by temperature might have a competitive advantage in comparison with the plants which require for the breaking of the dormancy also the completion of chilling and photoperiod (Körner & Basler, 2010). It is difficult to unambiguously testify this thesis because of lack of studies dealing with physiological demands of particular tree species, but some partial findings are in concordance with this thesis. While Norway spruce (*Picea abies*) is photoperiod sensitive (Partanen *et al.*, 1997; Partanen *et al.*, 2001) apple, pear and some other species of Rosaceae family are not (Heide & Prestrud, 2005). Silver birch (*Betula pendula*) and Downy birch (*Betula pubescens*) seem to be stimulated by photoperiod only to a limited extent (Myking & Heide, 1994). Stríž et Nekovář (2010) also pointed out that the onset of generative phenophases (*e.g.* flowering,

fruit ripening) can depend on the inner energy balance and accumulated energy of the plant whereas vegetative phenophases (e.g. leaf unfolding, leaf colouring, leaf falling) are more influenced by the climatic conditions.

Likewise in this study the most considerable shifts in timing of spring phases (BF, F, BLU, LU) were found for *Cornus sanguinea*, *Crataegus laevigata*, *Prunus spinosa*, *Robinia pseudoacacia* and *Tilia cordata* (Appendix, Table 6) which all are more or less shorter-lived early successful species and hence the findings were in concordance with above mentioned hypothesis. Despite the fact that there have been many papers about European plant phenology, for some tree species we lack data on their response to climate. As I mentioned above the most marked shifts in timing of spring phenophases were showed by the rather shorter-lived species. Other species expected to display this trend showed no or slight changes. For instance there was no significant shift in beginning of flowering of *Corylus avellana* although the findings revealed the advancement up to  $0.91 \text{ d y}^{-1}$  ( $P=0.04$ ) from Lithuania and by  $1.06 \text{ d y}^{-1}$ , ( $P=0.05$ ) from Latvia (Kalvāne *et al.*, 2009). Neither *Alnus glutinosa* showed significant change in timing ( $b= -0.171 \text{ d y}^{-1}$ ,  $P=0.3023$ ), but data from Alpine region (Estrella *et al.*, 2009) proved the significant advance by  $0.41 \text{ d y}^{-1}$ , ( $P=0.0187$ ). This discrepancy could be attributable to local environmental factors. The trend of beginning of flowering of *Sorbus aucuparia* ( $b= 0.275 \text{ d y}^{-1}$ ,  $P=0.0046$ ) in the Czech Republic fitted the map of phenological trends across Europe (Schleip *et al.*, 2009) but the shift was supposed to be greater. It should be mentioned that also late-successional species *Quercus robur* often shifted the timing of the spring phenophases. Its shifts of leaf unfolding were only slight but in a close concordance with the findings from Germany ( $b= 0.31 \text{ d y}^{-1}$ ,  $P<0.05$ ) for the period 1951–1996 (Menzel *et al.*, 2001). Similarly, the shifts of leaf unfolding for *Fagus sylvatica* by  $0.23 \text{ d y}^{-1}$  ( $P<0.05$ ) agreed with the finding from Germany (Menzel *et al.*, 2001).

Another pattern related to spring phenophases is the more striking response of early flowering species (such as *Corylus* spp. and *Betula* spp.) to the warming than that of late flowering species (Ahas *et al.*, 2002; Fitter & Fitter, 2002; Schleip *et al.*, 2009). Plants which begin to flower before the peak of summer temperature advance the flowering whereas plants which are in blossom later on delay it; the gap is so substantial that two ends of growing season occur in some parts of America (Sherry *et al.*, 2007). However, with the exception of *Prunus spinosa*, the species which shifted the flowering the most, were late-flowering species and thus this hypothesis cannot adequately clarify the findings.

While the spring phenophases are easily to recognize, the autumn phenophases are harder to define and therefore this can be followed by the problem of smaller data sample (Sparks & Menzel 2002) such as in my case. Furthermore there is a consensus that the primary driving force of onsets of the spring phenophases is air temperature (Chmielewski & Rötzer, 2002; Linkosalo *et al.*, 2009; Menzel *et al.*, 2006; Sparks & Menzel, 2002). Menzel *et al.* (2006) found a positive correlation between 63% of phenophases in 542 plants across the Europe and the mean monthly temperature of the month which preceded the of onset of a given phenophase. Likewise, Larcher (2006) revealed the close relation between the onset of flowering of Lilac (*Syringa vulgaris*) with the mean air temperature in April. However, activation of autumn phenophases seems to be more complex than a temperature weighted function. Estrella & Menzel (2006) attested that meteorological parameters such as threshold temperatures, sum of precipitation or number of dry days had an effect on onset of leaf colouring with the exception of mean monthly temperatures and found that the warm Septembers and Augusts delayed the leaf colouring whereas warm Junes and Mays advanced it. But all in all, it is generally assumed that the autumn phenophases are triggered by more variable factors (Sparks & Menzel 2002, Estrella & Menzel, 2006) and the differences can be considerable across Europe.

The temporal autumn phenophases changes (LC, BLF, LF, BFR) recorded for some of the tree species (*Betula pendula*, *Quercus robur*, *Acer pseudoplatanus*) included my work displayed by far more random results than those of spring time (Appendix, Table 6). One of the most remarkable shift in terms of leaf colouring was the case of *Betula pendula* ( $b = 0.535 \text{ d y}^{-1}$ ,  $P < 0.0001$ ). While this findings agreed with the trend found in Germany ( $b = 0.10 \text{ d y}^{-1}$ ,  $0.07 \text{ d y}^{-1}$ ,  $P < 0.05$ ) (Menzel *et al.*, 2001), there were noticeable contrasts with results from Latvia and Lithuania where the opposite trend was found ( $-0.27 \text{ d y}^{-1}$  to  $-0.80 \text{ d y}^{-1}$ ,  $P = 0.01$ ) (Kalvāne *et al.*, 2009). *Fagus sylvatica* ( $b = 0.513 \text{ d y}^{-1}$ ,  $P < 0.0001$ ) and *Quercus robur* ( $b = 0.614 \text{ d y}^{-1}$ ,  $P < 0.0001$ ) likewise matched with the trend from Germany (Menzel *et al.*, 2001) where they delayed the leaf colouring by  $0.07 \text{ d y}^{-1}$  and  $0.23 \text{ d y}^{-1}$  ( $P < 0.05$ ). *Acer platanoides* has significantly delayed the leaf colouring in the Czech Republic by  $0.49 \text{ d y}^{-1}$  ( $P < 0.0001$ ) in contrast to Latvia and Lithuania findings, where this species has significantly advanced leaf colouring by  $0.63 \text{ d y}^{-1}$  ( $P = 0.02$ ) and  $0.57 \text{ d y}^{-1}$  ( $P = 0.03$ ), respectively (Kalvāne *et al.*, 2009). Finally *Sambucus nigra* significantly ( $P = 0.0002$ ) advanced fruit ripening by  $0.457 \text{ d y}^{-1}$ , which is similar to the finding from

Germany where the advancement was  $0.30 \text{ d y}^{-1}$  ( $P < 0.05$ ) during period 1951–1996 (Menzel *et al.*, 2001).

Unexpectedly, the beginning of leaf falling has slightly accelerated. This could be partly assigned to the fact that this phenophase had the second lowest number of records and the lowest portion of significant shifts in timing. Even though the analysis of variability (Figure 2) showed that data are rather homogenous they might be still biased because of incompleteness and observers' mistakes. Similar problem accompanied the phenophase fruit ripening of conifers which is defined as the moment when the cones start opening and seeds begin to fall down and therefore it is not so easily detected. In contrast to fruit trees or those with readily observable fruits such as *Quercus* spp. or *Acer* spp., the observation of conifers' fruit ripening is rather difficult even for experienced observers and thus related to the lower number of records in comparison to other species. The delay of fruit ripening of *Picea abies*, *Pinus sylvestris* and *Larix decidua* is in any case remarkable especially with regards of deciduous trees which advanced this phenophase (Appendix, Table 6). The delay could be partly attributed to the need of the plant to throw down the cones on certainly wet soil and hence to have a guarantee of enough humidity which is necessary for the opening of cones. This hypothesis is supported by the fact that also the beginnings of winter (*e.g.* first snow, first all day freeze) delays in last years (Nekovář, *pers. comm.*). Regardless the potential observers' mistakes, the shifts in timing were so robust that there is a possibility of some other physiological cause, which demands further research.

## **5.2. Temporal trends in duration of phenophases**

With the regard to shifts in standard deviation no apparent trend was found. Provided there is any trend, it is likely related to the life history of the particular plant species. Theoretically, both changes - phenophases prolongation and compression (especially during spring time) such as flowering could bring advantages to the plants. A shortening for early spring flowering plants such as *Corylus* spp. or *Alnus* spp. would decrease the likelihood that the blossoms get damaged by the occasional spring freezes. On other hand, the lengthening of flowering of later-blossoming plants means that they could be pollinated by a wider spectrum of pollinators and thus prevent the potential mismatch accompanying the change in the timing of flowering (Harrington *et al.*, 1999).

Also here, naturally, were few tree species which have changed the duration of spring phenophases much more than others such as *Alnus glutinosa*, *Cornus sanguinea*, *Prunus*

*spinosa* and *Salix caprea*. The fact that *Alnus glutinosa* and *Salix caprea* showed little or no change in timing of spring phenophases indicated that the species which have not shifted the onset of phenophases changed the duration of phenophase. This prediction was tested in order to find out the correlation, but no significant results were found. Because all of them are shorter-lived early-successional species, the change in the duration of the phenophase could be only a different form of the same phenomenon which was described above – pioneer species are more adapted to the risky life (Körner & Basler, 2010) and thus probably more adaptable to changing climate. Considering that the most marked shifts in flowering were found for *Alnus glutinosa* and *Salix caprea* indicates the possibility that early flowering plants rapidly react to warming not only by shifting the time of the phenophase (Ahas *et al.*, 2002; Fitter & Fitter, 2002; Schleip *et al.*, 2009) but also by the changing its duration. Further research is needed to test this hypothesis with a larger sample of species.

### **5.3. Temporal trends in the length of the growing season**

The length of the growing season is an important indicator used in agriculture and forestry. The growing season is considered as the time between spring and autumn phenophases (Rötzer & Chmielewski, 2001; Schwartz *et al.* 2006; Menzel *et al.* 2006). As a result of acceleration of spring and postponement of autumn events, the winter time is squeezed and thus the growing season gets longer. The length mainly depends on the beginning of spring phenophases which varies more than of the autumn phenophases which are more synchronized (Chmielewski & Rötzer, 2001; Rötzer & Chmielewski, 2001). A well known phenomenon is the beginning and progress of the onset of the growing season in Europe from South-West to North-East (Menzel *et al.*, 2005). An average length of the growing season is related to the annual air temperature and the increase of temperature by 1°C prolongs the growing season approximately by 5 days (Chmielewski & Rötzer, 2001). According to Menzel & Fabian (1999) the growing season has lengthened by 10.8 days in Europe since the early 1960s. Almost the same figure was found for Germany – about 10 days for the time period 1951–1999 (Schaber & Badeck, 2005) and in Latvia and Lithuania the growing season extended by an average 7 days during 1971–2000 (Kalvāne *et al.*, 2009). In contrast the current study leads to suggest a lengthening of the growing season in the Czech Republic in average by 24.5 days during the period 1976–2010. But it should be pointed out that the prolongation of the growing season was biased by *Alnus glutinosa* which defied the results of the other species. It surprisingly advanced the leaf colouring instead of delay it and then it decreased the average length of the growing



season for the Czech Republic. The range of variability in the length of the growing season was documented by Rötzer & Chmielewski (2001) who found that the growing season lengthened by 12 days in the warm year 1990 however in cold year 1970 it shortened by 10 days in comparison with the long-term mean. But the period of 34 years (1976–2010) should be long enough to dilute such potential extremes. The results of lengthening of the growing season for the particular species were in the same lines. The prolongation of the growing season of *Betula pendula* by  $0.76 \text{ d y}^{-1}$  in the Czech Republic (1976–2010) did not agree well with the lengthening of this species in Germany (1951–1996) by  $0.44 \text{ d y}^{-1}$  (Menzel *et al.*, 2001). The differences among other species were similarly gross – *Fagus sylvatica* has lengthened the growing season in the Czech Republic by  $0.82 \text{ d y}^{-1}$  whereas in Germany by  $0.33 \text{ d y}^{-1}$  and *Quercus robur* even by  $1.01 \text{ d y}^{-1}$  and by  $0.49 \text{ d y}^{-1}$  in Germany (Menzel *et al.*, 2001). With regards of forest industry it would be rather interesting to find out the prolongation of the growing season also for *Picea abies* but due to the lack of data for leaf colouring the elongation of the growing season could not be counted for this species and neither for *Cornus mas* and *Pinus sylvestris*. *Robinia pseudoacacia* has prolonged the growing season the most which gains importance with the fact that it is important invasive species in the Czech Republic.

The length of the growing season should be always considered with regards of used definition which can vary among studies (Schwartz *et al.*, 2006) and thus the results can be sometimes incomparable. This example could be generalized to all phenological events because very often the authors do not offer any detailed description of examined phenophases and hence the comparisons among studies can be difficult.

The timing of the phenophases is a very complex phenomenon which is driven and influenced by many exogenous and endogenous factors. The dataset covered all geographical regions in the Czech Republic (Appendix, Map 1) and thus the influence of local climatic conditions might be substantial. The factors such as orientation, slope and altitude of the locality can considerably influence the findings (Rötzer & Chmielewski 2001). Moreover according to Ziello *et al.* (2009) the beginning of flowering of *Corylus avellana* can be delayed up to 5 days per 100 meters of altitude; on other hand, *Picea abies* included into the same study from the Alpine region showed the delay of beginning of flowering only by one day per 100 meters of altitude. This trend was generally buttressed also by Menzel *et al.* (2001), but at the same time they pointed out that some species' phenophases showed no significant correlation with altitude. Also in this case the

influence of altitude should be considered because in my study the range of the lowest and the highest phenological station was almost 1000 meters (Doksany – 155m a.s.l., Filipova Huť – 1102m a.s.l.). According to Estrella *et al.* (2009) also higher population densities or size of urban areas are correlated with advancement in onset dates because of the influence of heat islands. Not all stations in this study were further away than 10 kilometres from the settlement larger than 10 square kilometres. This area was determined as a limit from which the impact of increased temperature from the settlement is negligible (Zhang *et al.* 2004) and thus this effect cannot be ruled out. In addition a study on olive flowering (*Olea europaea*) revealed that there is no significant difference among different olive cultivars on regional and local levels (Garzia-Mozo *et al.*, 2007), thus the fact that dissimilar varieties of plants are observed and they might be better adapted to the local conditions must be taken into account. And last but not least, the personal attitude of voluntary observers and then the processing of data and methods used for example for detecting of outliers (Linkosalo *et al.* 1996) should be considered in the view of the fact that they can considerably bias the results.

## 6. Conclusion

There is no doubt that the global climate change is one of the hottest issue of the present day. It is very difficult to predict the impact of changing climate on natural systems but the findings from analyzed phenological series can contribute to discussion about potential scenarios.

Also in this study the long-tem phenological series were analyzed to find out the trends of phenophases for the different tree species in the Czech Republic. In general, the change of onset of spring and autumn phenophases were in a concordance with the results from similar studies across Europe which means that spring phenophases have in general advanced and autumn phenophases have delayed. The most substantial shifts in advancement of spring phenophases were revealed for shorter-lived, early successional species which might be related to their life history of pioneer species and insensitivity to photoperiod. This could bring a profit to these species in a form of better ability of tracking the changing climate (Körner & Basler, 2010). The second noteworthy finding of my study referres to conifers' fruit ripening which had an opposite trend than in deciduous species and delayed up to 2.89 days per year which was the largest shift of all species. Unfortunately there is no comparable study dealing with conifers and their fruit ripening but undoubtedly this phenomenon merits further attention. Apart from the timing I also analyzed the change in duration of phenophases. And similarly to trend in means, rather shorter-lived species prolonged or compressed the duration of phenophases the most. But the species which shifted the duration of phenophase and the mean timing were not always the same. Especially for foresters or farmers the information that the growing season prolonged can be interesting and it gains an importance in the view of fact that economically important species such as *Fagus* spp. or *Quercus* spp. have lengthened it by approximately 1 month during the last 34 years.

Natural systems are highly variable and the range of responses to the disruptions is sometimes puzzling. This fact and the complexity of connections in ecosystems however make the predictions about the consequences of the global climate change extremely difficult tasks. But the accomplished studies at least show the areas of expected changes. The timing of phenophases is a crucial mechanism for coexistence of plant species in

ecosystems which leads to reduction of competition for resources (Rathcke & Lacey, 1985). Disharmony in synchronization can promote the disruptions of relationships on intraspecific and interspecific levels through wide range of species and trophic levels (Visser & Holleman, 2001). The special cases are interactions between plants and their pollinators which are expected to be also disrupted (Memmott *et al.*, 2007) and thus the mismatch in synchrony caused by the fact that pollinators are cued to temperature and plants to photoperiod could have highly negative impacts on plant populations (Cleland *et al.*, 2007).

It is generally known that climatic conditions drive the range of plants and animals (Walther *et al.*, 2002) and hence they migrate to areas with suitable climate. The evidence of range shifts can be seen as the tree-limit rise in Scandinavia (Kullman 2001; Truong *et al.*, 2007) or expansion of shrubs in the Arctic (Sturm *et al.*, 2001; Tape *et al.*, 2006). Migration of new species naturally induces the change in the current communities (Cleland *et al.*, 2007; Walther *et al.*, 2002). Furthermore there is a well-founded presumption that the disruptions in plant communities might open the way for non-native and invasive species (Walther *et al.*, 2002). On the other hand, it is important to highlight that not all species display the change in phenology (Visser *et al.*, 1998) and the shifts can vary widely among particular species as was proved also by my study.

To date there are an ample evidence that the shifts in plant phenology occur due to the change of climate. The things which are still not clear-up is what patterns predispose the particular species to their reactions, the range of the responses which we can expect and mainly the consequences of changes in ecosystems considering their complexity and connectivity. There is no doubt that global climate change is an important topic which certainly will influence the ecosystems all around the world.

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## **8. Appendix**

### **8.1. Maps**

### **8.2. Tables**



**Map 1.** Location of phenological stations in the Czech Republic involved in the study.